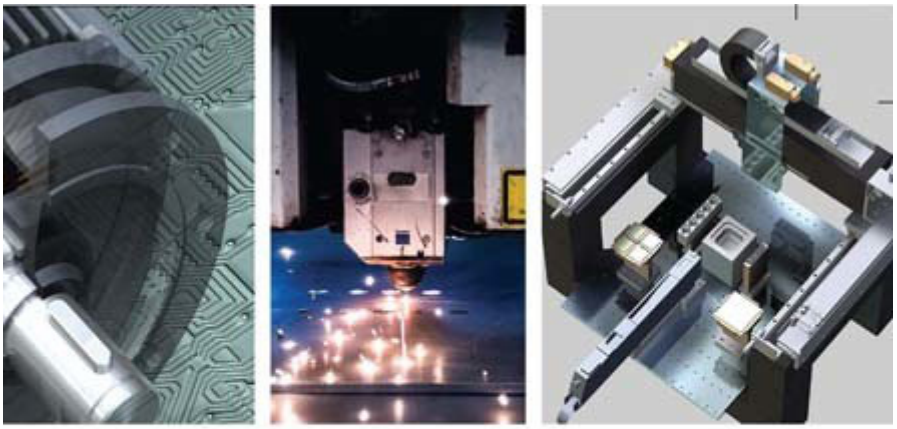

THE CNC HANDBOOK

DIGITAL MANUFACTURING AND AUTOMATION FROM CNC TO INDUSTRY 4.0

HANS KIEF
HELMUT ROSCHIWAL
KARSTEN SCHWARZ

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Hans B. Kief
Helmut A. Roschiwal
Karsten Schwarz

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Foreword

Anyone who works in machining or additive manufacturing technology today must have a solid technical basic knowledge of CNC technology. It is important to know how the individual components work and how they aff ect the overall system, the quality of the products produced, and the profi tability of production. A solid basic knowledge includes knowledge of today's machine tools as well as advanced knowledge of the numerous functions of CNC, electrical servo drives, tool systems, NC programming through digital information processing, and automation.

The planning of CNC-supported manufacturing systems begins with a competent communication between manufacturer and buyer. Often the focus is not on full automation, but on the quest for the technically appropriate and profi table, economical solution. A deep knowledge of the terminology is helpful or even indispensable for a better understanding and decision making. Every CNC user should also be knowledgeable and proficient in the very extensive possibilities and advantages generally off ered by CNC technology.

Because of the high technical eff ort and complexity of digitally automated manufacturing systems, people are still in demand who are trained in CNC technology, who plan and perfect suitable

solutions and who do not lose sight of the profi tability of the system. This includes many individuals, from the planner to programmer, from the set-up person, the machine operator to the specialist responsible for operation, maintenance, and repair. Their special knowledge and understanding of the interaction are prerequisites to keep the operation of such manufacturing systems always functional and profitable.

We have dedicated our book to this selected group of people.

Hans B. Kief Helmut Roschiwal Karsten Schwarz

The three editors are engineers and technical authors with many years of interdisciplinary experience in the areas of developing CNC machines and controls, planning FMS, the use of CNC/CAD/CAM technology, networking, and automation, as well as teaching and training for managers, industrial staff, and students.

The translator, Rupert Hector, has many years of experience in industrial fabrication, use of conventional and CNC machine tools, tool design, and process engineering. Other translations include “Optical Technology” and “Practical Knowledge in Precision Optics.”

THE CNC HANDBOOK

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1 Historical Development of Numerical Control Production

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3 What Is NC and CNC?

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GERMANY AFTER WORLD WAR II

1945–1948. All manufacturing facilities in Germany were destroyed or unusable and in some cases dismantled and sent abroad as war reparations. Production was completely crippled.

The inner cities had been devastated and were largely uninhabitable; tons of rubble blocked the streets and other transportation infrastructure. Electricity, gas, and water supplies were barely functioning, and apart from a few exceptions, industrial production was impossible.

1948–1955. After the monetary reform of 1948, the machine tool and manufacturing industry could be rebuilt. This happened primarily on the basis of previously existing concepts, for during the war and thereafter there was no development of new machine concepts.

Most machines were designed for manual operation, but there was a lack of skilled labor. The few machines that were still available were used for urgently needed mass-produced articles. The demand for goods was practically unlimited. The existing machines operated in two or three shifts in order to satisfy the need for urgently needed consumer products. New jobs were created, but there were not enough workers. More than 8 million Germans had been killed in the war, and over 6 million men were wounded, sick, or still held as prisoners of war.

The solution was found in the calling of *guest* Work was plentiful, and the positions were filled with workers from all the countries of Western Europe. The objective was to rebuild the destroyed cities, factories, bridges, houses, streets, and other infrastructure and to provide for the urgently needed transportation needs. This required all kinds of machines, particularly construction machinery, cranes, backhoes, and trucks.

The main focus of industrial manufacturing was on mass production using manual production machines, transfer lines, and automatic mechanical machines. The life cycle of the products being manufactured was at least 10 years; there was no need for quicker production changeovers. The cumulative result of this enormous need, smart policies, and energetic citizens was called the *German economic*

REBUILDING THE GERMAN MACHINE TOOL INDUSTRY

Because of the conditions just described, within a few years, from approximately 1960–1970, Germany possessed the newest machine inventory of any developed nation. The average age of the machines was five to six years. But these were only a few among the entire inventory; the statistics were misleading in the sense that some of the new machines were still based on prewar technology.

During a comparable period, from approximately 1960–1975, the United States mainly used 15- to 17-year-old machinery. Renewal was brought about through the use of NC machines, such as turning and milling machines and machining centers in the automotive and aerospace industries. The NC technology developed domestically was implemented in the industry much more quickly than in Europe. In addition, many industrial projects, for example, in the defense industries, were subsidized by the government.

American manufacturers of NC machines were very successful in selling their machines worldwide, but they neglected to systematically pursue further research and development. This led to a continuous rise in imports of inexpensive Japanese machines.

The rapid pace of improvements in numerical controls had major effects on all types of machinery and required new and adapted designs. These were often not forthcoming and led to the demise of many American machine manufacturers.

In the early 1970s, Japan started making large investments in machine tool production. These were simple and inexpensive NC machines but based on the newest technology. Soon it was possible to purchase these off the shelf for unbelievably low prices. These inexpensive machines were built according to a different set of requirements: series-produced standard machines without any major modifications, reliable, with standard NC and no choice of control unit.

While German manufacturers continued to supply their traditional European market, the Japanese based their strategy from the very beginning on the global market, with a focus on the United States and later also on Europe. Customer-specific modifications were systematically refused. By the mid-1980s, Japan had caught up with Germany in its share of the global market.

One sign of German manufacturers' diminishing competitiveness was the steadily increasing percentage of imports. From 1973 to 1981, imports increased by more than 10% and made up a third of all machines; by 1991, the rate was more than 40%.

MACHINE TOOL INDUSTRY IN EASTERN GERMANY

In Germany, the Saxonian industrial centers in the Leipzig-Dresden-Chemnitz triangle are considered the cradle of the machine-building industries. Before World War II, they employed 20,000 people. After the war, the industries were also mostly destroyed, this area fell under Soviet control, and the resumption of industrial activity turned out to be more difficult than in the rest of Germany.

In eastern Germany, what later became known as the German Democratic Republic (GDR), most of the surviving industrial enterprises were confiscated by the Soviet Union for reparations. Many industrial leaders, such as Pfauter, Pittler, Hille, and Reineker, moved their operations to western Germany, later known as the Federal Republic of Germany (FRG). Millions of citizens, among them many skilled professionals from the machine tool companies, migrated to the western part of the country out of fear of repressions from the communist regime because at that time the borders were still open.

After 1953, the Soviet Union ceased asking for reparations, and the industries could be rebuilt again, although not as the property of their former owners but as the property of the state under the names *VEB* (for "people-owned company") and *VVB* (for "association of people-owned machine tools and tools"). The state created an organization of tools and machine tools that combined still well-known machine builders such as Heckert, Mikromat, Niles, Auerbach, Union, Moduls, and others.

Because the GDR had almost no heavy industry, the state focused, until the beginning of the 1960s, on building machine tools for very large and heavy components for the construction of turbines and steel and rolling mills. After this demand was satisfied, state planning also provided for machines for small, medium, and large batch manufacturing. Automatic lathes, console milling machines, universal machines, round and flat grinding machines, boring and gear-cutting machines, and various special-purpose designs were part of the portfolio. Machine tools made in the GDR had gained a good reputation all over the world, and about 70% of the production was exported, although half of the exports went to the Soviet Union Unfortunately, the collapse of communism greatly hurt the GDR machine tool manufacturers because of this. In the mid-1960s, the central planning authority had focused on the subject of automation, and in 1964, the Leipzig industrial fair displayed machines with the first German numerical controllers, based on relay technology. Fabrication of numerical controllers started at a VEB in Karl-Marx-Stadt (today Chemnitz) that was a combination of the expropriated branches of Siemens and AEG. The VEB high-voltage-system industry centralized controller production in 1972 and rebranded it in 1978 as VEB Numerik “Karl Marx.”

FIGURE 1.1 GDR-produced CNC-600 controller used in a Heckert machine CW 500. This machine was also used as a module in a flexible manufacturing system.

Starting in 1965, the industry developed and produced a variety of controller generations whose capabilities initially were mostly equal to those of Western origin. Yet the development of control technology suffered under the embargo of the Western countries, which made the acquisition of modern microprocessors and storage modules very difficult. Attempts to develop own microprocessors were only partially successful, and the lead enjoyed by the West increased steadily. The reunification of Germany brought many Eastern machine tool companies close to ruin. Not only had the market in the GDR vanished, but the uncertain ownership of many enterprises, obsolete production

means, and the extremely limited width of the production spectrum also dragged the industry down. Yet most machine tool builders in the former GDR survived, and after some restructuring and ownership changes, they rose to world-class status.

WORLDWIDE CHANGES

In many developed nations, obsolete machines were being used for production even 10 to 15 years after the end of World War II. While at first these were sufficient, increased competition, the pressure to reduce costs, and consumer awareness necessitated modernization of the production machines. Moreover, the 1970s saw the beginning of a worldwide trend toward a buyer's market, meaning quicker product changes and shorter life cycles for almost all products.

The result: a shift happened away from mass production toward smaller lot sizes. Instead of rigid mass production on automatic machines and transfer lines, increasingly more flexible NC machines were used. In addition, the increasing complexity of products resulting from greater use of *computer-aided design* systems necessitated the deployment of up-to-date machine tools with seamlessly integrated data use for quicker NC programming.

New uses for NC machines emerged in the defense industries for tanks, armored fighting vehicles, transporters, and so on. The aerospace industries, with licenses to manufacture jets, helicopters, and other weapons, followed later with systems such as Airbus, MRCA Tornado, Alpha Jet, and the Dornier Do 27. The aerospace industries in France (i.e., Dassault, Aerospatiale, and Snecma), the United Kingdom (i.e., Hawker and British Aerospace), and the United States (i.e., Boeing, McDonnell Douglas, Fairchild, Lockheed, and Sikorsky) were also looking for new machine

concepts. These industries were seeking high-precision machines that could be quickly reconfigured, as well as new machine sizes (i.e., large surface-milling machines and drilling machines) and machining centers. In addition, a large and underserved segment for the use of NC machines was the many small and medium-sized supply companies.

ADVANCEMENT OF THE GERMAN MACHINE TOOL INDUSTRY

From 1968 onward, the FRG aerospace and automotive industries provided a major boost to the country's machine tool industry, advancing such concepts as:

■ Large-surface milling machines and machining centers with a high degree of automation

■ Three- and five-axis milling machines with simultaneous interpolation in all axes

■ Gantry-type milling machines for large milling widths with up to eight parallel main spindles

■ Electron-beam welding machines, flexible manufacturing cells, and a very high degree of automation in workpiece and tool handling, as well as machining

■ High-speed cutting machines for tool and die making

■ New programming and machining strategies such as the APT programming language, CAD, and *manufacturing* that provided for large contracts for many European manufacturers

During the 1970s, Germany became the world's largest exporter of machine tools. At first, a number of new features were simply

added to the old “tried and true” machine concepts without modernizing their basic design. As a result, these machines:

- Had too many parts
- Were too heavy
- Took too long to build and commission
- Had excessively complex designs
- Were too expensive
- Were prone to break down
- Had downtimes that were unacceptably long

Consequently, these machines were not cost-effective for regular industrial use. Only the redesigned and inexpensive machine concepts brought the urgently needed breakthrough in the machine building industry.

THE JAPANESE INFLUENCE

The Japanese standard NC machines, as opposed to those of European and in particular German manufacturers, were made in large batches for an anonymous mass market. Custom features were only available to a small degree. Therefore, Japanese machine tools were less expensive and had short delivery times. These machines and their numerical controllers, such as Fanuc and Mitsubishi, were of high quality and therefore found increasing acceptance. Their wide use in midsized companies and the subcontracting industry forced European machine builders to use Japanese controllers. This opened the door for German manufacturers to gain better access to international markets. The German manufacturers of numerical controllers, such as Siemens, Heidenhain, and Bosch, felt the pressure, saw the opportunities, and adapted their products to international standards.

THE CRISIS IN GERMANY

Starting in 1992, after the boom years of the late 1980s, the German machine tool industry was faced with its most serious crisis since World War II. By 1994, production had fallen by almost 50% and employment by 30%. Finally, the structural and financial difficulties of the machine manufacturers came to the fore.

The crisis was the result of a confluence of a number of problems. The German machine tool industry suffered from the same shortcomings as the American industry in the 1980s. Instead of marshalling their resources to counter the Japanese competition, German manufacturers tried to fend off the Japanese onslaught by means of price reductions—a tactic that could not succeed in the long run. Furthermore, German manufacturers worked against each other instead of collaborating to develop new ideas to make a stand against the ever-stronger Japanese competition. A good strategy might have been, for instance, standardization, such as uniform tool holders and tool changers, uniform pallet changers, and coordinated table heights. Such an approach would have made it much simpler, cheaper, and thus more attractive to introduce flexible fabrication systems employing a combination of machines from different manufacturers. There was also a lack of funds to develop new, less expensive machines.

The competitive atmosphere made it impossible to find common, coordinated, complementary strategic solutions, the kinds

of solutions that many major industries were looking for. As a result, profit margins fell to less than 5% and did not allow for any large-scale, future-oriented development projects. Many German machine manufacturers had no strategic plan; the ones that did lacked the funds to implement it. Instead, almost all manufacturers tried to escape “upward” to the field of specialized and custom machines. But this niche policy had no prospects for success because the custom machines were too expensive given that the basic saturation with standard machines was missing. In addition, potential buyers demanded extensive, detailed contributions from multiple manufacturers without bearing the associated costs. Many highly respected manufacturers headed into bankruptcy or were taken over by competitors in subsequent years.

CAUSES AND EFFECTS

German managers asked the following question openly: What is it that the Japanese are doing better than us? Was it their lower prices owing to lower production costs, their better technical ideas, or their better delivery times?

But that was only part of the equation. Much more profound was the fact that the Japanese had better business ideas, produced in larger quantities, and had a global market strategy! German machine manufacturers were looking for buyers of specialized and custom machines, whereas Japanese manufacturers were looking for markets for standard machines.

Japanese machines were of high quality and were made with about 30% fewer mechanical parts. Customers loved these advantages, which became even more pronounced as time went by. Even hard-core German traditionalists chose Asian products more and more. For the price of one German "super-special custom machine" with a long delivery time, it was possible to buy two or three Japanese standard machines off the shelf. This was not a hard choice to make!

It took until the end of the 1980s and the beginning of the 1990s for the surviving German machine manufacturers to finally realize that they had to build "different" machines to once again attract buyers and be successful. The niche market for German special machine manufacturers had become too small.

The solution for many German manufacturers lay in mergers, often forced on them by the banks. Today, many of these manufacturers have become competitive once again and use as a selling point the fact that they have reduced the number of parts in their modernized machines by 30% to 35%. These companies finally realized that they were on the wrong path, pursuing either obsolete ideas or applying "technical overkill" in the niche market. The industrial purchase departments finally accepted the fact that German machines were on par with Japanese machines and did not have a large number of customer-specific special functions. An important feature was the new and powerful menu-driven NC programming systems that allowed input both on programming stations and also directly on the machines.

The revival of the German machine tool industry was also helped by new technologies and completely new types of machines, such as high-speed cutting machines and high-power lasers for welding and cutting, additive manufacturing methods such as rapid prototyping systems, and machines for hard machining of metals and ceramics. Nevertheless, universal machines for the complete processing of one workpiece with a single setup have gained a certain interest. Furthermore, the use of new, highly dynamic servo drives has been making these machines faster and more precise.

FLEXIBLE MANUFACTURING SYSTEMS

In the 1970s, large American companies such as Caterpillar, Cummings Diesel, General Electric and a number of machine manufacturers such as Cincinnati Milacron, Kearney & Trecker, and Sundstrand began designing and installing the first *flexible manufacturing systems* These systems consist of several identical or complementary NC machines and a common workpiece transport and control system. Such systems can be used profitably to produce, depending on the order, either single parts or small to medium-sized lots. In special cases, FMSs also can be used for large-scale series production. During this time, the first FMSs were tested successfully in Japan and marketed internationally. Visitors came from all over the world and were impressed by the unmanned production in unlit factories.

In Germany, demand for FMSs was at first very guarded. The reluctance to embrace the innovation was due to the extensive engineering, such as the customer-specific planning and dimensioning of such systems at the customer's location and the very involved calculations pertaining to time, unit cost, and investment generally required by the customer. All this led to high costs and high prices. It was only when the futuristic visions of "factories without workers" gave way to "manufacturing with reduced personnel" based on affordable manufacturing concepts that German users started to take more interest in such systems.

In 1974, the Bauer Company of Esslingen, Germany, installed one of the first FMSs in Germany. It consisted of nine identical machining centers, made by the BURR Company, with Bosch/Bendix controllers, a recirculating pallet system for automatic workpiece transport, and automatic pallet transfer stations at each machine. It was a decisive factor that then the first NC systems became available that used program memory instead of punched-tape readers. In the following years, Bauer expanded this system to include 12 machines and in 1988 upgraded them with higher-performing *computerized numerical control* systems. More than 20 years of two- and three-shift operations have fully satisfied the users' technical and economic expectations. Finally, it was possible to produce goods to order, reduce warehouse inventory, and still deliver on short notice.

After the initial positive reports, other FMSs were implemented in many other manufacturing companies. In Japan, the United States, and Europe, FMSs, designed according to the state of the art, are being installed continuously. Positive experience gained with these systems and their cost-effectiveness have led to better FMS-compatible machines that are easy to combine and operate. The integration of robots for tool and workpiece handling also has led to improved systems. For early detection of planning errors, powerful simulation and *production planning systems* were developed.

Starting in the early 1990s, a certain sense of sobering set in concerning the use of FMSs. Even though these systems are highly productive, they are only flexible to a certain extent, and they are an expensive investment. Furthermore, the operation and maintenance of a FMS mandates highly skilled and thereby

expensive personnel. Thus, low-cost standard machinery made in Asia became an alternative to respond quickly and flexibly to market requirements.

Nevertheless, FMSs will continue to be employed where production technology deems them beneficial because of their increasingly powerful and reliable control and computer technology. But compared with the rapidly growing use of standard machines, the application of FMSs has declined.

In the GDR, before the fall of the wall, the use of FMSs as a means of increasing production was recognized. Thus the machine builder VEB "Fritz Heckert" (today "Starrag-Heckert") became the first manufacturer in the Eastern Bloc to implement a FMS for its own fabrication of console milling machines, called the FMS "Prisma." It contained nine cutting machines (milling, drilling, and grinding) in conjunction with various transfer stations, prep stations, and cleaning and cooling areas. The entire installation, completed in 1971, was controlled by a central computer. Each month it produced 500 components for its production of console milling machines, and the system operated for about 18 years. Until the end of the GDR, more FMSs were installed for use in the production of machines for agriculture, commercial vehicles, and machine construction.

WORLD ECONOMIC CRISIS OF 2009

The German machine tool industry started seeing a decline in orders at the end of 2008, and the decline lasted until the middle of 2010. The causes of the crisis occurred much earlier. The largest financial and economic crisis in two generations developed out of an array of inconspicuous events and aberrations. Today we know that faulty credit management led the global financial system to the edge of the abyss.

The crisis was triggered by mortgage banks that presumed that the prices of houses would continuously increase and offered their customers questionable mortgages. The bundled mortgages were then sold to Wall Street banks. Contributing factors were the increasing trade imbalance of the United States, a decreasing savings rate, and excessive borrowing to finance acquisitions. Early 2009 was just the beginning of mounting unemployment. Banks carried a debt of US$1 trillion, not yet depreciated. Because of the interconnectedness of most national economies, the crisis spread almost over the entire globe and triggered a giant political backlash. The major governments pumped trillions of dollars and euros into their economies, and the indebtedness in Germany, because of the rescue of the banks, was significant.

In Germany, the critical situation was countered with an intelligent ploy: mass layoffs could be averted by allowing companies to reduce work hours for up to 24 months. As the economy recovered, slowly at first starting in 2010, engineering teams and skilled labor in the factories were ready to fill orders.

In 2011–2012, the German economy in general and the machine tool industry in particular were in an upswing—orders were pouring in. Yet the previous two years had wrecked havoc in a hitherto unknown scope. First, there was a brutal synchronized crisis in liquidity; next, quite as rapidly, the German economy recovered and reached the precrisis level. Pundits even talked about a second German economic miracle. The same held true for some Asian countries.

SITUATION AND OUTLOOK

The CNC machine tool has become a mass product and is used equally in large-batch production and medium-sized manufacturing environments. Because of globalization, markets have moved to the East not only in terms of manufacture of machinery but also in machine applications. Germany is still a top-tier manufacturer, but manufacturers from Japan, China, Taiwan, Korea, and India can also be found among the top performers.

Thus, one is faced with a two-pronged situation. First, goods can be mass produced using simple, standard machines with a low degree of automation in a standalone mode. Next, the European high-production-cost countries require a highly automated fabrication technology with a minimum of personnel. CNC fabricators realized this trend and have come to offer an appropriate controller for each possible application. Besides the established manufacturers, such as Siemens, Fanuc, Mitsubishi, Heidenhain, Fagor, Chinese manufacturers, such as the renowned GSK, have entered the market in great numbers. Until now, these products are mostly used in the Chinese market, but it stands to reason that a global presence is only a matter of time.

Fabrication technology and automation advance continuously all over the world; new ideas and concepts blossom. An important feature is the CNC machine with an integrated robot, now available in many formats and adaptable for all possible applications. Highly precise linear drives, position-measuring

systems with extremely high resolution and precision, and state-of-the-art machine concepts make CNC machines an unequaled fabrication system and not just for cutting operations. Today, there is a high demand for robots. All industrial nations have developed their own robot systems and offer them for fabrication, handling, and assembly operations.

The increased application of robots drives the degree of automation. One could say "Yes" to automation, but not at any price! In order to stay profitable, several considerations must be addressed in the planning stage. An important aspect is the digitalization of the factory, and this is only possible with robots. *Digital fabrication* will play an ever-increasing role in the coming years.

FMSs will remain relevant; the rapidly increasing power of computerized numerical controllers and computer systems allows for a greater functionality and greater flexibility. Besides, to combine machine tools within a network for large-batch production and on a smaller scale, such as workshop and subcontracting settings, has become commonplace. Customers and producers today are connected through computer networks, and often production methods and quality assurance programs must be provided and documented, for instance, in the fabrication of aircraft components and medical devices, before actual CNC operations can commence. This implementation of the so-called continuous process chain, tailored to the appropriate production principles, will remain a challenge for the near future.

Beside these corollaries, the demand on the machinery and in particular CNC machines will increase. Whereas until the end of the twentieth century the use of a five-axis CNC milling machine was a high-end application, today such machines have become almost standard. To produce ever more efficiently, complete parts machining is coming more and more into focus. To perform as many processing steps as possible on one machine without reclamping is not only a question of time and productivity but also one of quality.

In addition to machining a workpiece on a five-axis milling machine on several surfaces through the tilting of the worktable and/or the tool head, multitasking technology is becoming ever more important. In machine tool engineering, this is to be understood as the combination of different cutting technologies, such turning/milling, grinding, laser processing, and so on. The combination of cutting technologies on multitasking or hybrid machine tools increases productivity and quality, yet the designers of the CNC machines and related processing systems must make these systems manageable. Highly automated production systems also require continuous monitoring of the process. Reliable systems to keep track of tool integrity and measuring probes to check quality with automated data-entry and correction procedures can provide for unmanned operation of production sites.

Finally, a word about the well-established fabrication processes used for *rapid prototyping manufacturing* Depending on the job at hand, different methods and processes are available to fabricate a test piece or workpiece on a CNC machine based on a CAD model. Tool and die making in particular has strongly adopted this technology. Generally, machines for RPM use lasers as a universal

tool for completely new production processes. Many German and European manufacturers are entering and becoming very successful in this area.

CONCLUSION

In the course of about 50 years, NC technology has brought about major transformations not only in the machine tools themselves but also in the entire manufacturing environment and the people involved. Manufacturers and users have learned not to strive for 100% automation on a purely theoretical basis but rather, when performing manufacturing and automation analyses, to include all parties involved in the process. Only in this manner can one achieve technically and economically viable solutions. Working together, machine and controller manufacturers have developed technically sophisticated manufacturing concepts at market-oriented prices and have managed to contain the initial Japanese success.

Today's manufacturing industry would not be possible without such high-performance components as computers, machine concepts, automatic transport and handling systems, reliable controllers, and intelligent monitoring systems. And that is certainly not the end of it!

To exploit the benefits of this technology profitably, highly educated and trained personnel are absolutely necessary—all the way from management to the shop floor. Only such personnel will be able to plan, implement, operate, and maintain these complex systems competently. In this regard, Germany has a great and internationally acknowledged advantage because of its dual education system. A highly trained labor force is the basis for

Germany's economic success, and this is particularly so for the machine tool industry. Despite the automation and great functionality, CNC producers must see to it that even a complex machine can be simply operated and that the control is reliable and trouble-free.

Since 2008, the topics of environmental protection and energy efficiency have been attracting more and more public discussion. Implementing these requirements also will have an effect on the mechanical engineering and manufacturing technology industries. Machine tool and controller manufacturers are already considering how they can optimize auxiliary drives, work processes, and NC parts programs for greater energy efficiency.

At the Hannover Industrial Fair in 2011, the term *Industry* for "fourth industrial revolution," was coined. It signifies the ever-increasing customization but, at the same time, affordable production of mass goods. For the machine tool industry, this means that from the product idea to its fabrication, the path must be a more consequent implementation of a contiguous process chain, with the use of the internet and CAD/CAM tools. It will be successful if all involved parties, such as machine builders, manufacturers of tools and auxiliary parts, metrology, and CAD/CAM systems, subscribe to the same objective and work fruitfully together.

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THE PATH TO NC

The primary task of control systems used in production machinery is to ensure that sequences of motions are repeated quickly and accurately, thus creating mass-produced articles of uniform quality without human intervention. Depending on the control components used, these systems can involve mechanical, electrical, electronic, pneumatic, or hydraulic controls.

In order to process a workpiece, a machine tool needs information. Before the introduction of NC technology, the path information was either entered manually by the machine operator or using mechanical aids such as templates or cam discs. Changes in the sequence of operations or changes to different products therefore involved relatively long downtimes for the changeover of the machines and controls. Adjustable cams and cam rails were used in combination with limit switches to terminate motions at precisely defined positions. The precise adjustment of these limiting cams was very time consuming. Added to this were the times required for manual changes to tooling, for specifying the spindle speeds and feed rates, for clamping the workpiece and fine-tuning the setup of the machine, and for exchanging the program. The overall scope of control of these program controls was very limited in part because of the small number of switching steps.

The flexibility needed for frequent changeovers could not be achieved in a cost-effective manner with these machines. This

meant that a new control concept had to be developed that would meet the following requirements:

■ The maximum possible scope of control regarding program length and motions

■ No manual assistance through intervention in the machining process

■ Sequential programs that could be saved, exchanged, and corrected quickly

■ No cams or limit switches for paths of different length

■ Simultaneous 3D motions of multiple axes that could be precisely defined for the machining of complex shapes and surfaces

■ Quick changing of tools, including feed rates and speeds

■ If applicable, automatic changing of the workpieces being machined

The goal was to create control systems that could be converted quickly and without error between various machining tasks. To control the relative motion between tool and workpiece, the dimensions from the workpiece drawing should be used. High-resolution position-measuring systems with measurement data that

could be evaluated electronically would allow precise relative motion between the machine and the tool.

Such control systems thus would function through the input of numbers, that is, numerically. This defined the basic idea of numerical control systems. In addition, it should be possible to use additional numerals to program feed rate, spindle revolutions per minute (rpm) and tool number. It should also be possible to use additional on/off commands (M-functions) to activate automatic tool changing and to switch the coolant on and off.

All the numerical values arranged step by step according to the processing sequence constitute the NC program that is used to control the machine.

From NC to CNC

The first NC systems were constructed by using relays and were either hardwired programmed or simply hardwired. The first electronic function modules followed in rapid succession: vacuum tubes, transistors, and integrated circuits (ICs). But it was only with the advent of microelectronics and microprocessors that control systems became more economical, more reliable, and more powerful.

In order to process workpieces, in addition to the path and switching information, CNC systems have to constantly process additional numerical values, for example, to compensate for various tool diameters and tool lengths or clamping tolerances. Thanks to their high processing speeds, such systems are able to

execute a complete range of administrative, display, and control functions in a timely manner. Notwithstanding this, it is also possible to input the parts program that has to be processed next on the machine using graphical dynamic support.

HARDWARE

The electronics of modern CNC systems make use of microprocessors, ICs, and possibly special modules for the servo control circuits In addition, the systems can contain electronic data memory for a number of programs, subprograms, and many compensation values:

FIGURE 3.1 Examples of highly integrated microelectronics components.

■ Read-only memory (ROM) and erasable programmable read-only memory (EPROM) components usually contain the fixed parts of the CNC operating system plus frequently used fixed cycles and routines.

■ Flash erasable programmable read-only memory (FEPROM) is used to store data that can only be determined during commissioning and that must not possibly be lost but be modifiable, such as machine parameters, special cycles, and subprograms.

■ Random-access memory (RAM) with expandable capacities stores subprograms and compensation values.

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The graphical displays and dynamic simulations likewise require a great deal of computing power and memory. For this reason, most controllers use additional special customer-designed very large scale integration (VLSI) chips. These are highly integrated microelectronic modules that are designed according to specific customer requirements and are produced in large quantities. In this manner, it is possible to obtain compact component dimensions and control units with high reliability and speed and minimal maintenance requirements in subsequent operations.

All the electronic modules are located on one or more printed circuit boards (PCBs), which are plugged into a module rack and are connected to each other via an internal bus connection In order to prevent the CNC system from malfunctioning, the electronics are built into a metal case that provides electrostatic and electromagnetic shielding. The case also should prevent contamination by oil and dirt because even the finest metal particles would jeopardize the proper functioning of the system if they were to become deposited on the circuit boards.

FIGURE 3.2 Plug-in electronic module for an industrial PC (IPC). Drive, CNC, and programmable logic controller functions are combined on one card. It contains TCP/IP, Profibus, and SERCOS interfaces.

Therefore, circulating air must not be used to cool the interior of the case, even if it passes through a filter, because filters could become clogged, thus rendering the cooling system ineffective. If

the heat is not dissipated from the surface of the case adequately, the only acceptable solution to the problem is an active cooling unit. This increases the allowable ambient temperatures to a range of +10 to +45°C (+50– 113°F). The humidity should be between 40% and 50%. Even at lower humidity levels it is often necessary for the user to guard against excessive accumulation of condensed water, which also can lead to malfunctions and damage.

SOFTWARE

CNC systems require an operating system, which also may be described as control software or system software. It essentially comprises two parts:

- The standard software
- The machine-specific software

The standard software is used, for example, for data input, display, interfaces, or table management, and in some cases, these actions can be handled by standard commercial computers. The machine-specific software has to be designed especially for the machine type being controlled because there are often major differences in the kinematics and operating characteristics of different machines.

One advantage of CNC systems is that modifications and adaptations can be made without changes of the CNC hardware. The machine-specific features, say, whether a machine becomes a lathe or a milling machine, can be determined via parameters or machine data during commissioning or can be preconfigured by the CNC manufacturer as a lathe, milling, or grinding controller.

The operating system has a decisive influence on the overall performance of the machine. The software also manages a

number of processes that run continuously in the background: monitoring and error diagnostics and logging of machine data and data interfaces. This also includes the CNC-integrated programming system with graphical simulation of the machining process and processing of the compensation values. It is also possible to manage machine-specific variants via the software. Such variants may consist, for example, of the number of axes; parameters for the servo drives, various tool magazines, and tool changers; software limit switches; or monitoring devices. The machine parameters only need to be entered once during commissioning; they are stored permanently and may only be changed by authorized personnel.

CNC manufacturers develop their control and system software using an integrated programming language. The core of the CNC controls interpolation, movement control, and CNC commands can only be altered in close cooperation with the controller manufacturer. The machine manufacturer can specifically configure the machine via parameters and machine data. Additionally, custom graphics, for instance, for machine-specific modules or routines, such as chip conveyers, pallet changers, and relief routines for emergencies, can be provided. Processing macros or cycles can be provided by the machine manufacturer or the user, thus supporting individual cutting technologies or custom tools.

CONTROL METHODS

In terms of their initial development, a distinction can be made among four different levels of controller performance:

1. Point-to-point control systems These systems operate only in positioning mode. All the programmed axes always start simultaneously at rapid traverse speed and continue motion until each axis has reached its target position. Tools are not engaged while the positioning is underway. Machining does not begin until all the NC axes have reached their programmed positions. Examples: Drill presses, punching presses, and feed motions of cutoff machines.

2. Line motion control systems. Motion in these systems can take place along the individual axes one after the other at a programmable feed rate; the tool can be engaged during this time. The travel motion is always parallel to the axis, and the feed rates have to be programmable. These severe technological limitations, and the fact that line motion control is only slightly less costly than path control systems, make this option applicable only in specific circumstances. Examples: Feed control for drill presses and workpiece handling.

3. Continuous-path control systems. These systems can interpolate the motions of two or more NC axes; that is, they can execute their motions in an exact ratio to each other. This motion is coordinated by an interpolator, which calculates the points along the path between the start and end points in a block-by-block manner. The NC axes do not stop at the programmed end point, however, but rather

continue to move without interruption to the end point of the subsequent path section. The feed rates of the axes are controlled continuously in such a way that the designated cutting speed is maintained. This is called three-dimensional continuous-path control or 3D control for short. It allows tool motions to be executed in a plane or in space. Examples: Milling machines, lathes, wire-cutting machines, machining centers—all types of machines, in fact.

4. For the simultaneous interpolation of multiple NC axes, different interpolation methods are available.

a. Linear interpolation 3.4 and In this method, the tool moves linearly, that is, in a straight line from the starting point to the target point. Theoretically, linear interpolation could be programmed for any number of axes. For machine tools, it is practical to apply linear interpolation for up to five simultaneous axes; these five would include X, Y, and Z for determining the spatial target point to which the motion should be directed plus two additional rotational motions, for example, A and B, for determining the position of the cutter axis in space or for machining on inclined surfaces. This makes it possible to produce all kinds of profiles and curves in space by approximating them with polygon lines. As the individual points of support become closer to each other, that is, as the tolerance width becomes narrower, the approximation to the specified profile becomes more accurate. However, a greater number of points also require a greater amount of data to be processed per unit time, requiring the appropriate processing speed of the CNC.

b. Circular interpolation Theoretically, it should be possible to approximate all kinds of paths by means of linear interpolation with polygon lines. The use of circular and parabolic interpolation reduces

the amount of input data, resulting in easier programming and more accurate approximation of these paths. Circular interpolation is limited to the principal planes XY, XZ, and YZ and is programmed using various methods depending on the type of controller being used. These methods include programming in quadrants, in a full circle, by specifying the arc center, or by programming the arc end points and radius.

c. Parabolic, Spline, and Nano/Picointerpolation. Advanced computerized numerical controllers allow the interpolation of parabolic or splines curves and the interpolation in higher resolution (see Chapter Spline curves are smooth, continuous curves passing through specified fixed points and are used mainly to program sculptured or free-formed surfaces (see "Spline Interpolation" in Chapter As a result of nano- or picointerpolation, the NC axes run much more smoothly in interpolated path execution, thus producing better surface quality on the workpiece.

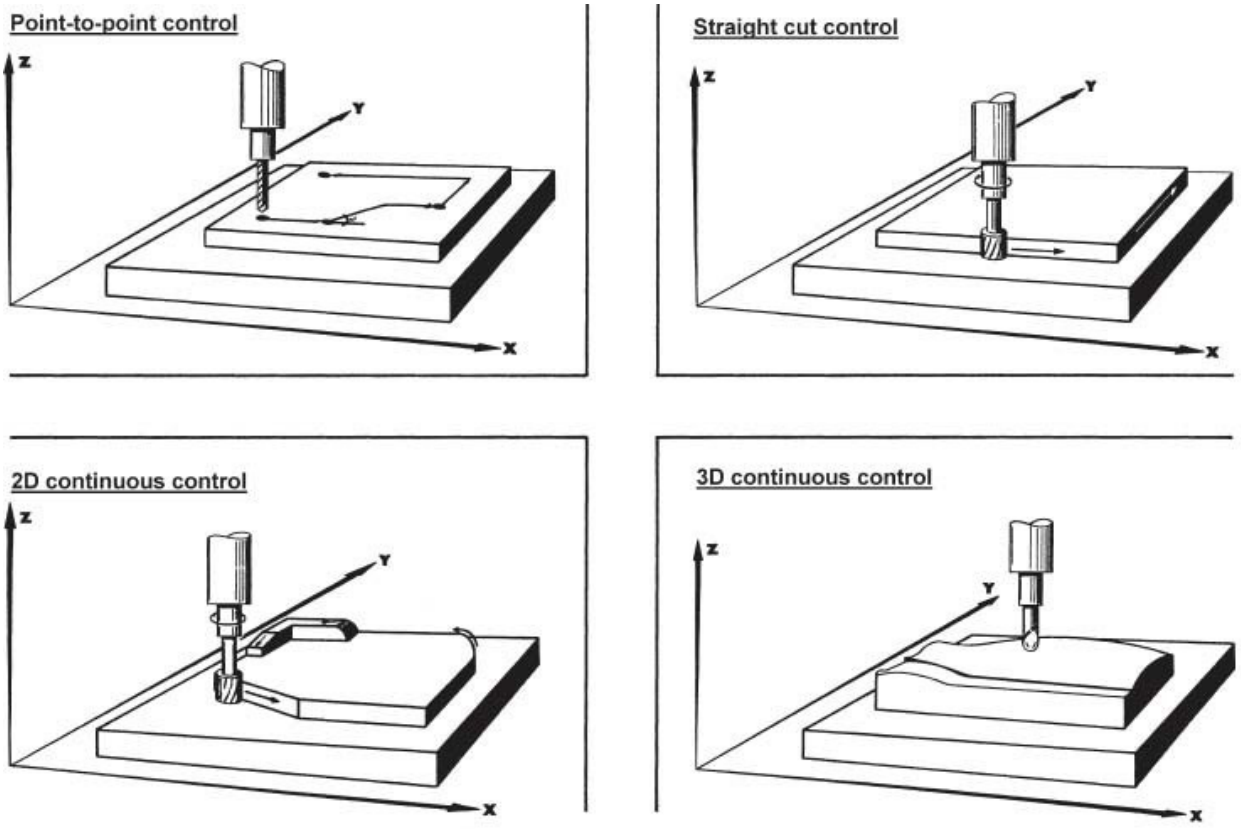

FIGURE 3.3 Development of NC technology from point-to-point to 3D continuous-path control.

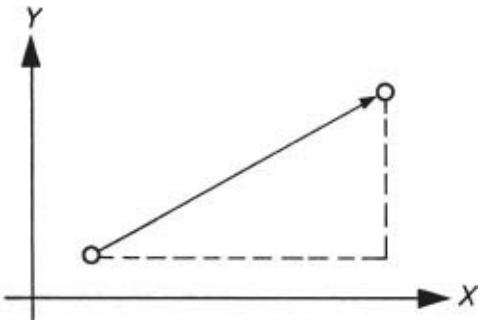

FIGURE 3.4 Linear or straight-line interpolation.

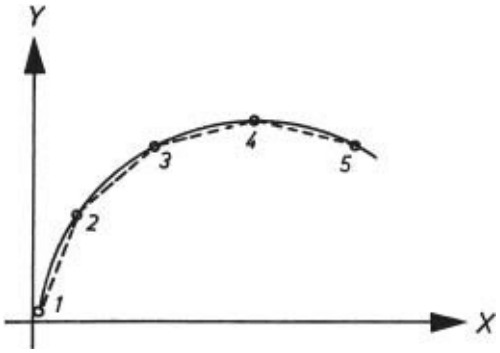

FIGURE 3.5 Poly line (dotted) as an approximation to a curve.

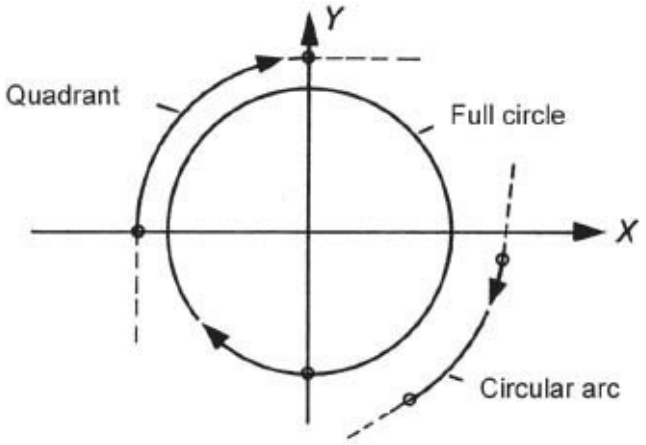

FIGURE 3.6 Circular interpolation.

NC AXES

Depending on the specific machine, the coordinate axes can be designed as translational or rotary axes. Translational axes generally are perpendicular to each other, thus allowing movement to every point in the workspace. Two additional rotary and swivel axes allow the machining of inclined workpiece surfaces or tracking of the cutter axis.

For axes to be controlled numerically, each NC requires:

- An electronic path-measuring system
- A servo drive

It is the task of the CNC system to compare the target positions predefined via the CNC system with the actual position values returned by the path-measuring system. If these values differ, the CNC system must issue a control signal to the axis drives that then will compensate for the deviation This is called closed-loop control. Continuous-path controls output new position values on an ongoing basis, and the controlled axes must follow these values. Continuous-path motions thus are achieved. On lathes, the main spindle is also designed as an NC axis when live tooling is used for drilling or milling. With drilling and milling machines, it is also possible to design the spindles as NC axes in order to allow programming of the functions spindle orientation and helical interpolation.

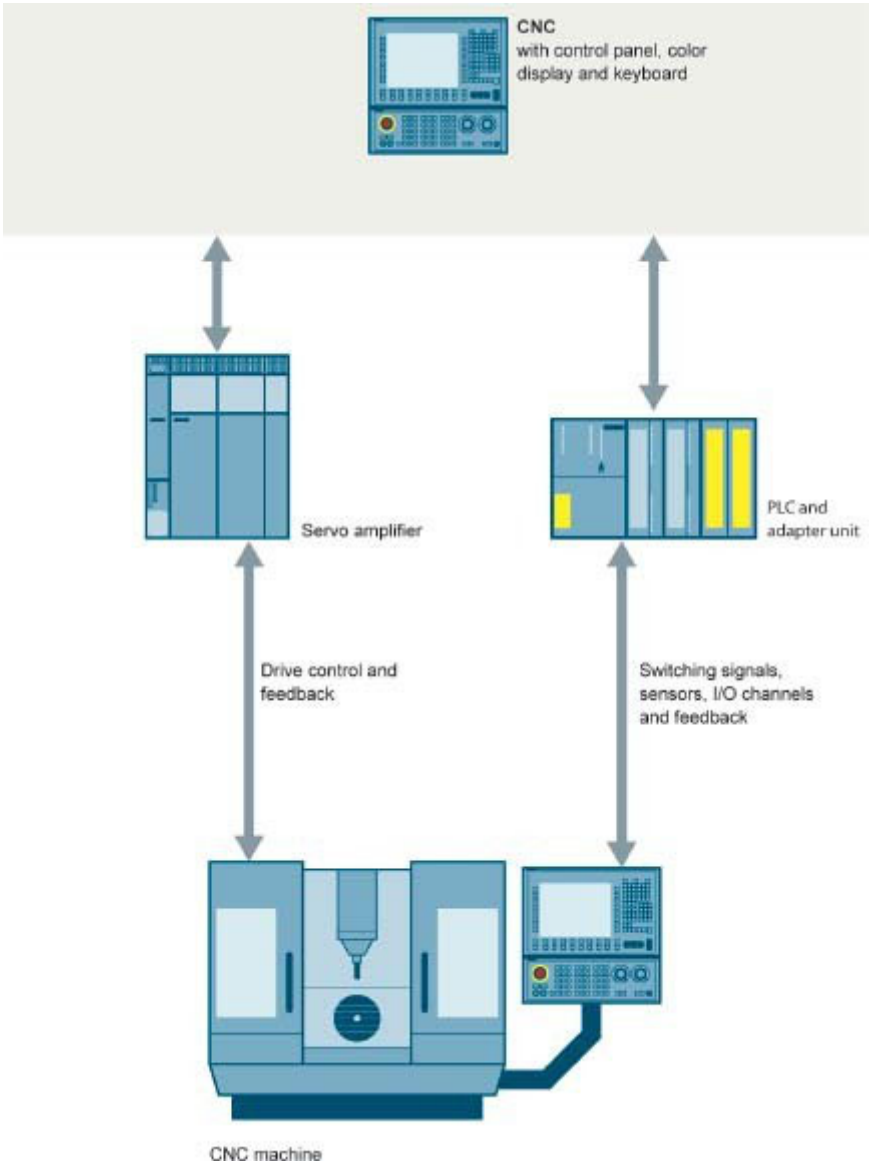

FIGURE 3.7 Principle of a CNC with operator input, programmable logic controller (PLC), and servo amplifier.

Machining centers are usually equipped with numerically controlled rotary tables. Increasingly, individual positions in the workpiece magazine are also controlled in the same manner as NC axes. The use of position-measuring systems means that there

is no need for costly coding devices for the detection of the magazine position numbers or tools. This makes the entire process for finding and changing tools much faster.

The axis designation of the machine follows the rules of the Cartesian coordinate system:

- Translational axes with the address letters X, Y, Z

- In addition, parallel axes with U, V, W

- Rotational or swivel axes A, B, and C (see “Numerically Controlled Machine Tools” in Part

PROGRAMMABLE LOGIC CONTROLLERS

Programmable logic controllers (PLCs) are, in a way, the "electronic successors" of the relay controls that were used previously for the same purpose, but with the additional advantages of smaller dimensions, lower failure rates, and quicker response times. The essential function of a PLC is to control and monitor all the integration and interlocking tasks. Some functions that are always executed in the same sequence, for example, tool changes and workpiece changes, are merely "initiated" by the CNC via an on/off command. The rest of the process is performed automatically, with each step controlled and monitored by the PLC. Once this cycle has been completed without errors, the PLC sends a signal to the CNC to continue the NC program sequence (see Figure

All the control tasks are stored in the PLC as software. This is especially advantageous in the event of changes, modifications, and expansions, as well as with regard to the electrical equipment of series production machines. The PLC hardware can be integrated completely into the CNC system; that is, the described logic functions are adopted by the CNC processor, and the control signals are output to the interface section. In the case of more complex machines, the manufacturer generally prefers to use a separate PLC. This has the advantage that the machine manufacturer can create and test the PLC program independently of the CNC system. This means that many functions can be put into operation even before the CNC system is delivered (see Part Chapter "PLC - Programmable Logic Controllers").

The PLC is also being used to monitor the machining process itself. Spindle rpm or emergency signals, for instance, in case of tool failure, can be detected by the controller directly, and corrective measures can be taken in the context of the PLC cycle time. But because the reaction time of highly dynamic machines and processes might not be sufficient to prevent damage to the machine or the workpiece, most CNCs contain a limited number of quick input and output channels that communicate with the CNC directly. Examples for the use of these quick input/output channels are the processing of signals from cam switches and measuring probes.

INTERFACE SECTION

A distinction is made between an interface section and an interface controller (see Figure An interface section comprises the electrical cabinet, including all fuses, motor circuit breakers, transformers, contactors for auxiliary drives, and amplifiers for high-performance drives and terminals. The interface section is used to operate the auxiliary drives, which move, for example, the mechanical components for tool and workpiece changing or the switch on the coolant and chip-removal system.

If a CNC machine has a separate PLC, it is also built into the interface section.

The task of the interface controller is to decode, interpret, and execute logic operations and control machine-specific sequences of functions. In today's CNC systems, this is the main task of the PLC. The necessary hardware generally is integrated into the CNC circuit board.

COMPUTERS AND NC

The development and use of computers and CNC systems happened almost simultaneously from the beginning. Their fields of use expanded very quickly.

Computers in CNC

Today, microcomputers are the central element of every CNC system. Because the hardware components of industrial personal computers (IPCs) have become standardized, mass-produced products, the development focus for computer users has shifted to the software. Thanks to computer technology, it has been possible to incorporate more and more CNC functions into smaller and smaller spaces. Using software, it has become possible to improve the integrated system monitoring and error diagnostics of CNC systems to such an extent that malfunctions could be eliminated.

The most important effect, however, was increasing performance while simultaneously reducing costs and prices. The miniaturization of CNCs also has resulted in visible benefits. The previously bulky electrical cabinets became smaller; in some cases they have turned into smaller control cabinets attached to the machine.

Computers for NC Programming

Computers have long been used in the programming of NC machines. There have been considerable reductions in the expense of programming work and the time required to program

geometrically complex workpieces and 3D surfaces. Integrated contour calculators can handle difficult and therefore time-consuming geometric calculations of points of intersection, transitions, contour segments, phases, curvatures, and shapes. Today, the NC programmer only needs to enter the required data from the drawing or import the data directly from the CAD system. There is no need for auxiliary calculations.

Because computers have become smaller, more powerful, faster, and more economical, it also has become possible to integrate machine-specific NC programming systems directly into the CNC system. This gave rise to CNC systems in which interactive, graphically based programming can be performed on the machine. These manual data input controls for shop-floor programming (SFP) provide excellent programming tools and graphical displays. Clearly, the best programming aids available today are color graphics and interactive programs. Modern CNC systems often come with integrated simulation software that displays the planned processing of the workpiece, including the cutting and clamping tools used. The output can be switched between 3D and 2D views. In order to display the correct execution of back-cuts or covered cuts, the software allows a programmer to access sections of the workpiece. Possible collisions that might occur in the work area thus can be largely eliminated. Simulation can also calculate the processing time, which helps cost analysis efforts.

Computers for Automation

Computer technology also has had a major impact on the design of CNC machines. CNC-controlled loading and unloading stations for workpieces increase the degree of automation and the flexibility

of machines. Exchangeable tool cassettes make it possible to prepare complete sets of tools externally for rapid change. The integration of robots makes tool changing faster and more flexible. The systematic use of new control and drive technologies allows for a reduction of about 25% to 30% in the number of parts and the price of machines while simultaneously boosting performance.

An increasing number of specific tasks in manufacturing operations are being assigned to networked computer systems in order to make production as cost-effective as possible. These computer-integrated manufacturing (CIM) systems are already being used profitably in a wide range of configurations.

Combining multiple CNC machines into a flexible manufacturing system (FMS) could only be implemented when the task of overall production control for such a system could be assigned to one or more designated computers. Not only does this include direct numerical control (DNC) systems for the automatic transfer of NC programs to the CNC systems, but it is also necessary to have all workpieces, tools, and data available at the right machine at the right time. Additionally, the movement of all parts through the FMS must be controlled and monitored, and the entire process must be documented. In case of minor problems in the system, operations should be maintained making use of emergency strategies in order not to lose valuable production time.

The combination of CAD, NC programming, and CNC manufacturing is called digital manufacturing. No other alternatives are in sight, given the demand for faster conversion of CAD data into prototypes and for quicker introduction of new products. Computers are being used more and more for planning,

preparation, transport, measuring, testing, monitoring, installation, and adjustment

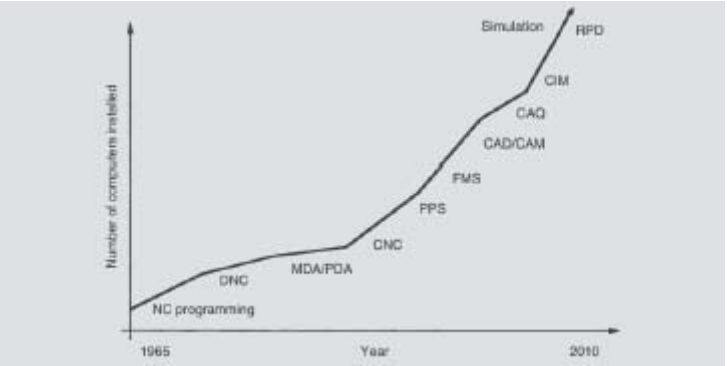

FIGURE 3.8 NC manufacturing and automated data processing mean that more and more computer systems are being used to perform a wide range of tasks in the manufacturing sector. The trend is continuing.

NC PROGRAMS

In order to process a workpiece using a CNC machine, the user creates a workpiece-specific NC program Depending on the organization or the complexity of the workpiece, this can take place either during production planning or directly at the machine.

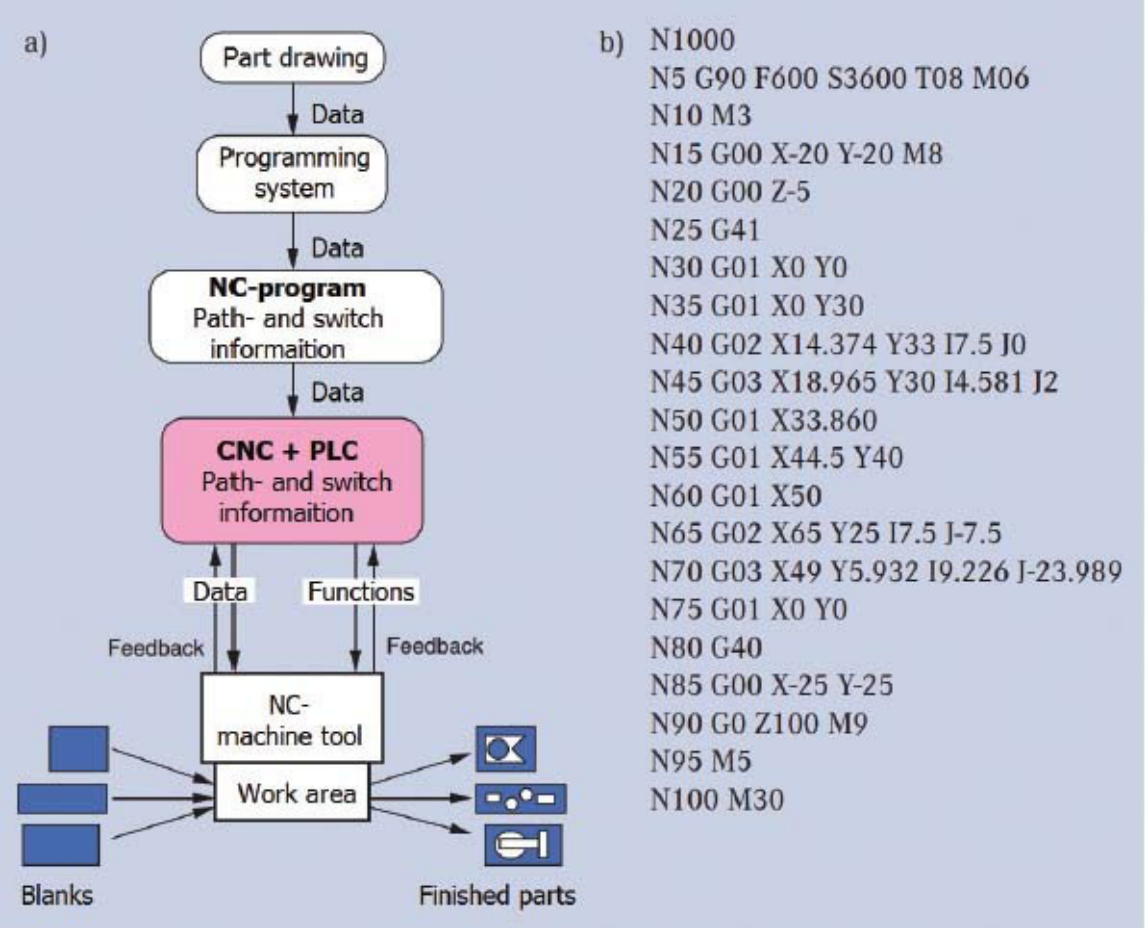

FIGURE 3.9 (a) Conversion of workpiece and machining data into path and switching information for an NC machine. (b) NC program example.

An NC program contains all the information pertaining to the motion along the axes (path information) and for activating the switch, or M-functions. This information is combined in a step-by-step manner, called a block, in the sequence required for machining. The information is saved on a machine-readable data-storage medium for input into the CNC. If there is a direct data link to the computer (DNC), then the NC program is transmitted to the connected CNC directly.

The standardization of program structure was an essential prerequisite for the introduction of NC machines. At a very early stage, it was agreed that the international standard code would be based on an International Standards Organization (ISO) recommendation, which was subsequently incorporated into the German Industrial Standard DIN 66 025. This provided the greatest possible uniformity in program structure for all NC machines, making it possible to perform programming in an external, machine-independent manner with any programming system. Special adaptation to a particular CNC machine is the task of the postprocessor. This converter program can be implemented either in the CAD computer or in a downstream programming system (CAM). Standardized program structure is described in Part Chapter 1 "NC Program." Programming systems (CAD/CAM) make programming easier, avoiding lengthy and time-consuming auxiliary calculations. The subsequent graphical-dynamic simulation of the machining process on the screen means that the programmer can be sure that there are no programming errors. If the workpiece is designed with a CAD system, the workpiece data can be imported into a CAM system and be used directly for NC programming

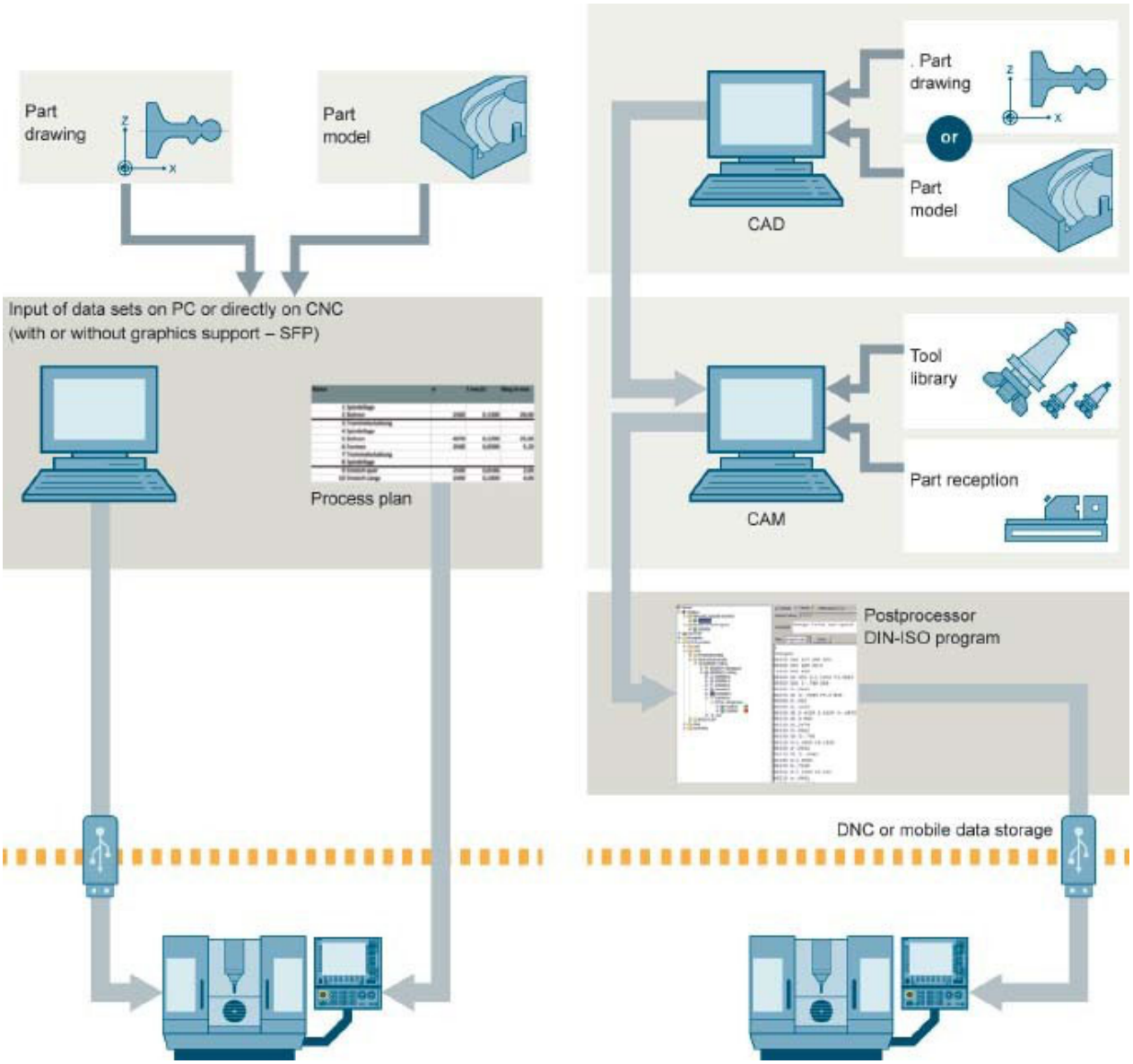

FIGURE 3.10 (a) Principle of manual NC programming: step-by-step input of machine motions. Path and switching information are brought together step-by-step in the NC program and transferred to a mobile machine-readable data carrier. Or the individual data sets are typed into the CNC system manually. (b) CAD/CAM principle: inputting the geometries of the unfinished and finished part; the machine generates the machine motions based on them automatically. The workpieces are designed on the CAD system; the NC system generates the machine motions (CAM) based on the CAD data.

PROGRAMMING

NC parts programs can be programmed and entered into the CNC directly or generated on a CAD/CAM system and entered via a data link provided by a USB stick The program must be modified as needed. It cannot be assumed that the machine is operated by a skilled worker in a midsized company. Due to the lack of skilled labor and/or the great production costs in Western countries, often unskilled hands operate the CNC machine. Therefore, it is imperative that the user interface be clear and logical. Modern CNC machines support the entire process of workpiece fabrication in workshops

FIGURE 3.11 Use of various programming methods in the metal cutting industry. Approaches vary depending on company organization, experience of machine operators, and nature of the products produced.

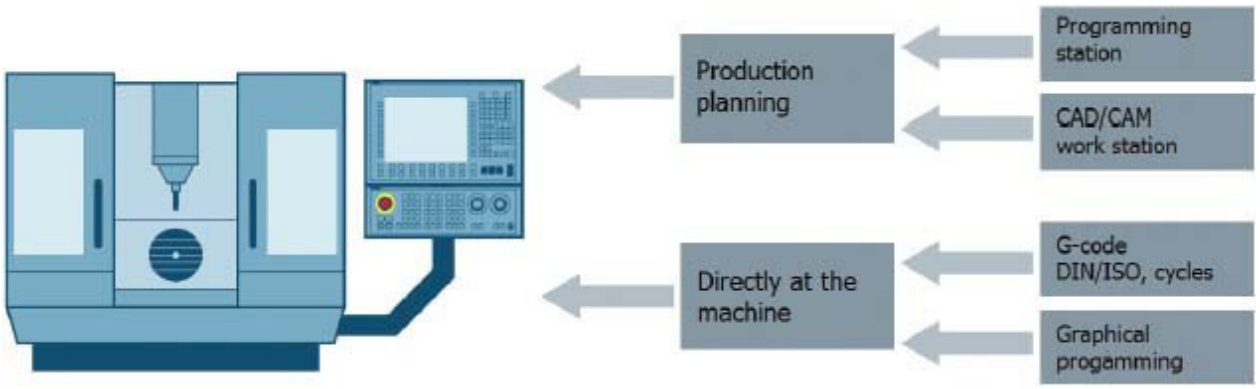

FIGURE 3.12 NC programs can be created in the production planning office or directly on the machine.

A CNC operation begins with the setup of the machine. The NC program and tool data are entered into the machine, and the workpiece zero stop, or reference point, is determined. The machine is likely to have a measuring function for the tool values, as well as a data and tool administration.

Depending on the complexity of the part, the experience of the operator, and the structure of the workshop, it might make sense for small batches to enter the data manually. For this there are several possibilities. In the easiest case, the operator enters G-code commands into the CNC system. Yet here the overview and readability are limited and could prove complicated when the machine has several operators during a two- or three-shift workday. Depending on the CNC system one might find support for macros or cycles to a greater or lesser extent. These can be found for turning, milling, and (not as frequently) grinding. These technology cycles combine operations such as centering, boring, thread cutting, facing, plano milling, and cutting off in subprograms. Data such as cutting depth, fallback plane, feed rates, spindle rpm, and

so on must be entered as parameters by the machine operator. The entire set of instructions will then be executed as a subprogram or cycle.

Many CNCs come with graphical programming support; that is, the processing cycles will be aided with easy-to-understand graphics and simulation A midsized company might use CAD/CAM programming or direct input of G- and M-code into the CNC depending on personal preferences, degree of education and training, local customs, philosophy of management, and the hardware and software at the site.

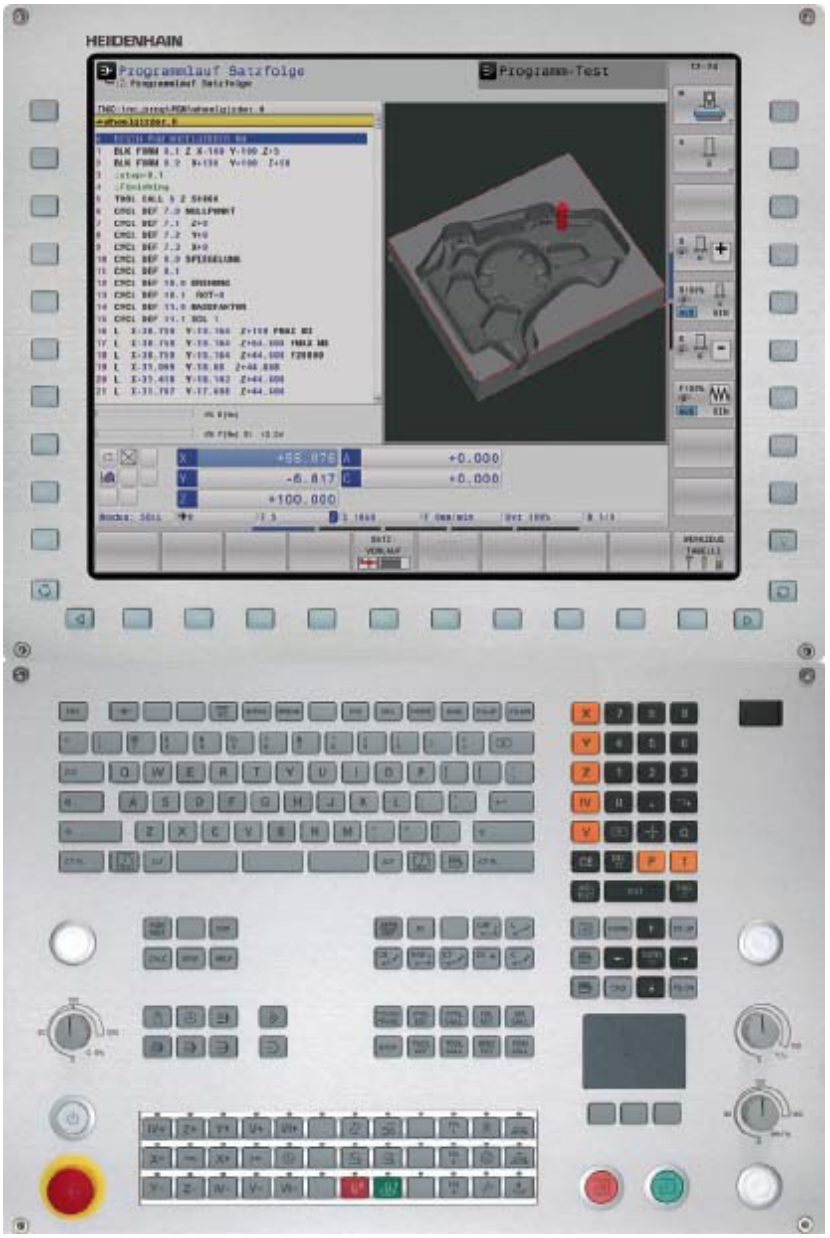

FIGURE 3.13 Example of a user interface on a standard CNC. Heidenhain.)

Most modern CNC machines support all programming methods. Most likely not every production site will apply all possible programming tools. Large-badge fabrication thus will favor cycle technology or graphical programming because the NC program is optimized to the limit and leaves little room for changes in the

process. Yet the smaller the lot size, the more likely it is that programming is performed on the CNC. For this, the operator must be sufficiently qualified.

DATA INPUT

The NC program is entered into the CNC system using the same devices and data-storage media that are used on modern PCs:

■ An ASCII keyboard for manual data input and for making corrections (editing)

■ Electronic data-storage media and the associated interfaces (USB 2)

■ Directly from a computer (network, DNC, wireless local area network [WLAN], etc.)

Keyboard

Almost all of today's CNC systems allow quick computer-based parts programming or program corrections at the machine. ASCII keyboards are the type most often used worldwide for interactive CNC systems and PCs.

Electronic Data-Storage Media

These media are mainly used for quick saving, transporting, and entering NC programs and all compensation values in a CNC system. A secondary requirement is to be able to output and store the data again after use in the CNC.

The size of available CNC memory has increased dramatically in the last decade, along with the advancements in computer

technology in general. Whereas at the end of the twentieth century NC memory was measured in the kilobytes, today storage is almost unlimited. Storage for CNC programs can be optionally expanded in form of compact flash (CF) cards, USB sticks, or hard disks. Considering office PCs, one must be mindful of computer viruses. A virus that finds its way into a CNC system can cause data loss and any number of problems.

Life expectancy of data-storage media is rather unlimited except in the face of improper handling. It must not be underestimated that data, particularly on portable media, can be easily read, changed, and/or deleted.

Distributed Numerical Control

Distributed numerical control (DNC) refers to the connection of CNC systems to computers via a data link (data bus) for direct transfer of NC programs. While this type of data input is not a data input device in the usual sense, its advantages made it the input method of choice. One or more dedicated computers are used for saving and managing all NC programs for all the connected CNC machines. They also transfer the programs to the CNC systems on request while also performing designated safety checks. In addition to the NC programs, the necessary tool data, tool histories, and compensation values are transferred (see Part Chapter "DNC"). The NC programs are called up either manually or automatically by the CNC system.

Once the NC program has been transferred and saved, the CNC machine will execute it as often as instructed. The connection to the DNC computer is no longer needed, unless the

NC program is too long for the storage capacity of the CNC system to hold. In such a case, the program is downloaded incrementally.

OPERATION

Operating procedures that are well thought out and suitably designed make a significant contribution to the cost-effectiveness of a CNC machine User help systems and interactive programs that support the operator and help to prevent operator errors will promote safety in working with the machine. In this respect, modern CNC systems offer very good support.

FIGURE 3.14 Sinumerik 840oD sl with user input panel, CNC, servo amplifier, linear motor, servo motor, and torque motor. Siemens.)

Depending on the use of a CNC machine tool, the demand on the CNC can vary. In large-batch production, such as in automotive and medical technology, there is typically not much operator input or programming required. These machines are parts

of large assembly lines and FMSs and process mostly a small variety of parts. They need to be easy to set up and allow quick troubleshooting and error correction. The CNC parts programs are almost always created off-site and, because of the quality and data-collection mandate, must not be modified. In this production context, the fraction of a second processing time is more important than a great ease of operation. A CNC machine is expected to offer a high degree of performance and reliability and to be easily integrated into the existing company network. After the NC data set has been sent to the CNC, production management has an interest in controlling and evaluating the entire process and use of the machine, tools, and consumables. In addition to the network interfaces known from the operation of the PC, the CNC needs software modules and interfaces to satisfy these requirements.

Today, CNC machine tools have become a commodity in midsized companies that support subcontracting and prototype work and tool and die making. In this context, the requirements are opposite those of large-scale production. Small-batch production calls for frequent tool changes. Accordingly, the ease of operation becomes an important factor. Machine operation and human interference must correspond to the habits of the operator and must not be complicated and cumbersome. A simple, logical operating procedure has a significant effect on the subsequent productivity and profitability of the machine. A well-organized human-machine interface (HMI) is now considered very desirable.

SUMMARY

In the span of a few years, the design and operation of CNC machines have changed to the extent that manual interaction often proves impossible. Typically, the operator only becomes involved during unforeseen situations. In order to protect the person and the machine from harm resulting from input or handling errors, modern CNC machines are equipped with a number of safety and control features.

Although all CNC machines work according to the same principles, different machine types require customized CNCs with numerous special functions. Given identical CNC hardware, this is accomplished with CNC operating software.

Modern CNC machine tools are equipped with several numerically controlled main axes, simple auxiliary axes, and many switch functions. Specific processes, such as laser cutting or high-speed milling, require extremely precise and fast machine movements, which can be achieved only with highly dynamic servo drives.

The components of a universal CNC for three axes and one main spindle are shown in Figure Because of their high performance, CNCs will execute any number of functions, so they can be used for fully automated and technically perfect operations in individual machines and in FMSs.

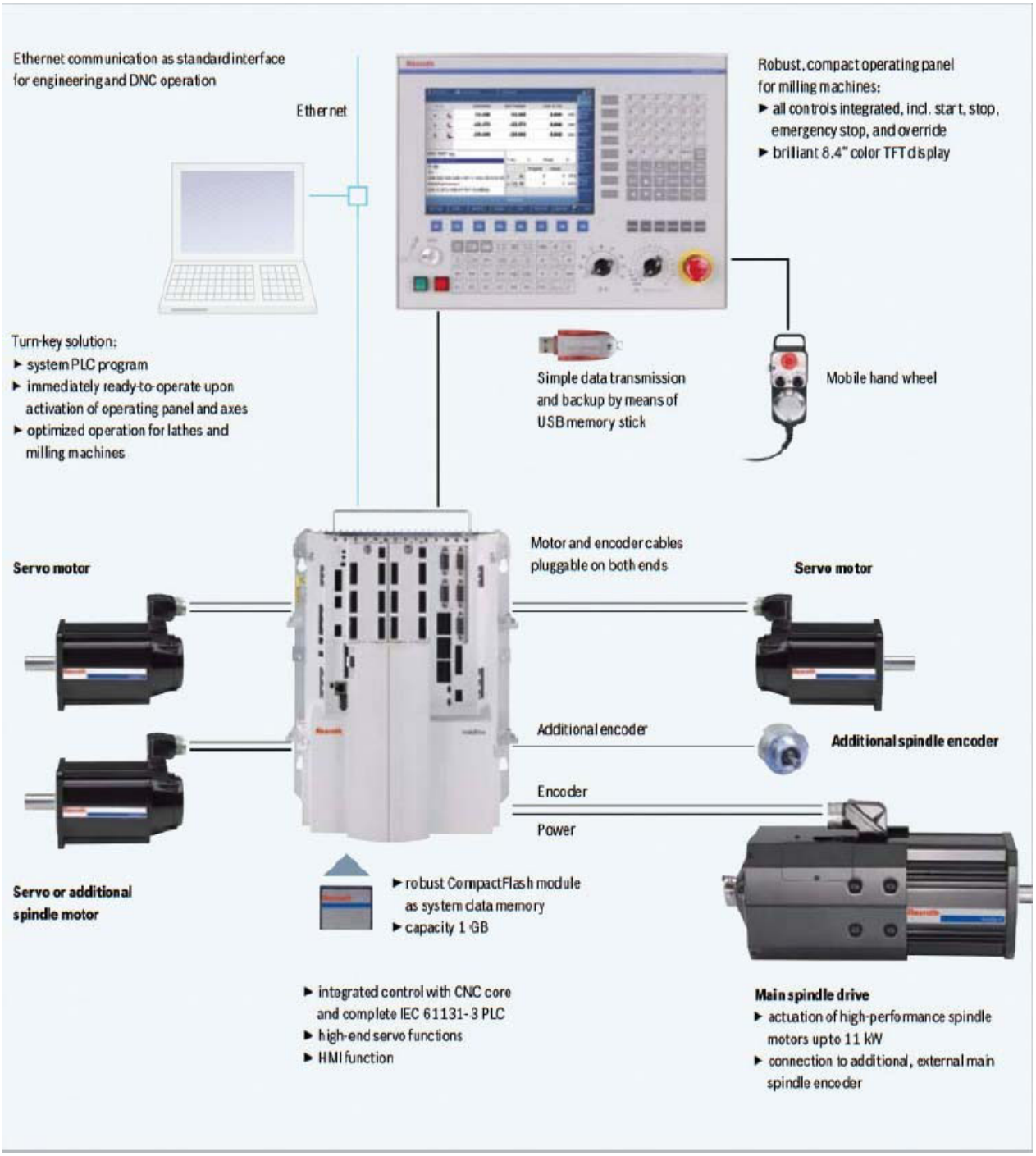

FIGURE 3.15 Four-axis CNC for a lathe-milling machine. Bosch Rexroth.)

These will be explained in the ensuing text and include, among others:

■ NC programming on the machine during ongoing operation

■ Management of extensive tool tables with up to 50 data sets per tool

■ Automatic generation and output of lists of tool differences when a new NC program is input

■ Automatic communication with external computers, for example, computers connected to measuring machines, DNC systems, and PPSs

■ Workpiece management in flexible manufacturing cells (FMCs) and FMSs, reporting production quantities, rejects, rework, and irregularities and/or specifying processing priorities

■ Integration of software for production data acquisition and machine data acquisition (PDA/MDA) for troubleshooting, maintenance, service, error detection, and a large number of graphical depictions to support the operator

IMPORTANT POINTS TO REMEMBER

■ NC stands for numerical control, that is, controlling with numbers. When used in connection with machine tools, this term refers to the direct input of the dimensions of a workpiece to be shaped.

■ Microprocessors are used in the construction of modern numerical controls. These controls are called computerized numerical control (CNC).

■ Microprocessors offer such high processing speeds that one single processor is sufficient to control multiple machine axes simultaneously and with great precision.

■ Continuous-path controls are the most universally applicable and most commonly used controls. The number of axes that can be controlled simultaneously can be expanded in a modular fashion.

■ Continuous-path controls, of course, also can be programmed as point-to-point controls and straight-cut controls.

■ The performance of a CNC machine is determined by the system software of the CNC developer and the applications of the machine builder.

■ Customer-specific adaptations, such as special functions and project-specific requirements, can be complemented and integrated into the user interface; own cycles and NC functions can be added. Different CNC models offer special software for this.

■ NC programs can be entered into the CNC controller via the keyboard or interfaces such as DNC, Ethernet, WLAN, USB media, and so on.

■ CNC machines are freely user-programmable machines; that is, the motion sequences of the individual axes can be specified by means of exchangeable NC programs.

■ CNC machines are typically designed with a combination of translational and rotational axes. Each axis is equipped with a digital measuring system called an encoder and a controllable drive.

■ Technical functions of CNC machines are also programmable, such as feed (F), spindle rpm (S), tool number (T), and auxiliary functions.

■ Routine operations, such as the automatic changing of tools or workpieces, are determined by the machine. They are engaged by means of an M-function (M00–M99) and then run automatically. Signals to the regulators are output via a PLC and appropriate amplifiers.

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4 Positional Data Input

5 Switching Functions

6 Operating Functions of Numerical Control Systems

7 Programmable-Logic Controllers

8 Effects of CNC on Machine Components

Components Components Components

Components Components Components

INTRODUCTION

The characteristic functional element of all CNC machines is the position control loop, that is, the combination of feed drives and position measurement. Other characteristic components are automatic tool changing and workpiece changing. The CNC affects the machine configuration, such as the machine frame, guides, and main drives.

CNC machines tool have a fully automatic sequence for all the functions that are necessary to execute a machining operation on a workpiece. For this, the information for the sequence of instructions is saved in digital form, which means that it must be converted into machine functions. A distinction must be made here between the path information that determines the dimensional data of machine motions and switching information that triggers fixed machine functions.

If the tool is planned to engage with the workpiece in a freely determined direction, then two additional rotational axes are necessary. In large machines or machines in which a number of tools can operate simultaneously, there will be even more axes, some of which may be parallel axes. Table 4.1 provides an example of how many axes are necessary or typical in various tool machine types and which machine functions are automated.

TABLE 4.1 Different Requirements of Various Machine Tools on the Extent of the Automation

Automation Automation

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Note: a = automatic; m =

AXIS DESIGNATIONS

To position a tool on a surface requires two translational axes; to position a tool in space requires three translational axes. These are typically ordered in the Cartesian coordinate system, perpendicular to each other

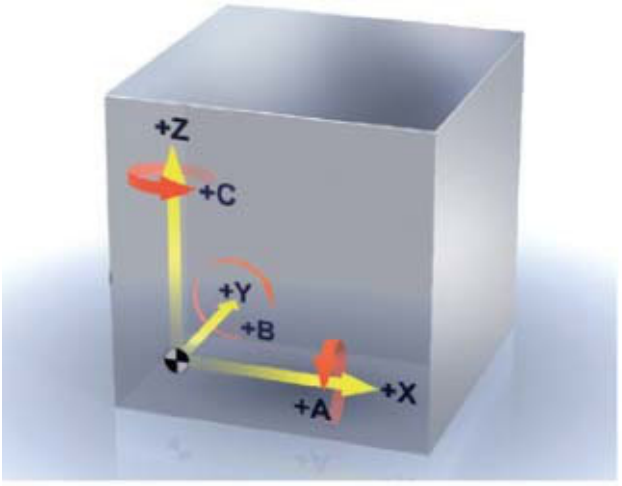

FIGURE 4.1 Cartesian coordinate system.

The designation of coordinate axes and directions of motion in NC machine tools is defined in DIN 66217/ISO 6938. This standard is related to *International Standard Organization (ISO)* Recommendation R 841. Both of these standards are based on the three-finger rule, in which the right hand is used to define the directions of the main axes and which are perpendicular to each other. The thumb represents the the index finger the and the middle finger the The tips of the fingers point in the positive direction.

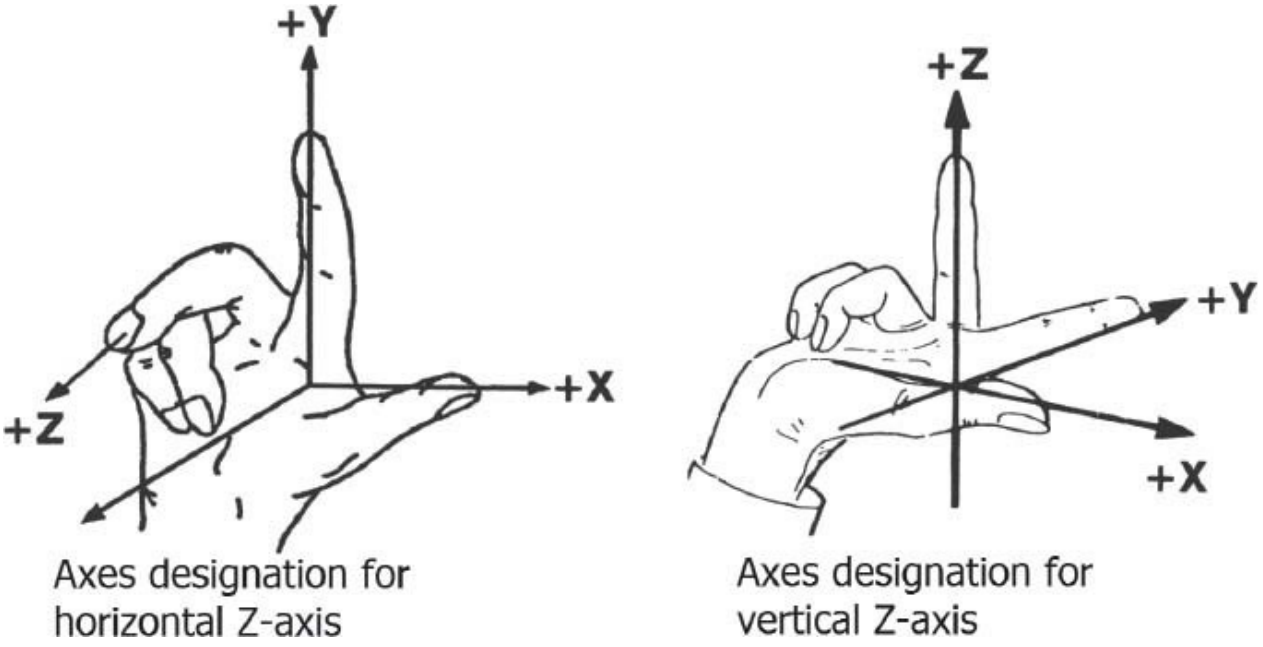

FIGURE 4.2 Use of the three-finger rule with the right hand.

In order to use this rule to define the axes of a CNC machine, one needs to imagine that one's middle finger is inserted into the tool holder of the spindle. This is the and the finger points away from the workpiece in the retraction direction of the spindle. Then you turn your hand in such a way that your thumb points in the direction of motion of the longest axis. This is the which generally lies horizontally. This also automatically determines the Y-axis: The index finger is pointing in the positive direction.

All additional axes are based on these three basic or main axes: and *C* are rotary or swivel axes, with or *Z* as the central axis; that is, *A* rotates around *B* rotates around and *C* rotates around The positive direction of rotation of the rotary axes corresponds to clockwise rotation viewed in the direction of the positive axis. This is also known as the corkscrew rule: during "screwing in," the direction of the tip and the rotary motion are positive.

and *W* are parallel axes to the three main axes and and *R* are additional axes that do not necessarily have to be parallel to the main axes. *R* (for reference surface) is used primarily in drilling cycles as an address for the reference plane of the workpiece, that is, where the switches over from rapid traverse to the feed rate.

Sometimes there are designations such as and These involve movable gantries or traverses, called *gantry-type axes* Because these axes have two widely separated guide tracks (one on each side), they require two separate drives to move precisely in parallel even with unevenly distributed loads. These axes thus are not independent axes with mutually independent motions but rather axes that move together and are also programmed under the same address: *X* or

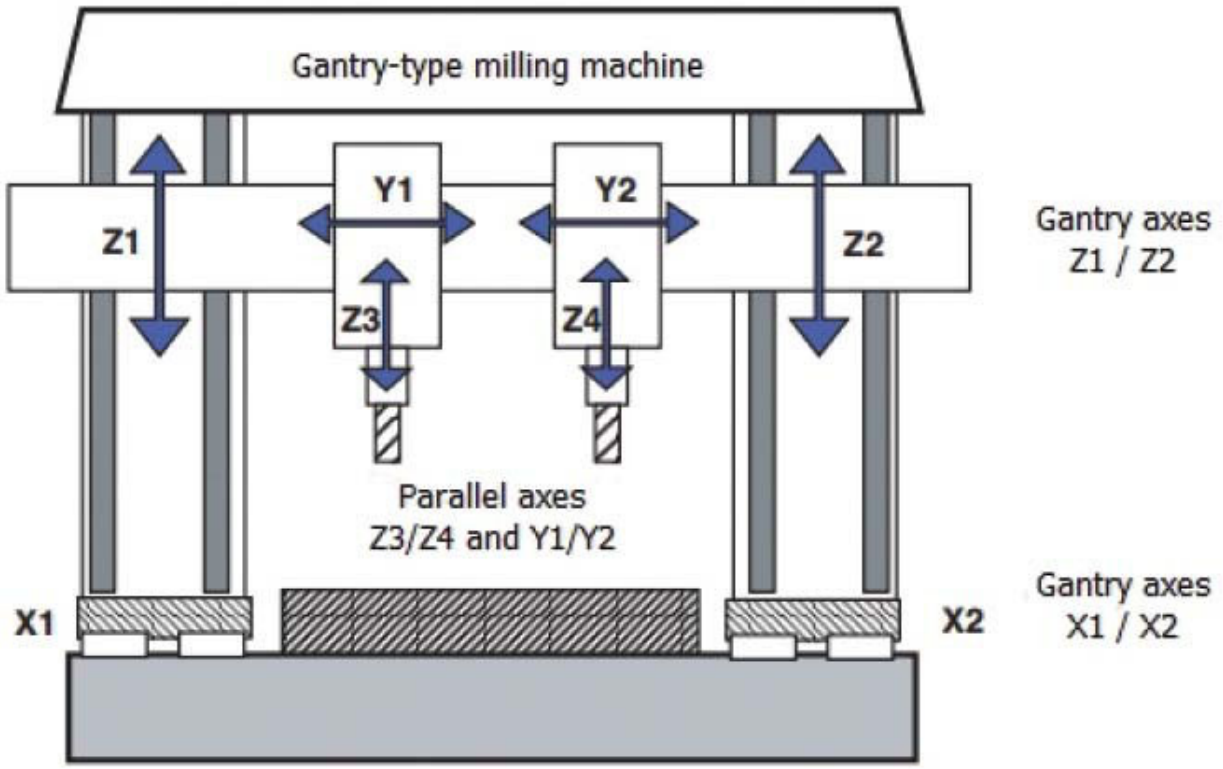

FIGURE 4.3 Difference between gantry axes and parallel axes.

When defining the positive axis direction, it is assumed that the tool is always moving and that the workpiece is always stationary. In this case, the positive axis directions are designated in the same way as the positive motion directions: or If, however, the workpiece is moving, such as with coordinate and rotary tables, then the direction of motion and the axis direction are opposite to each other. If the table moves to the right, then the tool performs a relative motion to the left. In this case, the actual axis direction is specified, but the address is marked with an apostrophe: or Specifying the axis direction in this manner has the advantage that the programmer can create the programs independent of the structural design of the machine. The desired relative motion between the tool and workpiece is always executed in the correct direction regardless of the machine's configuration.

CLOSED-LOOP POSITION CONTROL

During the development period of numerical controls for machine tools, a wide variety of different systems was used to control the machines' travel. Since then, closed-loop position control has proven to be the most versatile and reliable of these systems and has become standard. Previously, open-loop control systems were also often used due to their simplicity. These made use of special drives called *stepper* They differed from closed-loop control systems in that there was no feedback of the actual position; thus there was no closed circle of issuing a command and checking for the actual execution of it. Because this technology is hardly used anymore, it will not be part of this account.

In closed-loop position control, the system constantly verifies and provides feedback on the current position of the machine axis, thus ensuring highly reliable, error-free motions. Figure 4.4 depicts the principle of a closed-loop control using a translational axis as an example. The variable being controlled—the position of the machine slide—is captured continuously and compared with the command position from the higher-level CNC system. The difference between the target position and the actual position (closed-loop deviation) is amplified by the position control and put out as a control signal to the axis drive, which, in turn, compensates for this deviation. Continuous-path controls put out new position values on an ongoing basis, and the controlled axes must follow these values. This means that it is possible to achieve continuous-path motions. Thus each CNC axis requires the following:

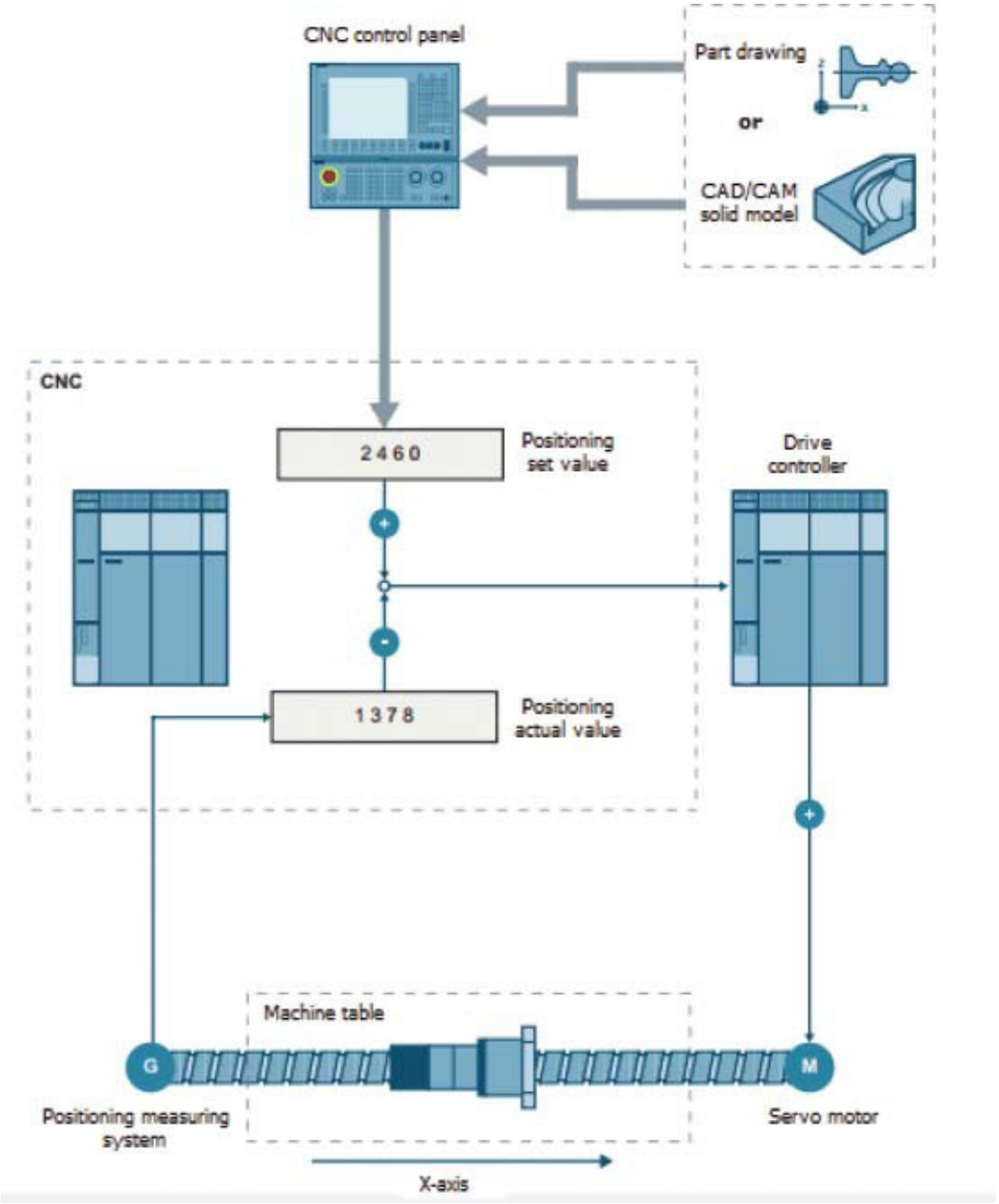

FIGURE 4.4 Principle of input and processing of geometric information in closed-loop control.

- An electronic position measuring system

- A servo drive that is subject to closed-loop control

An important characteristic of the position feedback control of a feed servo drive is the achievable factor, which describes the proportional amplification for position control. The position feedback control is designed as a *proportional* (P-) control. An important characteristic of P-control is a persistent deviation. The lasting deviation of closed-loop position control is the difference between the command position and the actual position. It is proportional to the current velocity of motion and is referred to as the *following error* (also called *contouring error* or *servo* That is,

$$X_s = \frac{V}{K_v}$$

where is the following error (in millimeters), is the amplification or factor (in meters per minute per millimeter), and V is velocity (in meters per minute).

The size of the following error for a certain traversing speed thus is determined by the amplification factor factor) that can be achieved. The factor thus is a measure of the machining precision and the dynamic characteristics of the feed servo drive.

Closed-loop control is subject to oscillations. If the amplification factor is too high, there could be excessive oscillations. Because this may have extremely negative effects on the quality of the workpiece being machined and must be prevented, the amplification factor of the control loop is limited here. In order to increase the value and thus reduce the lag or following error, the simple closed-loop position control is expanded with lower-level control circuits for motor revolutions and motor current, as shown in Figure Here the closed-loop deviation is the input variable for the lower-level motor

revolution control loop. The revolution control loop gives the amplified revolution deviation to the lower-level current controller as an input variable. The proportional-integral (PI) regulator response of revolution controllers and current controllers makes it possible to correct for even the smallest control deviations with no residual deviation between the command and actual positions.

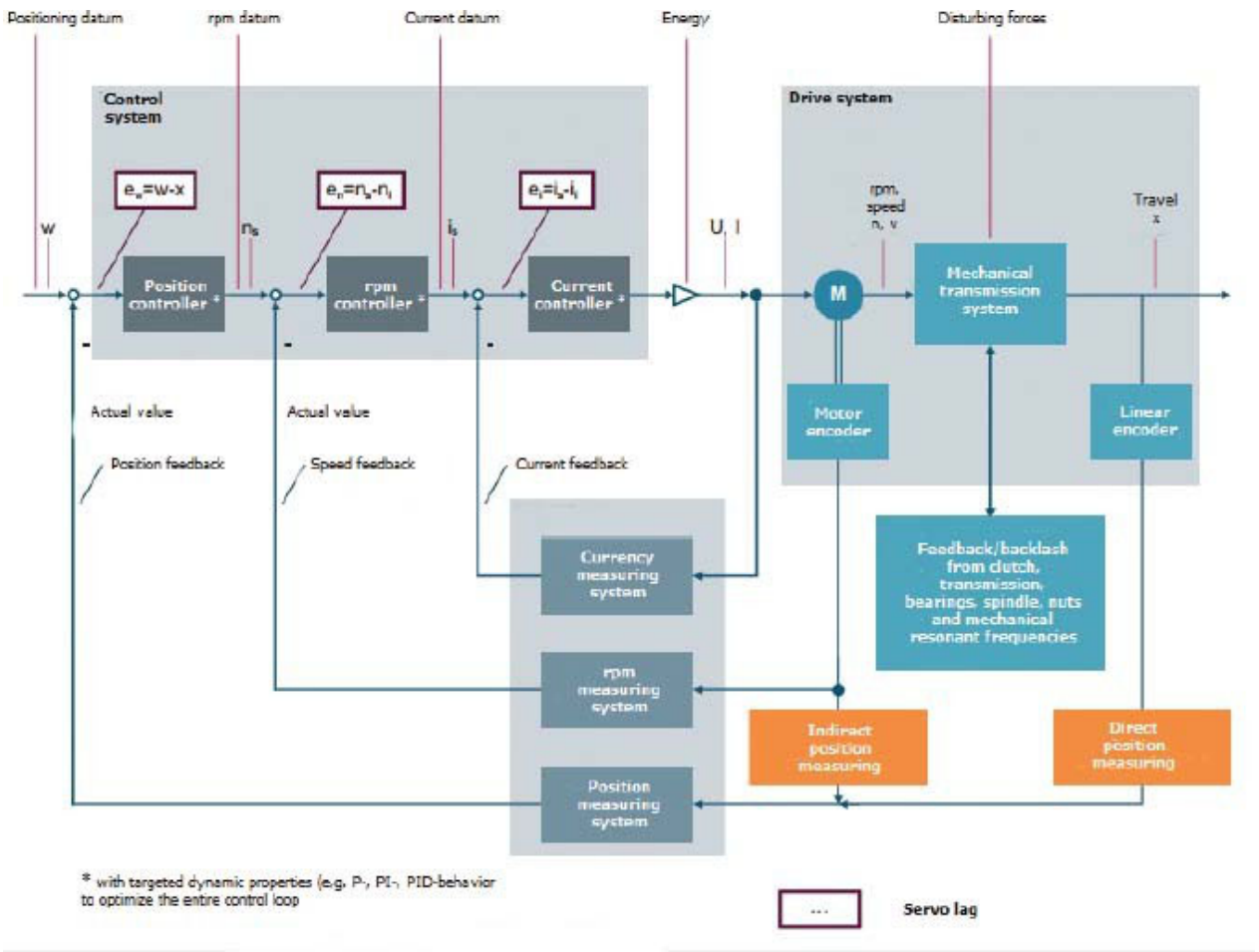

FIGURE 4.5 Schematic of closed-loop control.

The amplification factor that can be achieved for a feed servo drive is also affected by the design of the mechanical elements that are involved. The various design potentials that arise here will be described later.

■ As with every other oscillation-prone system, the masses being moved should be as small as possible, and the driving elements should be as stiff as possible.

■ Any nonlinearities in the system, such as friction and backlash, should be as small as possible.

Friction and backlash between the path-measuring system and the slide are also the source of reversal errors. The reversal error is the distance between the two actual positions that are reached when a programmed or nominal position is approached from the opposite direction. It causes position deviations and therefore should be kept as small as possible. It can be compensated for to a large extent by means of special correction data that are measured and stored in the CNC system.

Placement of the measurement device, that is, whether a direct or indirect measurement system is used, also has a very large effect on the result. Figure 4.6 shows the difference.

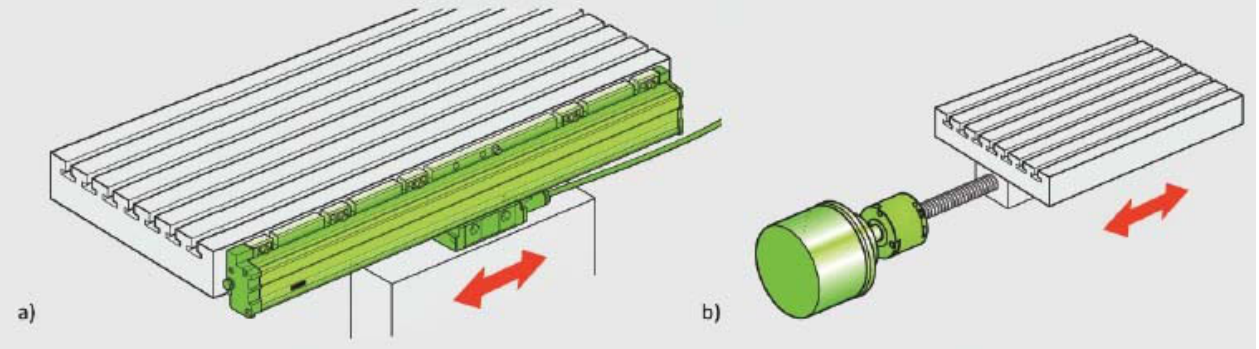

FIGURE 4.6 Principle of position measuring with (a) a linear encoder and (b) a rotary encoder.

POSITION MEASUREMENT

The position accuracy of a feed axis is an important factor in the precision of a CNC machine. When designing the layout of the position-measuring system, several important factors must be considered. The requirements for the measurement system are very high because of the extreme variety of operating conditions. The axis must be positioned with the highest precision despite changing workpiece weights and processing speeds. Reliable measurement systems are also responsible for the productivity of the machine because the machine must perform without maintenance in an adverse environment over a span of years.

Closed-loop technology has prevailed for precise machine tools because it satisfies the requirements of precision and reliability. The following considerations about position measuring of linear axes are also applicable for angular measurements on rotary axes.

Semi–Closed Loop versus Closed Loop

The position of a numerically controlled axis can be determined in two ways:

1. If the position is captured through a combination of a ball-screw servo drive and a rotary encoder The ball-screw drive serves two purposes. As a drive component, it must transmit large forces, and as a position-measuring component, it must have high accuracy and reproducibility of the spindle pitch. Its function as a drive component elevates the temperature of the ball-screw drive (see Figure and thus may cause thermal deformation. But because the positioning control

loop only includes the rotary encoder connected to the ball-screw drive, its deviations are not measured and therefore not compensated for. This case is termed as a *semi-closed-loop* Positioning errors of the axis are inevitable and can have a significant impact on the quality of the workpiece.

2. If the position of the axis is captured with a linear encoder the position control loop comprises the complete feed mechanism. The term for it is *closed* Backlash and inaccuracies in the mechanical transmission elements of the machine have no impact on the accuracy of the actual measured position. The accuracy of the measurement depends only on the precision and position of the linear encoder.

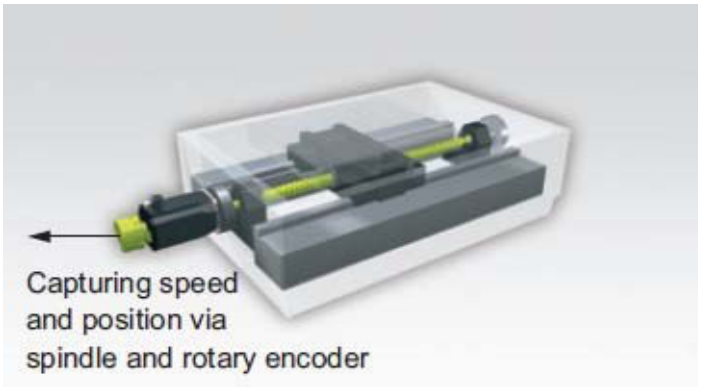

FIGURE 4.7 Semi-closed-loop operation.

Position Deviations through Mechanical Influences

Kinematic Errors

Kinematic errors that can be directly attributed to position measuring via the lead screw and spindle and rotary encoders (semi–closed loop) are caused by pitch errors of the ball screw and backlash or play in the mechanic. Pitch errors have a direct impact on the

measuring result because the pitch of the ball screw serves as a standard for capturing the length. Play in the feed mechanic results in reversal errors.

Compensation of these pitch errors and reversal error is possible with most CNC systems. But to determine these compensation errors, it takes extensive measurements with external systems such as interferometers or a cross-grid encoder (see Figure Also, reversal errors don't tend to be constant over time and must be postcalibrated accordingly

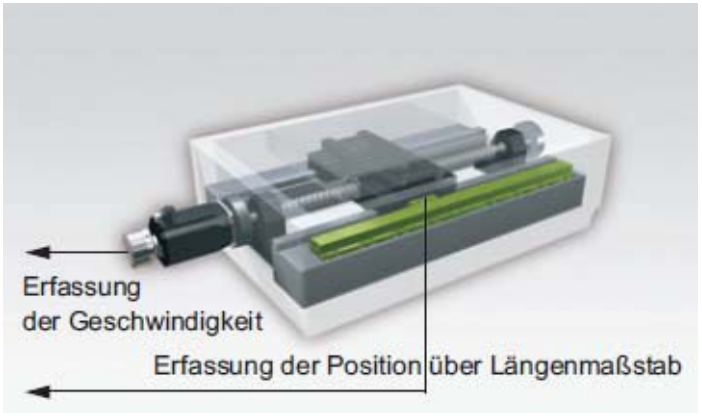

FIGURE 4.8 Closed-loop operation.

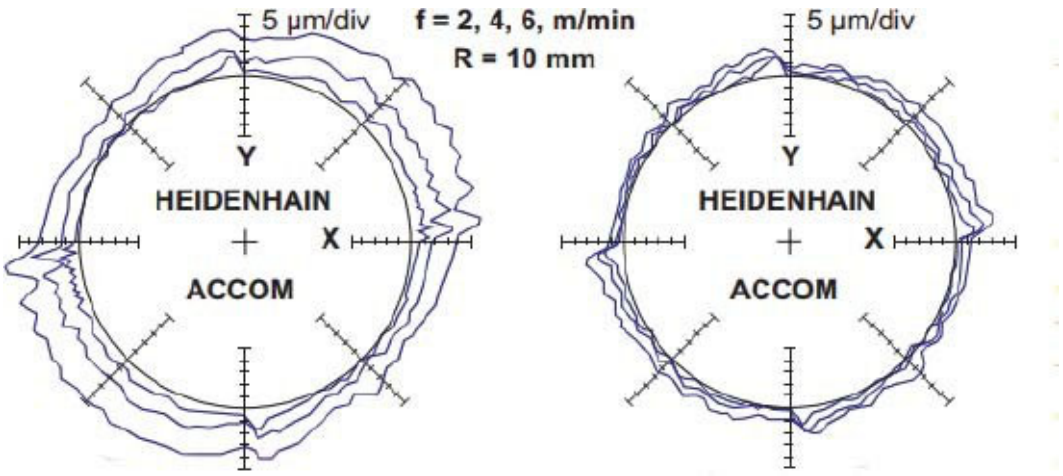

FIGURE 4.9 Circular form tests of a machining center without a linear encoder: New and after 1 year. The backlash in the has increased noticeably.

Deformation of Feed Mechanic through Forces

Forces that can deform the feed mechanic lead to a displacement of actual slide position relative to the captured position of the feed spindle with the rotary encoder. These are mainly the acceleration forces of the slide, process forces during the cutting, and frictional forces in the machine slides.

Acceleration Forces

Given a typical mass of a carriage of 500 kg and a moderate acceleration of 4 the result is typically deformations of 10 to 20 µm that are not recognized by the spindle/rotary encoder system. Given the general trend toward higher accelerations, continuously larger deformations will be evident. Figure 4.10 provides a typical example of acceleration- and speed-dependent errors on a vertical machining center in a semiclosed-loop operation. In the case of position feedback control with a spindle and rotary encoder, the circles significantly deviate at higher tool path velocities from the ideal form. With the use of a linear encoder, the same machining center performs with a distinctly better contour accuracy.

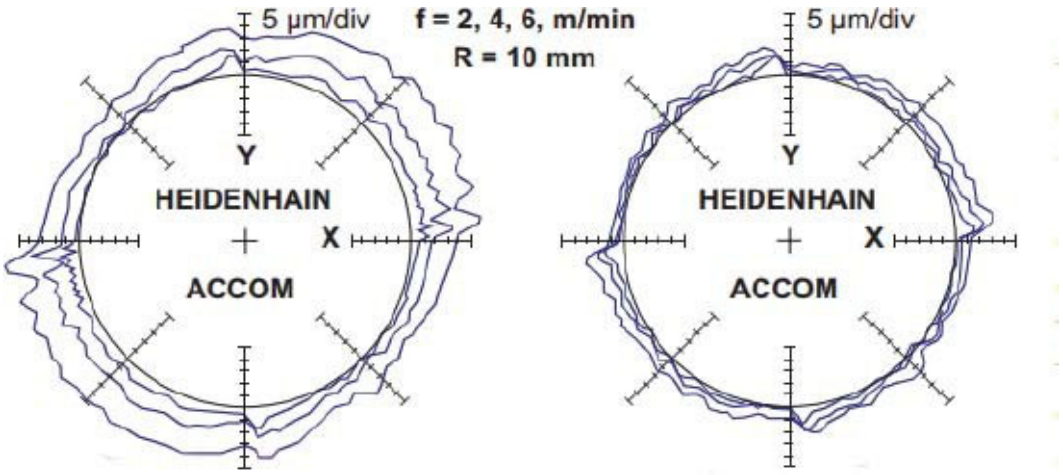

FIGURE 4.10 Circular form tests of a machining center retrofitted with a linear encoder. With position control via spindle/rotary encoder, the circles deviate drastically from the ideal at high feed rates. With linear encoders, the contour accuracy is noticeably better.

Cutting Forces

Cutting forces can easily reach the kilonewton range. They impact the feed system as well as the entire structure of the machine. The deformation of the feed system typically plays only a small part of the deformation of the whole machine. A linear encoder accordingly recognizes at most this rather small portion of the deformation that can be compensated for by the controller. Workpieces with high precision requirements are therefore finished with small feed forces that cause appropriately smaller deformations of the machine.

Frictional Forces

Frictional forces in the slides, depending on the design, are 1% to 3% of the normal force for roller guides and 3% to 12% of the

normal force for slide guides. Given a normal force of 5,000 N, deformations of the feed mechanic of 0.25 to 6 µm can

Position Deviation through Warming of the Ball-Screw Spindle

Position deviations through warming of the ball-screw spindle are the largest problem for position capturing in semi-closed-loop control. The cause is to be found in the dual function of the ball-screw drive. It must transmit the turning motion of the servo motor to the linear feed motion, but it also must serve as a precise standard. This dual function represents a problematic compromise.

The stiffness and warming depend on the preloading of the ball-screw nut and the stationary bearing. The largest portion of friction in a feed system is created in the ball-screw nut. A typical ball-screw servo drive with a diameter of 32 mm has an idle or friction torque of between 0.5 and 1 Nm. In reality, at a fast motion of 2,000 1/min, 100 to 200 W of friction heat is created in the ball-screw nut.

In recent years, the maximum revolutions of ball-screw servo drives have more than doubled. Yet preloading and, consequently, the friction of the ball-screw nut cannot be reduced because of the constantly increasing requirements on the acceleration of the drive. Consequently, these drives generate ever more heat during operation In extreme situations the ball-screw nut must be cooled to prevent excessive wear.

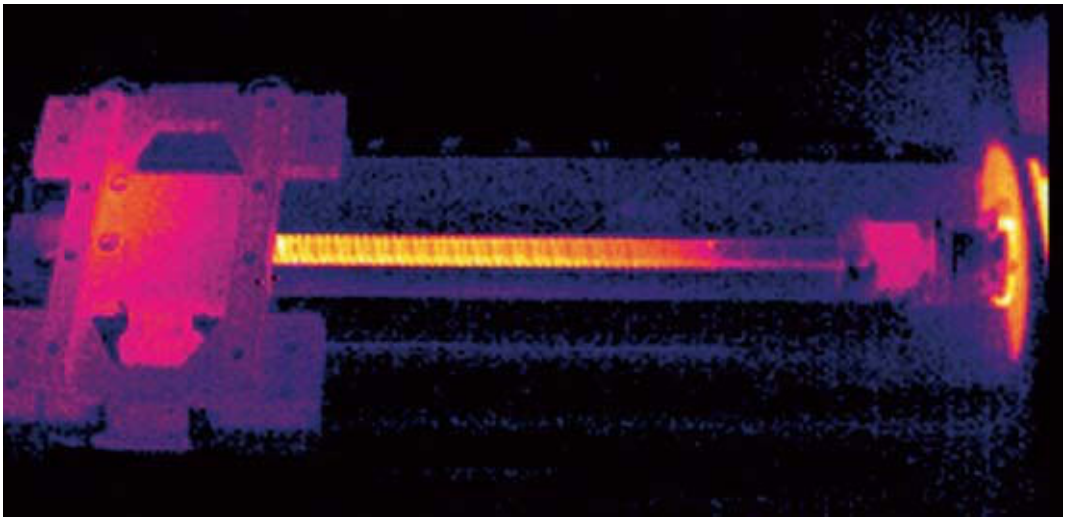

FIGURE 4.11 Heating of a ball-screw servo drive operated at a medium feed rate of 10 m/min. The thermograph indicates temperatures of 25°C (dark colors) up to 40°C (bright colors).

The influence of friction heat on the accuracy of the feed axis is very evident in an examination of a machine based on ISO/DIS 230-3. This standard provides suggestions on how thermal displacements on lathes and milling machines resulting from external and internal heat sources can be captured in a uniform manner. Basically, one distinguishes deformation of the machine structure because of changes in the environment and because of heat generation in the main spindle drive. The standard suggests measuring processes for both kinds of errors. Additionally, the position deviation of the feed axis must be considered.

Frame Deformation

Frame deformation can be captured with, for instance, five digital indicators. These indicators measure in a possibly insulated environment a measuring cylinder that is clamped to a tool holder

FIGURE 4.12 Measurement of frame deformation of a machining center according to ISO/DIS 230/3.

Axis Drift

To measure axis drift, the machine is moved in a defined movement profile. At two positions that lie possibly at the end of the traverse path, a change of position is recorded until a saturation of the position change has been reached. For this axis test, a laser interferometer can be used; a simpler test makes use of test indicators. Thus these tests can be performed in each shop without great effort. Comparison measuring devices can be used to capture axis deformations in two dimensions simultaneously Besides the

measurement along the axis, such a device can capture maximum deviations of ±1 mm perpendicular to the axis. The two-dimensional (2D) reading head operates in a non-contact way; therefore, no mechanical influences of the device can affect the result.

FIGURE 4.13 Comparison measurement device to measure axis drift.

Example Measurement of Position Deviations: Workpiece with Hole Pattern

Given a simulation of the series production of a simple workpiece with an equally spaced hole pattern, it is possible to visualize the drive accuracy of the feed axis. For this test, the fabrication of several units from a series production run is simulated on one single part. Figure 4.14 illustrates the procedure. In the first step, two end faces and three holes are machined. Next, the fabrication of more workpieces is simulated by repeating the process steps 30 times

without actually machining the part. Next, the command of an infeed of 2 mm is given, and the first step is repeated where the tool is cutting again. The procedure ends after 10 runs, that is, 10 cycles with the tool cutting and 270 repetitions without tool engagement. The process takes 70 minutes.

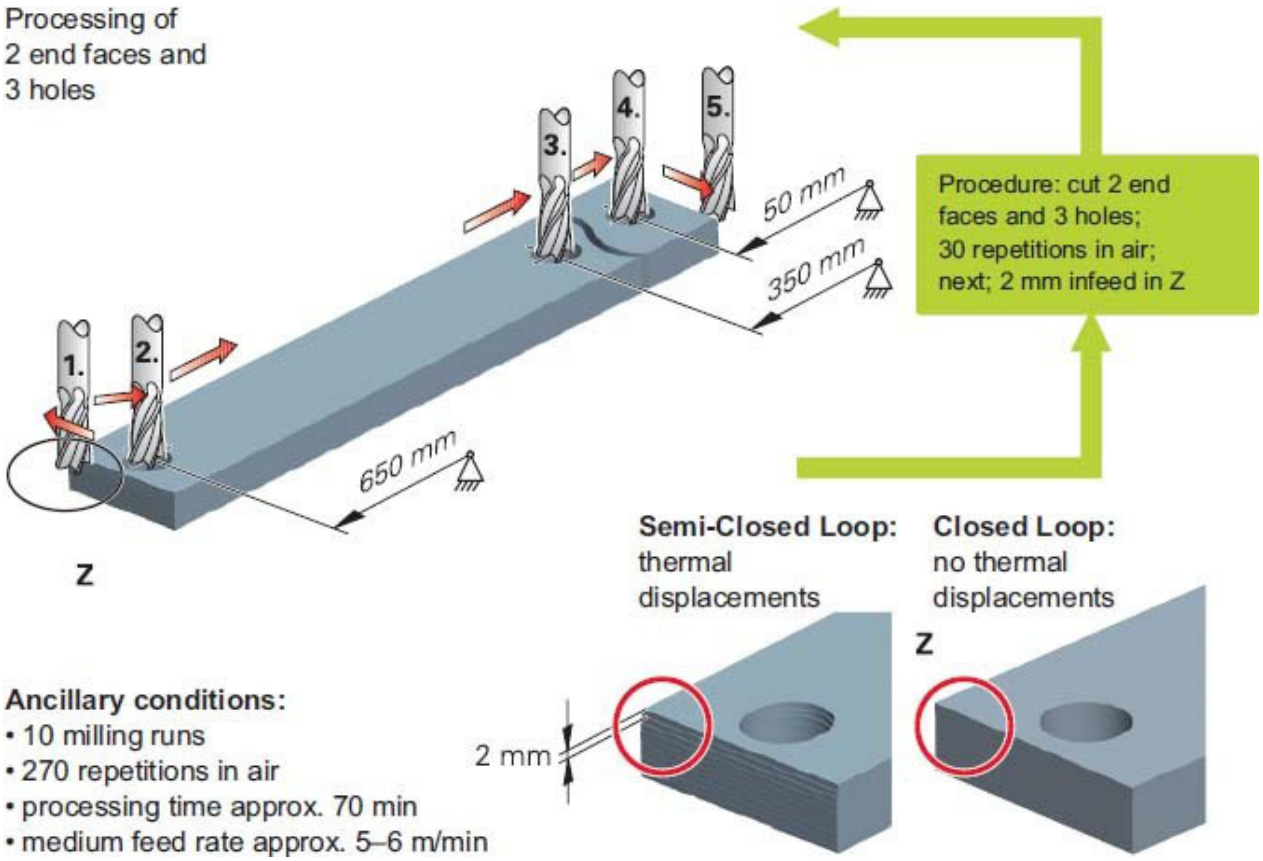

FIGURE 4.14 Use of a simple workpiece to visualize thermal displacements in semi-closed-loop operation.

In the course of this trial, the semiclosed-loop operation reveals that heat-caused deviation is evident in the form of steps on the end face and in the holes, giving testimony to the warming of the ball screws. The thermal drift of the hole at the furthest extent of the stationary bearing of the ball screw is 213 µm

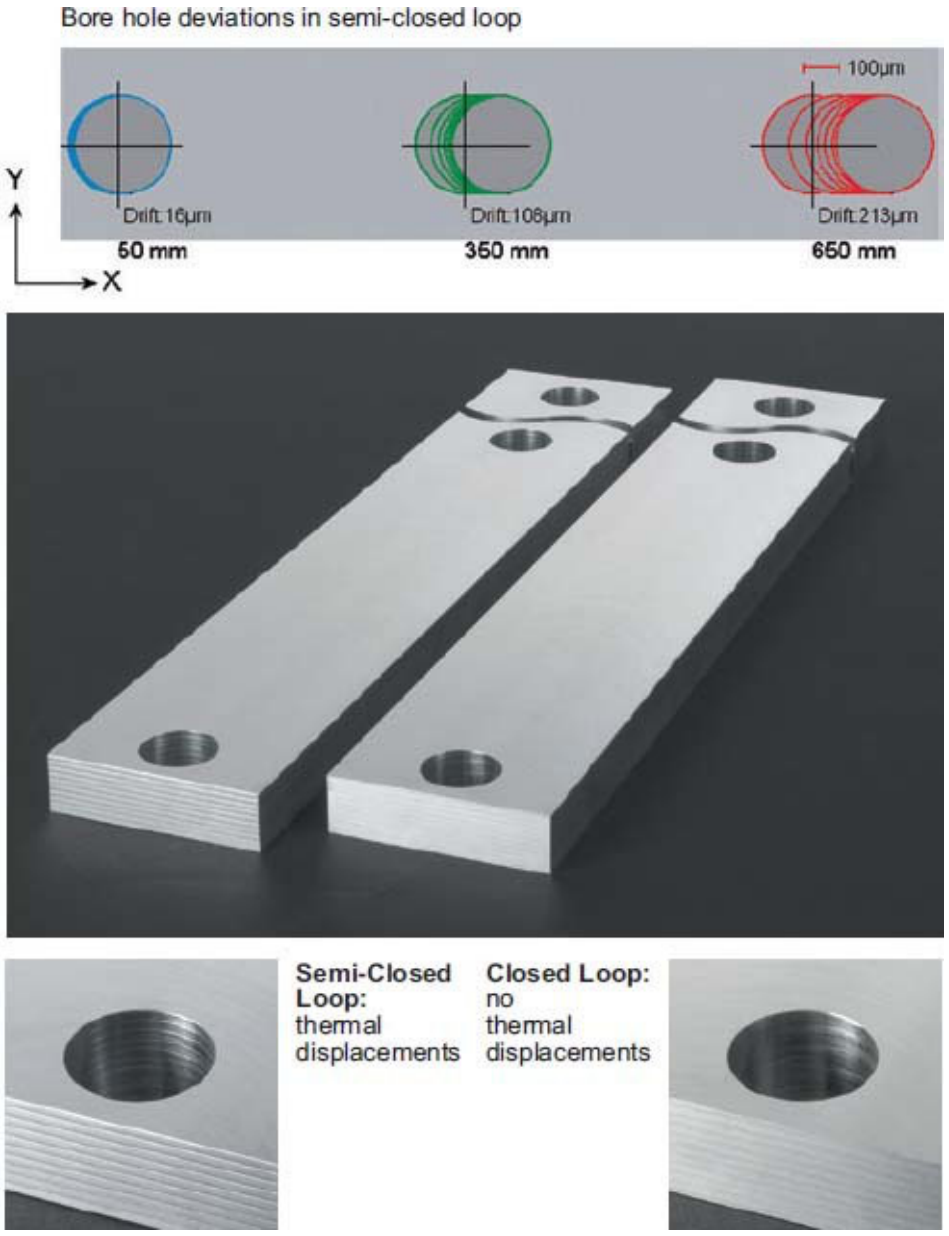

FIGURE 4.15 Comparison of both workpieces: (left) up to 213 µm of deviation in semi-close-loop operation; (right) 4 µm of deviation in closed-loop operation.

Comparable results will be gained using the test of thermal position stability according to DIN ISO 230-3 using a cross-grid encoder. For this test, the axis is moved back and forth with a feed rate of 5.6 m/min for 70 minutes. With the increasing distance of the ball-screw nut from the stationary bearing, the position drift

increases In closed-loop operation, this thermal drift can be compensated for with the use of a precise linear encoder. The usual machine accuracy tests performed at machine commissioning according to VDI-DGQ 3431 and DIN/ISO 230-2 do not capture these thermal errors.

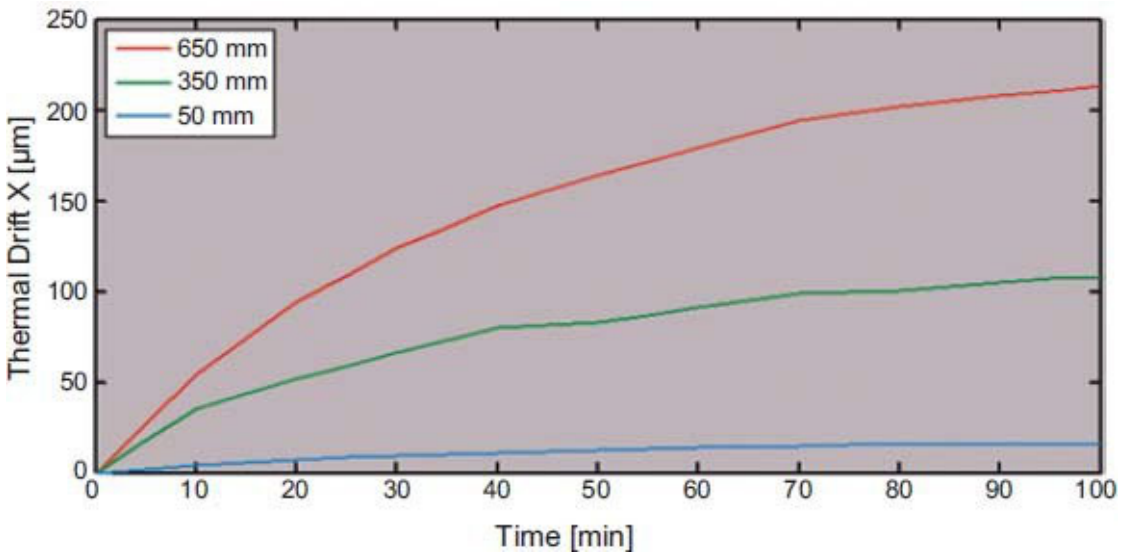

FIGURE 4.16 Drift of three positions when measuring position accuracy according to ISO/DIS 230/3. In semi-closed-loop operation, a distinct drift is present as a result of thermal expansion of the ball-screw servo drive.

Design and Function of Capped Linear Encoders

Regardless of the measuring principle, such as optical or magnetic, and the measuring process, such as incremental or absolute, capped linear encoders have the design shown in Figure A scanning carriage, typically tightly affixed with five ball bearings, is moving on a glass scale. A clutch between the mounting bracket and scanning carriage provides for the necessary assembly tolerance for mounting in the machine. Compression and tension springs keep the carriage in its proper position. For protection, the mechanism is encased in a housing of aluminum or steel; additionally, one of two pairs of

sealing lips will keep out contamination and moisture. In order to increase this kind of protection, the housing can be connected to a source of low-pressure air.

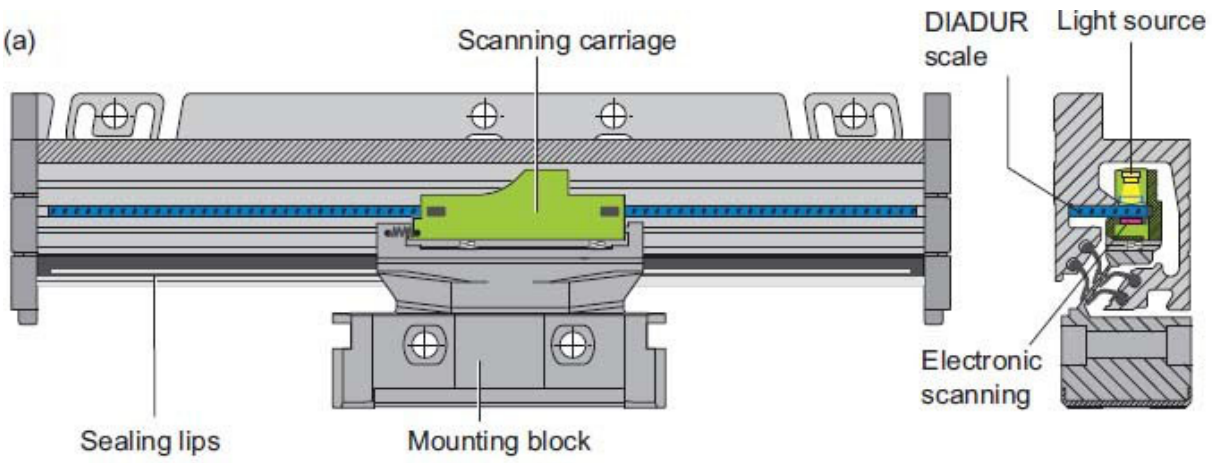

FIGURE 4.17 (a) Schematic of a capped optical length measuring device, or linear encoder. (b) Linear encoders for machine tools.

Measuring Methods

Principally, there are two measuring methods used for machine tools: absolute and incremental measurements. With the absolute measuring method, the position value is available after the machine has been turned on and can be called up by the CNC system at any given

time. For evaluation of the absolute position, a combination of a relative coarse pseudorandom code and a fine incremental track has been established The incremental track typically has a signal period from 100 to 20 µm and can be interpolated to a high degree. The code track measures the absolute position—each division line of the basis length of the code, for instance, 16 bits, is available only once on the scale. The device's electronics combines both tracks and calculates the position value. This value is transmitted to the CNC system via a digital serial protocol.

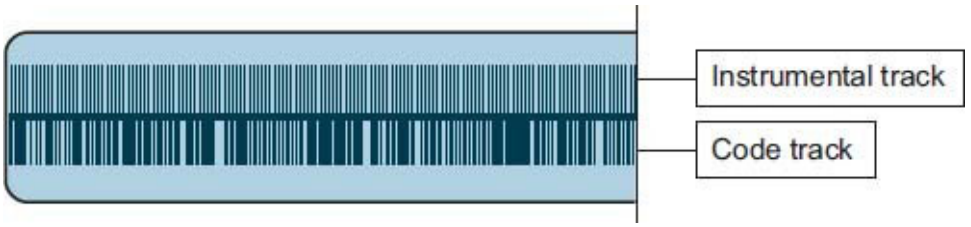

FIGURE 4.18 Diagram of code structure with an additional incremental track.

With *incremental* measuring devices, the machine must be turned on and be moved a certain distance to the next reference mark to obtain the reference point of the appropriate axis. In order to shorten the distance to the first reference point, so-called distance-coded reference points have been established. The distance between two adjacent reference marks is unique for this particular scale, so the CNC system definitely recognizes the position after capturing two reference points. Today, the maximum distance to travel is merely 20 mm The output signals are often sinusoidal with amplitudes of 1 Vpp (volt peak to peak).

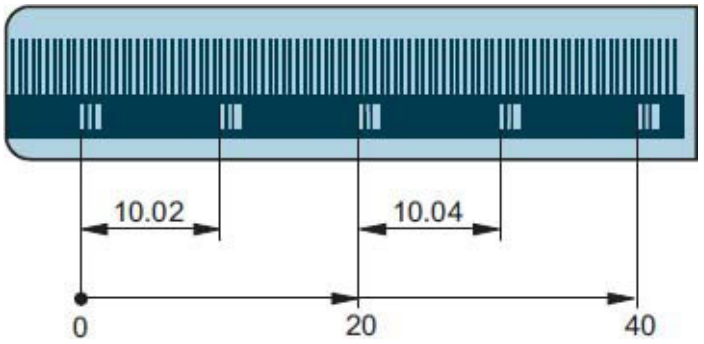

FIGURE 4.19 Schematic of an incremental graduation with distance-coded reference marks.

Measurement Principles

Capped linear encoders mainly use optical measurement methods This is because of the smaller signal periods compared with magnetic or inductive measurement principles. Thus an optical measurement device can reliably read a 20-µm track. Small signal periods allow for small measurement steps; these are responsible for a homogeneous surface for a workpiece.

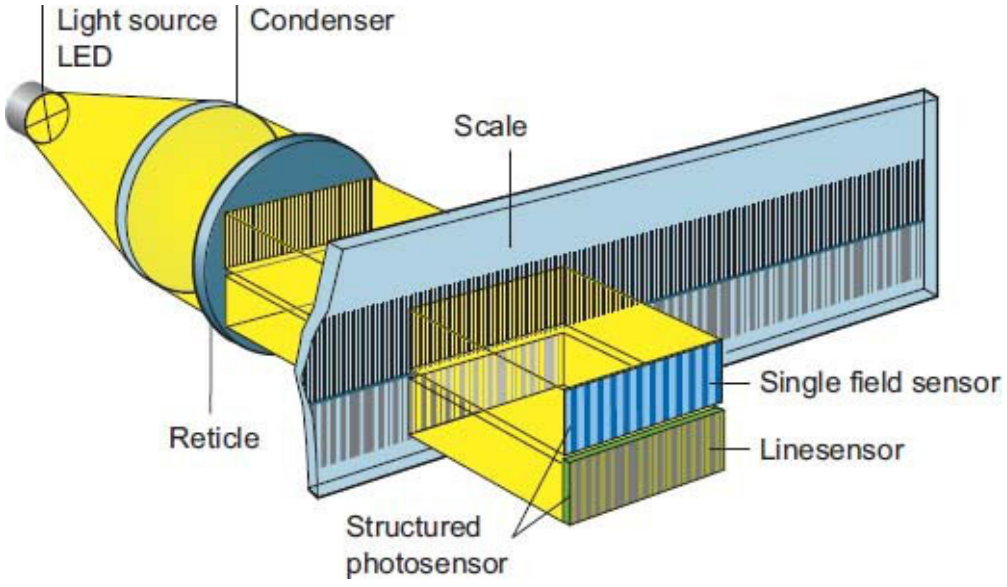

FIGURE 4.20 Diagram of a sensor with a single-field scanning principle and pseudorandom code.

The reliability of the measurement device rests to a large extent on the design of the optic. Single-field scanning for the incremental track and push-pull scanning for the pseudorandom code have proved to be the most secure combination.

Measuring Accuracy

The two characteristics quality class and interpolation errors are distinguished concerning the accuracy of capped linear encoders The quality class provides the deviation of a measured value from the target value for a given measured distance, say, 1 m. The interpolation error provides the position deviation within one signal period.

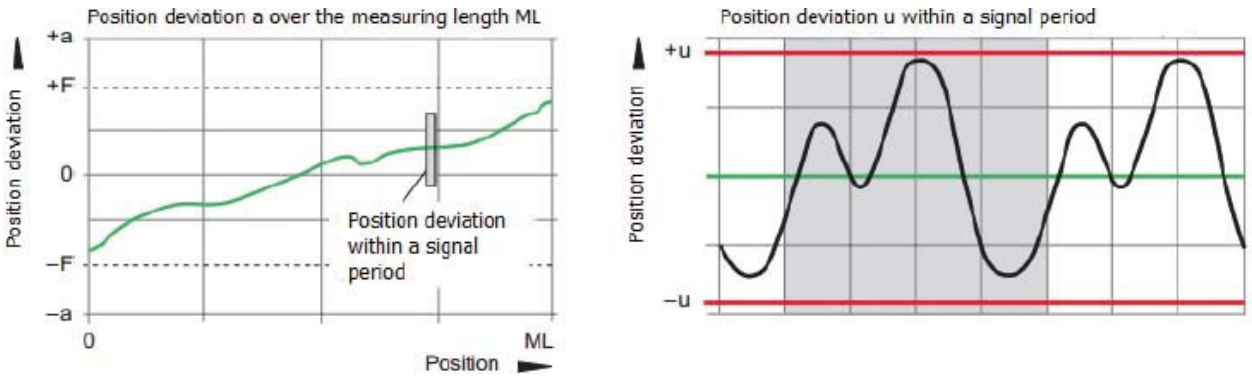

FIGURE 4.21 Definition of quality class and interpolation error.

Because the quality class allows for conclusions on the position accuracy of the machine when measuring large distances, the position deviation in a signal period influences the surface quality and the dynamic, particularly with direct servo drives such as linear and

torque motors. Because the human eye has a distinct acuteness for small, periodic structural deviations, position deviation within a signal period should not exceed ±0.2 µm in order to generate the best possible workpiece surface.

The test workpiece in Figure 4.22 shows evidence of the interpolation error on the workpiece surface. The left surface was cut with a machine whose linear encoder exhibited a ±0.5-µm interpolation error. A distinct wave pattern is recognizable. An interpolation error of ±0.2 µm is still evident in the center. The right surface has been cut with a machine whose linear encoder exhibits an interpolation error of well under ±0.2 µm. Deviations are not visible on the surface.

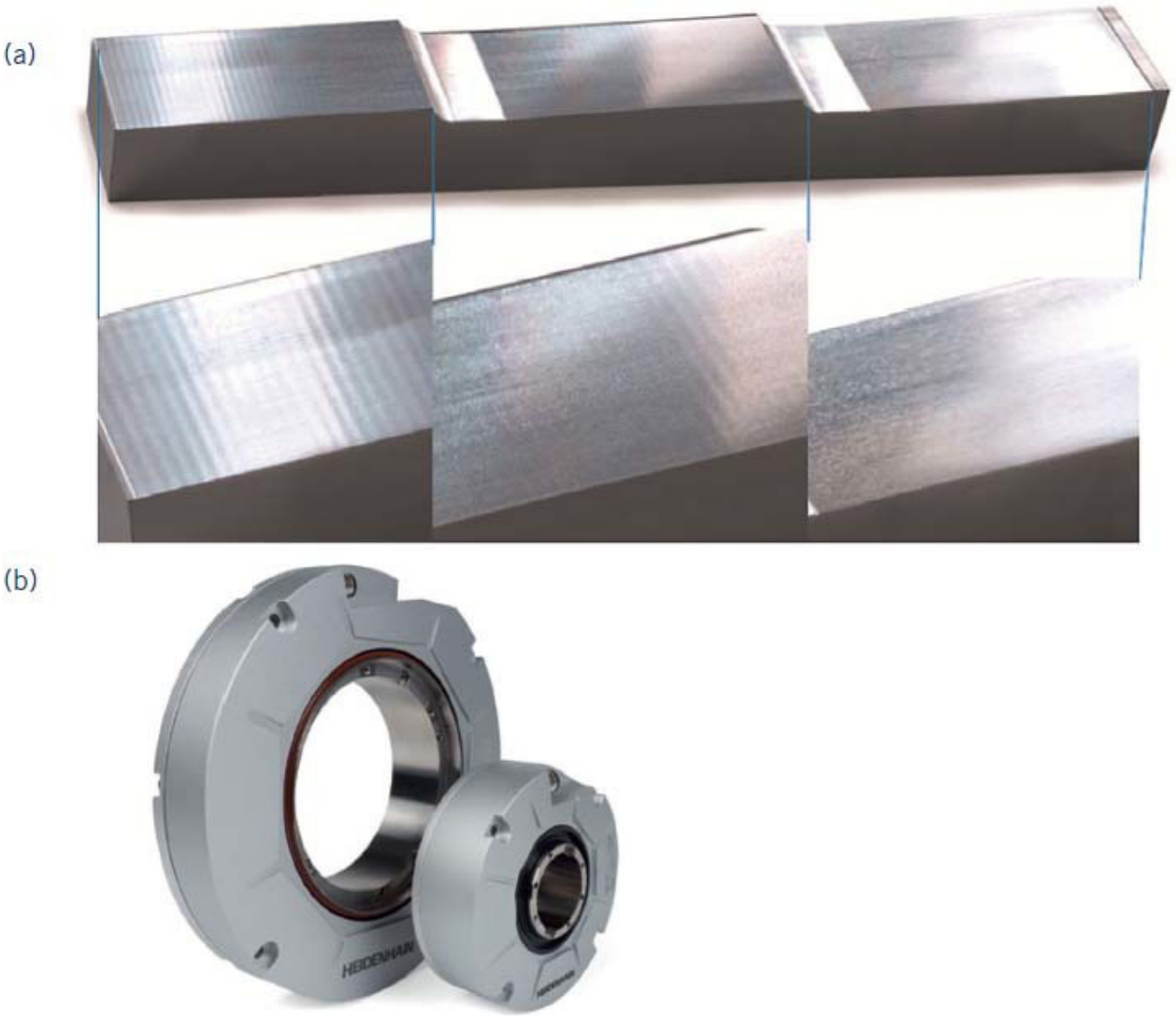

FIGURE 4.22 (a) Surface errors because interpolation errors of the linear encoder are too large. (b) Photograph of angular encoders for machine tools.

Accuracy of Rotary Axes

Position deviations of a feed axis in semiclosed-loop operation as a result of heat generation are not limited to linear axes. Rotary axes can attain a high degree of precision and reproducibility because of highly accurate angle-measuring devices or angular encoders.

Figure 4.23 shows the asymmetric temperature distribution of a rotary table driven by worm gears in the first 15 minutes of an oscillation from the starting position to 180 degrees, back to the starting position, and next to –180 degrees and back to the starting position. The maximum rpm is 12.5. A distinct temperature elevation from 21 to 30°C will lead to angular errors of up to 10" in semi-closed-loop operation. In closed-loop operation with an angular encoder, these temperature elevations do not impact position accuracy

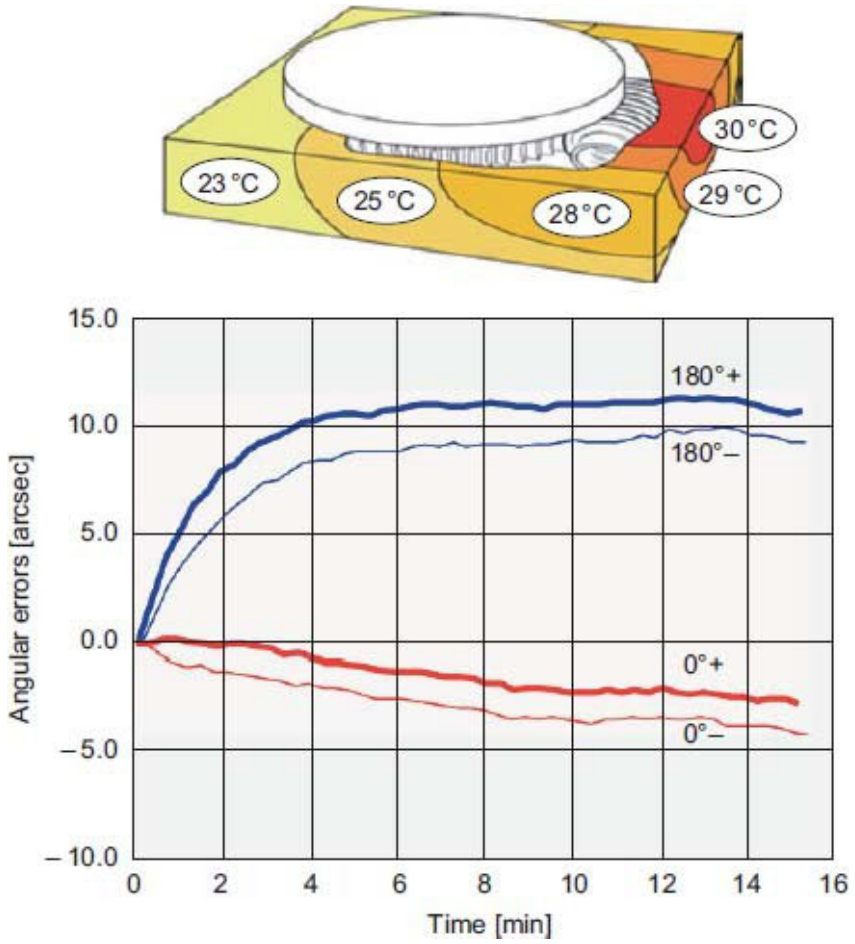

FIGURE 4.23 Angular errors in semiclose-loop operation.

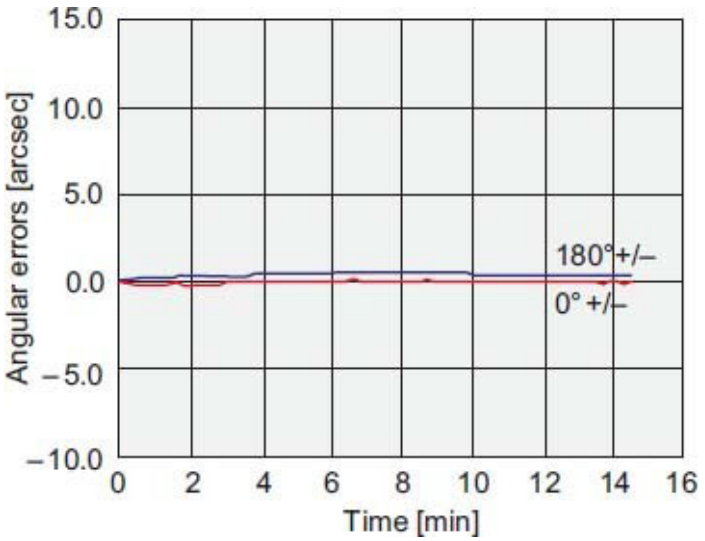

FIGURE 4.24 Angular errors in closed-loop operation.

Requirements of Direct Servo Drives on the Measuring System

Direct servo drives generate feed motions without mechanical transmission and ball-screw spindles, respectively. They directly transform electrical energy into the desired motion. Direct servo drives for rotary axes are torque motors; for linear axes, linear motors 4.25 and Torque motors are multipole electric direct drives from the group of slow-speed motors. They have a high torque at relatively slow revolutions, mainly resulting from the high number of pole pairs and the large diameter.

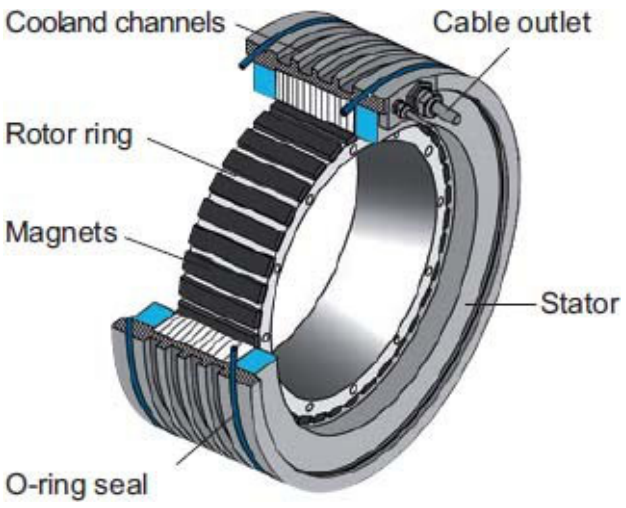

FIGURE 4.25 Schematic of a torque motor. ETEL.)

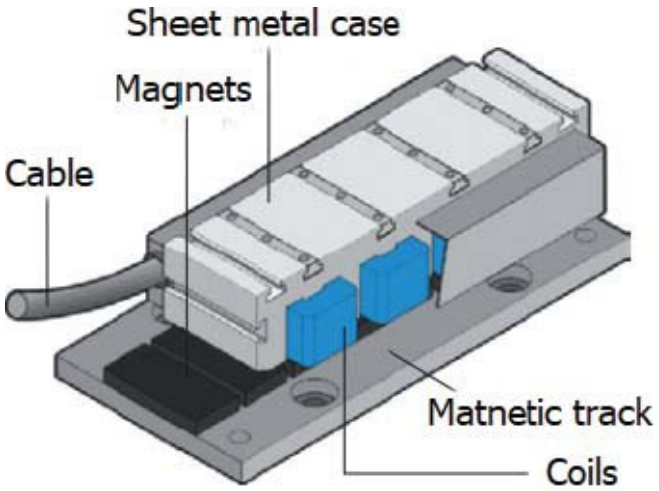

FIGURE 4.26 Schematic of a linear motor. ETEL.)

As a result of wear resistance and high productivity, this drive technology is applied in ever more machine tools. Whereas linear motors must move the large mass of the machine table, thus reducing dynamics and efficiency, the torque motor in a rotary table can play out all its advantages.

To take full advantage of the technical capabilities of the direct drive and not to limit its dynamics, the measurement system must exhibit the smallest possible interpolation errors. The reason for this connection lies in the special control circuit of this drive technology The measurement device provides the signals for position and speed controllers. The amplification factor in the control circuit, needed for the high dynamics, also elevates the signal errors of the measurement device. This can have undesirable effects such as high noise levels and loss of motor output.

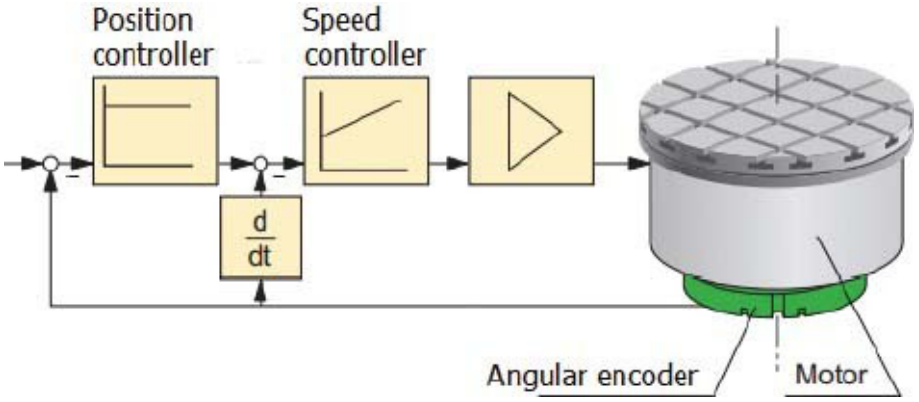

FIGURE 4.27 Control loop for a torque motor.

Power Loss from Large Interpolation Errors

In precise machine tools, elevation of the drive temperature must be avoided. Encoders with low resolution and large interpolation errors interfere with the synchronism of the direct motor. The control circuit attempts to eliminate the speed differences through decelerations. This power loss leads to warming of the motor and, consequently, warming of the entire machine Warming of a rotary table is clearly visible in the thermal images in Figures 4.29 and

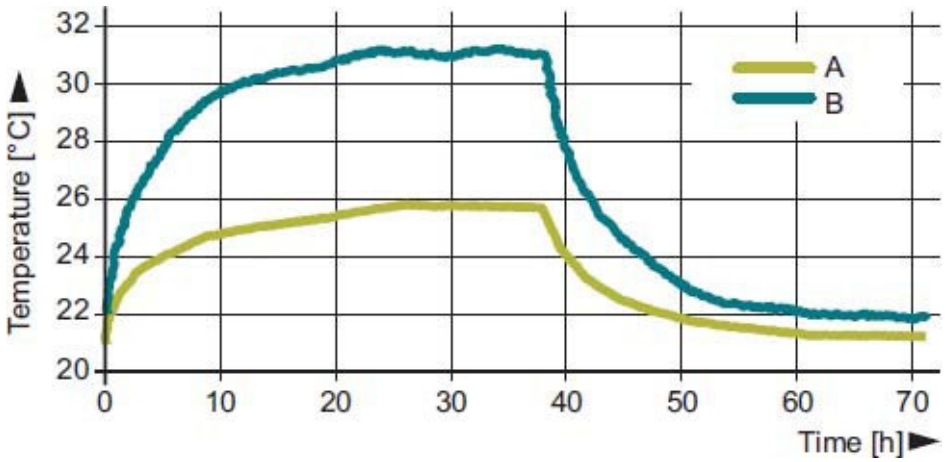

FIGURE 4.28 Temperature graph of a direct drive with a measuring device with a large interpolation error (B) and small interpolation error (A).

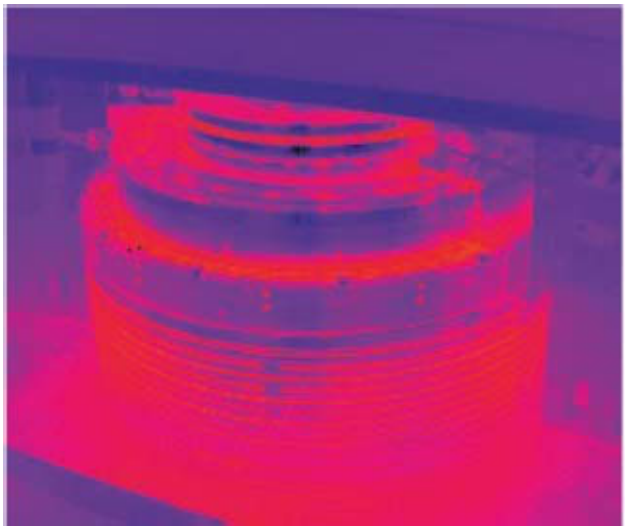

FIGURE 4.29 Lower temperature measured with device A.

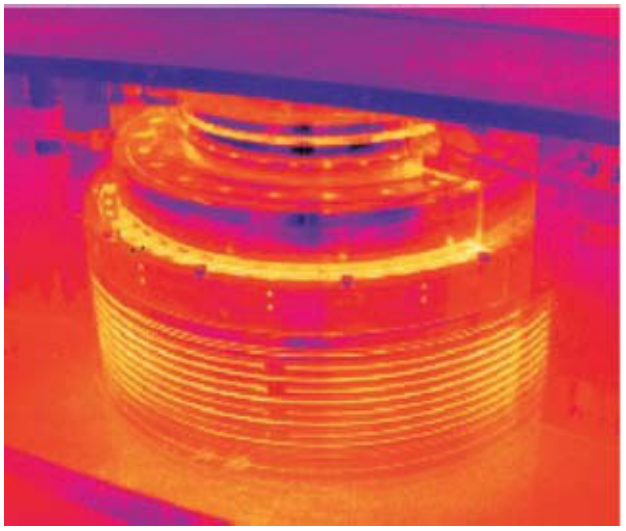

FIGURE 4.30 Higher temperature measured with device B.

SIMPLE DIAGNOSIS OF MEASUREMENT DEVICES

As described earlier, angular and linear encoders in highly precise machine tools are decisive for performance and fabrication quality. Furthermore, the machine users expect high availability and planning reliability of equipment and processes. For this, downtime of machines must be prevented, and maintenance cycles must be reduced to the essentials 4.31 and

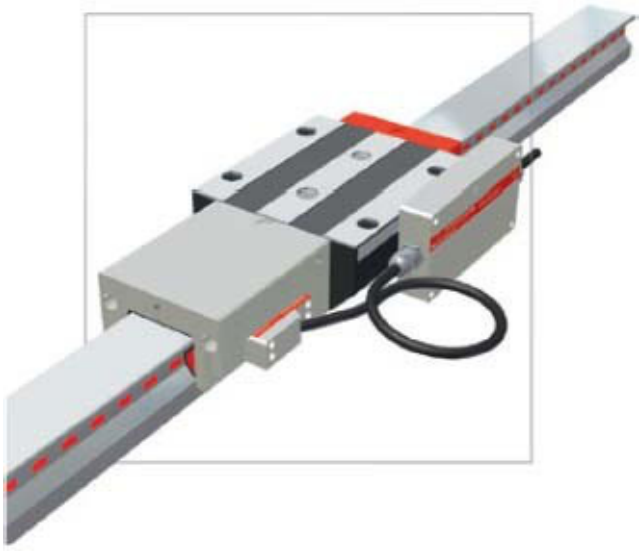

FIGURE 4.31 Recirculating roller guide with integrated measuring carriage, read head, and evaluation electronics. Schneeberger.)

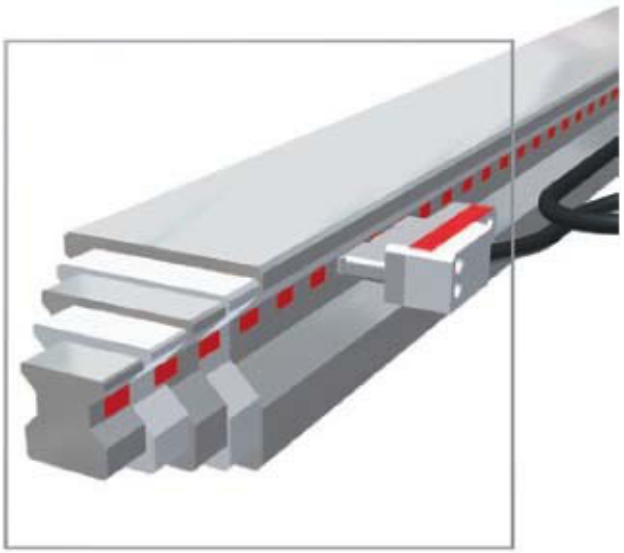

FIGURE 4.32 Integrated position-measuring system with depiction of various command variables. Schneeberger.)

Modern encoders serve more than the high requirements regarding dynamics and accuracy. Furthermore, they provide the necessary information for commissioning, monitoring, and diagnosis. This information can be called up with the CNC system, displayed, and, if configured accordingly, evaluated by remote diagnosis.

Fully Serial Interfaces

Modern measurement systems are equipped with fully serial interfaces. Because there is no transmission of analog signals, significant savings of otherwise necessary wiring can be realized. Position values are digitized in the encoder and transmitted to the subsequent electronics. This minimizes interference on the position information and its transmission because the signals are usually sinusoidal.

A digital interface for position data also allows transmission of the so-called electronic nameplate, meaning the data for commissioning

of the measuring device and the CNC system. Additionally, the interface transmits information such as the winding temperature of the drive and diagnostic data. Depending on the interface, it is possible during operation, at the regular maintenance or malfunction, to transmit information about the functional state of the position-measuring device quickly and reliably.

Simple Diagnosis via Evaluation Figures

For evaluation of the functional reserve in closed control mode, modern measuring equipment generates so-called evaluation figures These easy-to-understand numbers give detailed information about the state of the internal incremental and absolute sampling signals and the position value formation and thus about the current state of the measuring device. These data give testimony about the functional reserve. In contrast to analog measuring instruments, no expert knowledge is required to determine the condition of the device.

Scaling and relevance of evaluation figures are typically identical for all measurement equipment from one manufacturer; thus continuous evaluation is possible. Transmission takes place within the closed control loop and does not affect the time of position data transmission.

Remote Diagnosis

The remote diagnostic functions integrated in modern CNC systems allow the data displayed on the screen of the CNC to be retrieved via remote diagnosis tools. For the service personnel of the machine manufacturer or maintenance technician, the problem can be diagnosed remotely, and a service activity can be planned based on the cause of the malfunction (see Figure

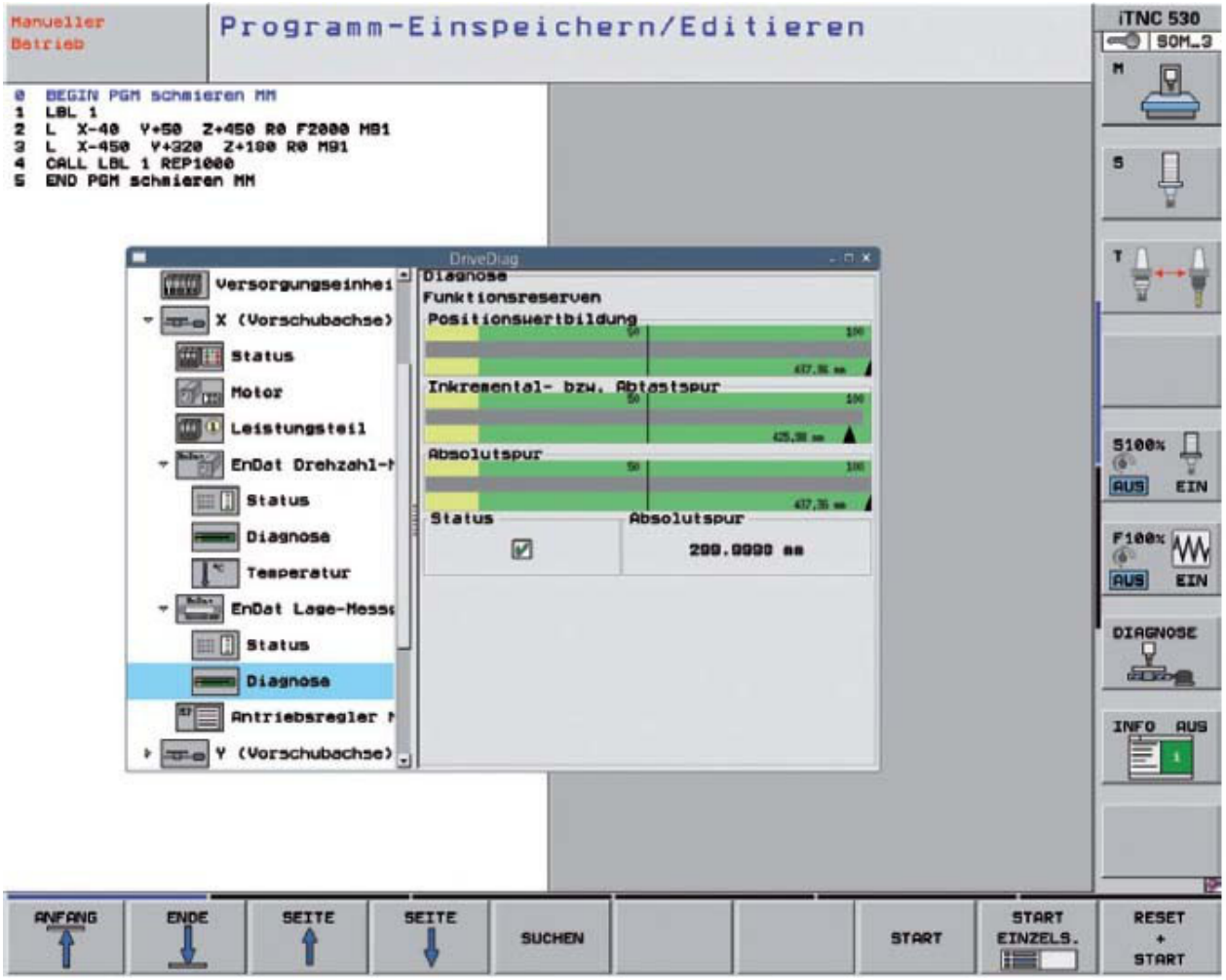

FIGURE 4.33 Screen of a CNC system with display of diagnosis results as rating numbers. HEIDENHAIN.)

COMPENSATIONS

The accuracy of machine tools will be compromised by mechanically caused deviations from the ideal geometry or errors in the power transmission and measurement system. During machining, temperature variations and mechanical forces can lead to a decline in precision.

A part of this systematic deviation typically can be captured during commissioning and compensated for during operation based on position feedback of the encoder and additional sensors. For this, modern CNC systems possess axis-specific compensation functions. Yet it should be considered that compensations via the CNC system are merely an aide for corrections in a limited scope. First and foremost, the precision of a machine is based on the mechanical design and its accuracy.

Compensation functions in the CNC system can be created individually for each machine via the machine parameters. The normal actual and desired position indications do not consider the compensation values; the position values of an “ideal machine” are displayed. The following compensation functions are available.

Backlash Compensation

Given a transmission of energy between a machine component and its drive, for instance, a ball screw, a *backlash* or *play* occurs. To create a mechanism that works without play is nearly impossible and would come with unacceptable wear on the machine’s parts. Backlash also occurs between the machine and the measuring system. This

mechanical backlash can have a negative influence on the output of a machine tool For instance, if an encoder runs ahead of the machine table because of backlash, the targeted position is reached earlier, but the actual travel of the table is too short, thus resulting in a deviation from the target dimension on the workpiece.

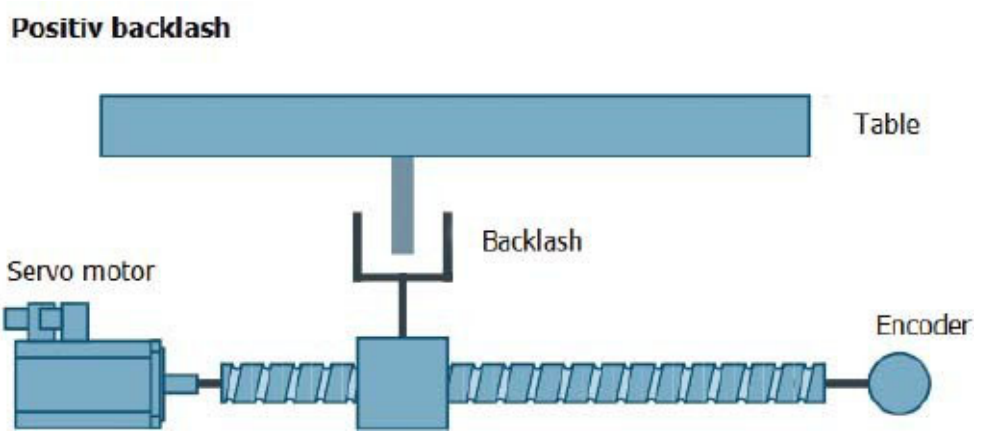

FIGURE 4.34 Mechanical backlash influences the quality of a machine tool. The encoder moves ahead of the machine table, for instance, in this case of positive backlash. Because the position captured by the encoder is ahead of the actual position of the table, the position of the table will be short of where it is supposed to be.

During commissioning, the machine manufacturer must measure this backlash by approaching one particular position from two sides. The position difference thus obtained must be added to the parameters of the machine. During operation, these compensation values are automatically activated, and the backlash value is appropriately considered for each position change of the axis in question

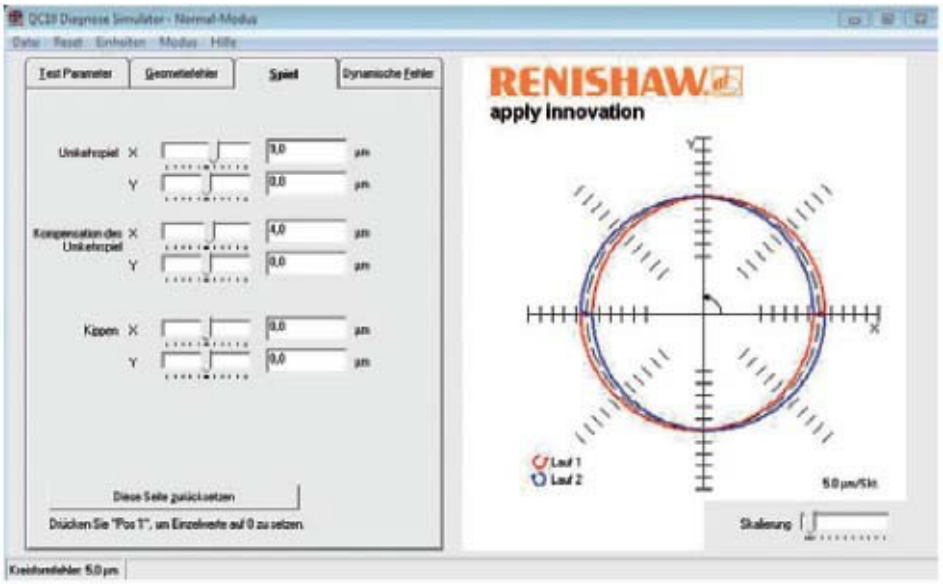

FIGURE 4.35 With the aid of a circular form test, the backlash of the can be measured. This error will be corrected via the backlash compensation in the CNC system.

Spindle Pitch Error Compensation

The measurement principle of *indirect measurement* employed on CNC machines, where the position generator is located in the servo motor of the drive axis or at the other end of the ball screw, works under the assumption that at any given spot within the operational range, the pitch of the ball screw is constant. In this way, the actual position of the axis can be inferred from the position of the drive spindle. Yet, because of the manufacturing tolerances of ball screws and based on the quality class, dimensions vary to a smaller or larger extent; such a condition is called *spindle pitch* Additionally, the errors inherent in the measuring system and its mounting to the machine may cause measurement deviations called *measuring system*

To correct these errors, the *natural error curve* of the CNC machine is measured with an external measuring system, for example, a laser-

based measurement Next, the required correction values are stored in the CNC system and applied during operation as a position-dependent correction value.

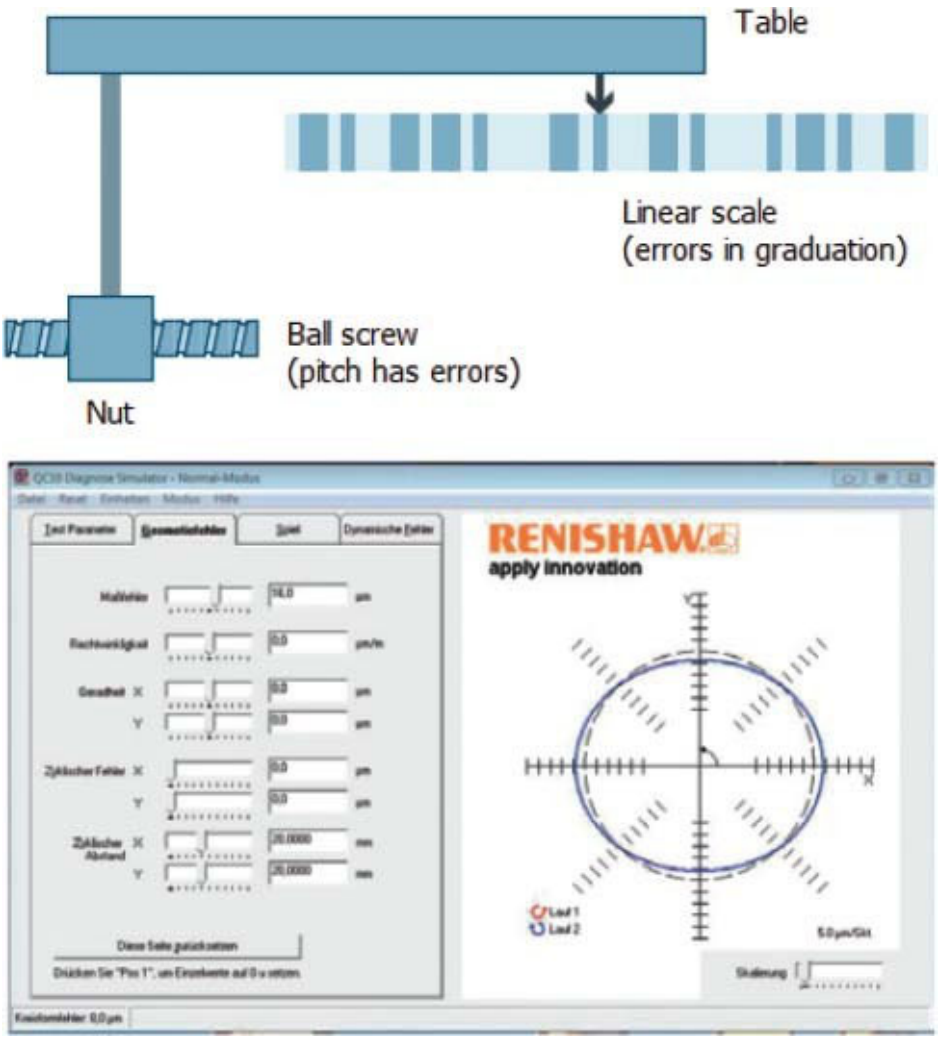

FIGURE 4.36 The measurement offset in the and resulting from manufacturing tolerances of the ball screw produces interpolation errors of the axes. This type of error can be measured with the Renishaw circular form test and compensated in the CNC system with the use of spindle pitch compensation.

Friction or Quadrant Error Compensation

Besides inertia and machining forces, the frictional forces in the drive and the slides of the machine have an influence on the behavior of the machine axes. The contour accuracy of an axis is particularly affected when accelerated from the resting position through the transition from static friction to sliding, or dynamic, friction.

Given this steep change in friction, a briefly elevated drag error occurs. In the case of interpolating axes, such as slide axes, this can lead to significant contour errors. Contour errors on cylinders result from the resting position of one of the affected axes at the moment of a directional change, particularly on quadrant transitions.

Frictional or quadrant error compensation is being applied at the time of acceleration from the resting position, meaning during the transition from sticking to sliding friction in the form of an additional revolution target value impulse. In this way, contour errors at quadrant transitions of circular contours can be avoided almost completely.

During commissioning of the machine tool, the manufacturer must investigate the quality of a circular contour at quadrant transitions with the help of the circular form test. This test can be performed with an onboard tool of the CNC machine or with an external device, for instance, the Renishaw QC10 ballbar test. The deviations obtained must be entered as compensation values into the correction table, under machine data, of the CNC 4.37_through

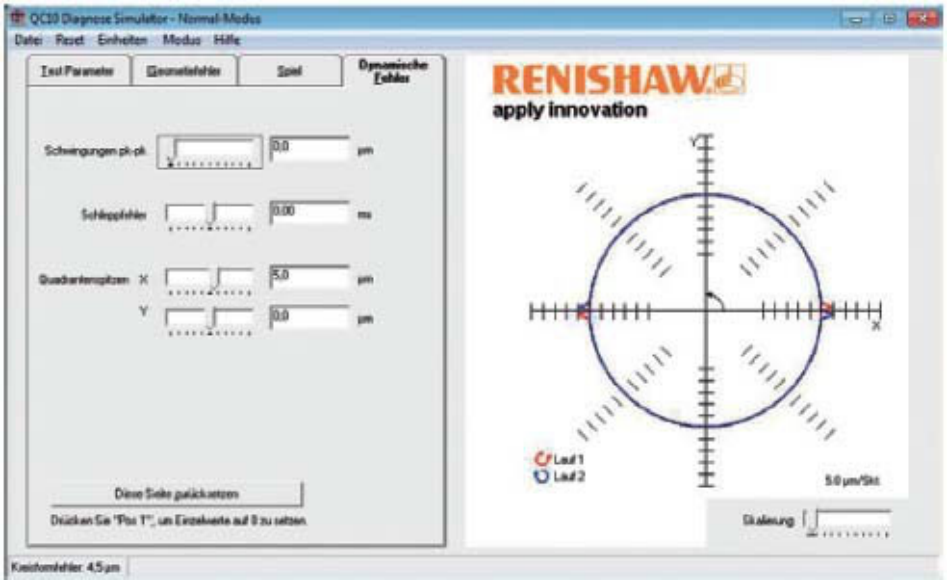

FIGURE 4.37 Quadrant error resulting from acceleration in the direction reversal of the It is measured with the Renishaw circular form test and can be compensated for with friction compensation.

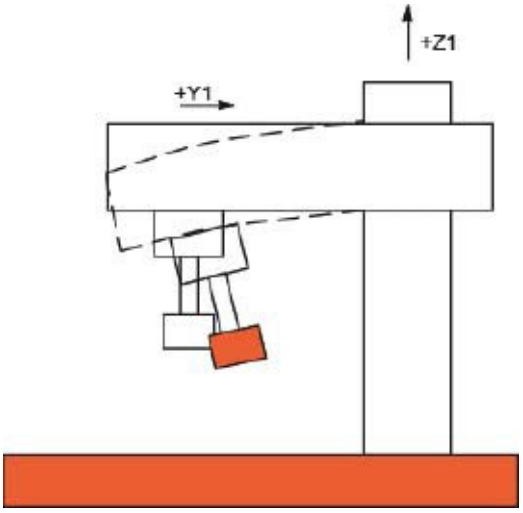

FIGURE 4.38 Bending in the negative from the weight of the tool head axis.

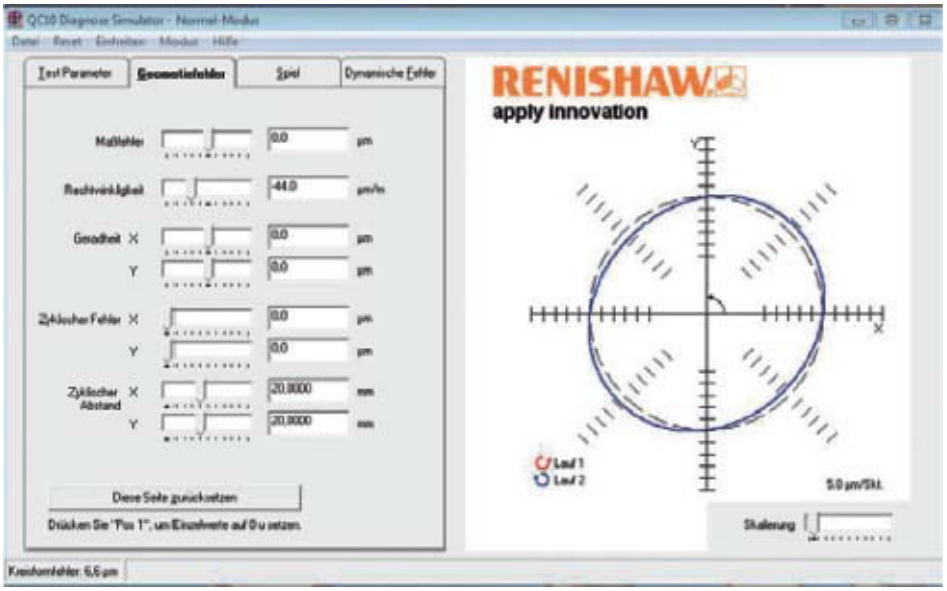

FIGURE 4.39 Result of a Renishaw circular form test: geometry errors in the perpendicularity relative to the and The error can be compensated for in the CNC system with the use of sag compensation.

Compensation of Sag and Angle Errors

Given the weight of the mechanical components of a machine tool, a position-dependent shift and tilt of the moving parts can occur because machine parts, including slides and guides, can bend. This can cause a sag error.

If motion axes are not located in the desired position, for instance, perpendicularly, the result will be a positioning error the further the motion moves away from the zero position. This angular error can be caused by the weight of machine parts and because of the weight of tools and workpieces.

The compensation values are determined at commissioning and entered in the CNC system as a compensation table. During operation of the machine tool, the axis in question is corrected by

adding the position target values as the axis is linearly interpolated between the set points. While doing so, within the interpolation network there is always one base axis and one compensation axis. This means, for example, that if the squareness of the is not correct in the interpolation network of the and then this inaccuracy will be compensated for with the

Temperature Compensation

Because of the heat generated by the motors of a machine tool or other sources, such as sunlight or draft, the machine bed and machine parts expand. This expansion depends on the temperature difference and the thermal conductivity of the machine components. As a result of the expansion of the machine components, the actual positions of the individual axes change. This change negatively impacts the precision of the processed parts. The CNC system can compensate for these position changes specifically for each axis. During commissioning, the manufacturer captures an infrared image of the machine that is in operation for a defined time, for instance, 24 hours. This image is used to study distinct heat sources within the machine, and it allows for measures to provide cooling. For temperature compensation to work, a number of data have to be collected. These are the actual position values provided by the encoders and a temperature profile generated by a number of sensors in the machine.

The position of the axes change will be measured relative to the temperature.

In the programmable logic controller (PLC) program of the CNC, registers are created and formulas are stored that express the machine-specific relationships between the expansions of the axes

relative to the measured temperature. Because temperature-based machine changes happen quite slowly, the data for the creation of a temperature profile can be captured every few minutes or so.

This results in error graphs for different temperature values. These graphs must be entered into the CNC system as parameters and processed with the result that a temperature-dependent correction value is added to the position nominal value of the axes.

Volumetric Compensation (VCS)

Rotary axes such as swivel heads also exhibit systematic geometric errors. These are caused by the position of the circular axes, their offset, the orientation of the tool holder, and lastly, the position deviations of each circular axis

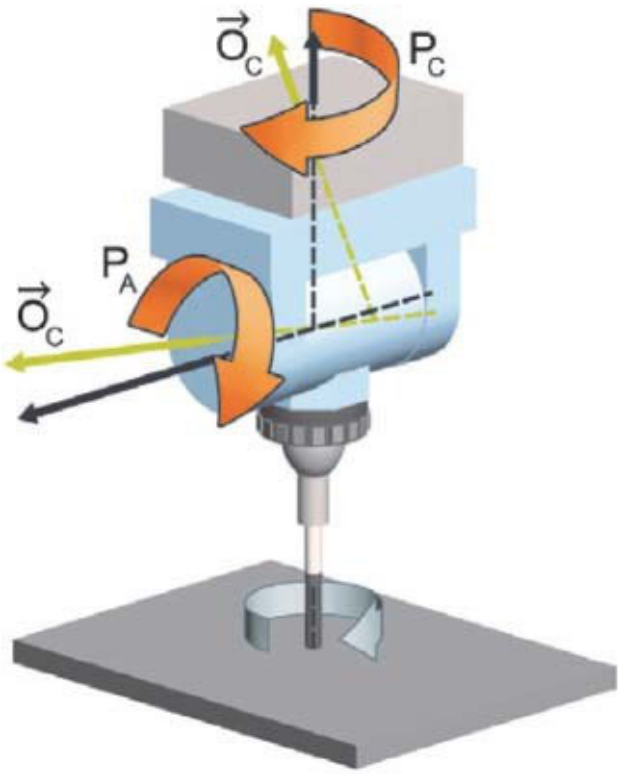

FIGURE 4.40 Systemic geometric errors of the rotary axes of a portal milling machine (O: orientation error, P: position error).

As highly precise as a machine tool might be, inherently each machine has slight systematic geometric errors in the guide system of the feed axes. With linear axes, these are linear position errors and horizontal and vertical straightness errors, as well as rolling, pitching, and yawing. Other errors occur in the orientation of the machine components toward each other, for instance, perpendicularity deviations. For a three-axis machine, these add up to 21 geometry errors on the tool holder: 6 kinds of errors for each linear axis times 3 axes plus 3 times perpendicularity errors = 21 errors. Figure 4.41 illustrates the situation.

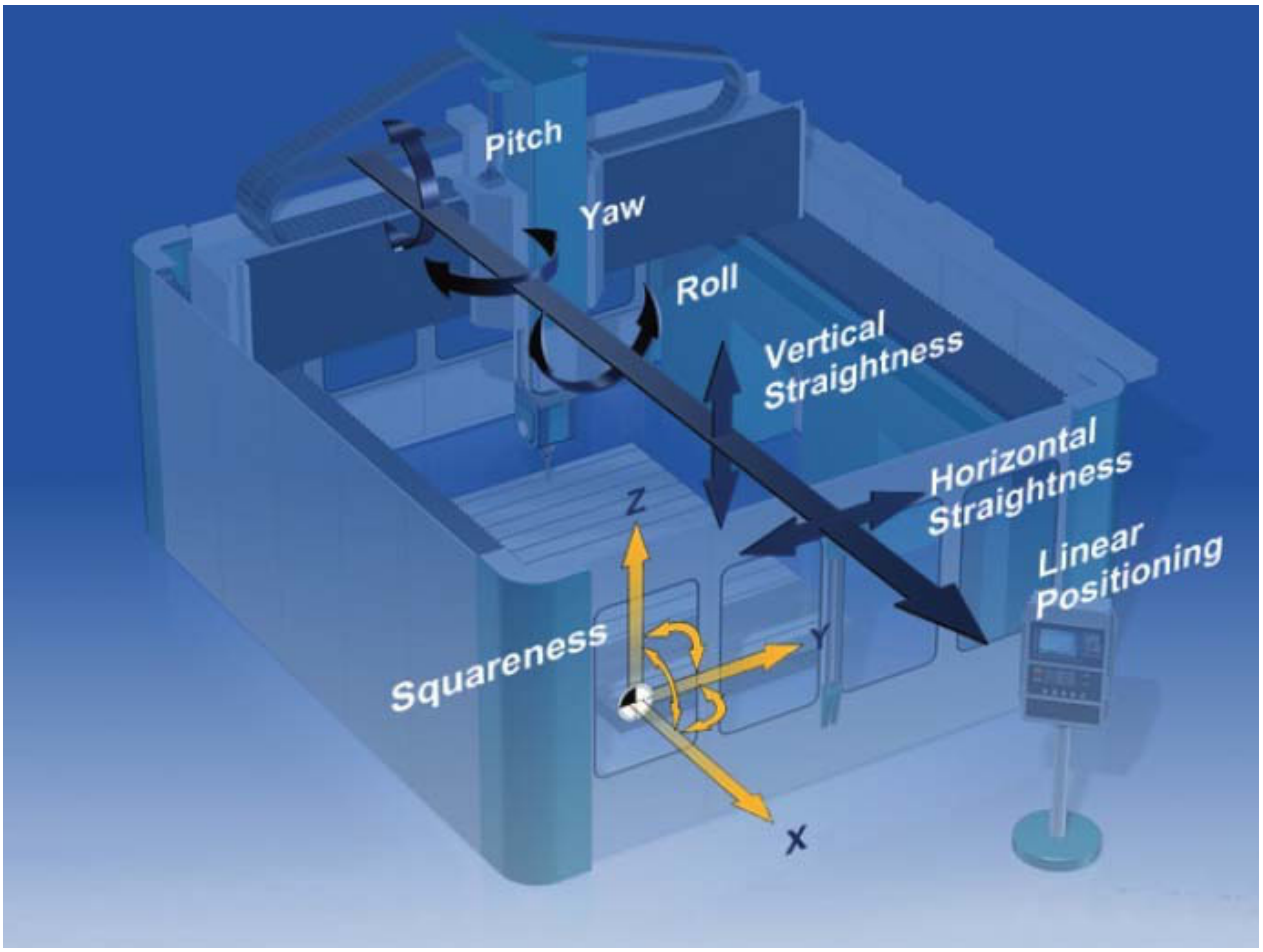

FIGURE 4.41 Systemic geometry errors of the feed axes of a machine tool (here

Each of these systematic errors actually occurs. The individual deviations superimpose to create a total error called *volumetric* The superimposition of all systematic individual errors in linear and rotary axes on each position within the work area causes:

■ A location-specific offset of the tool tip from where it is programmed to be, and

■ A location-specific deviation of the tool from the desired orientation.

The volumetric error describes the deviation of the actual erroneous position of the *tool center point* in the workspace as opposed to an ideal, error-free position. It stands to reason that the volumetric error varies within the workspace of the machine depending on the position of the TCP 4.42 and

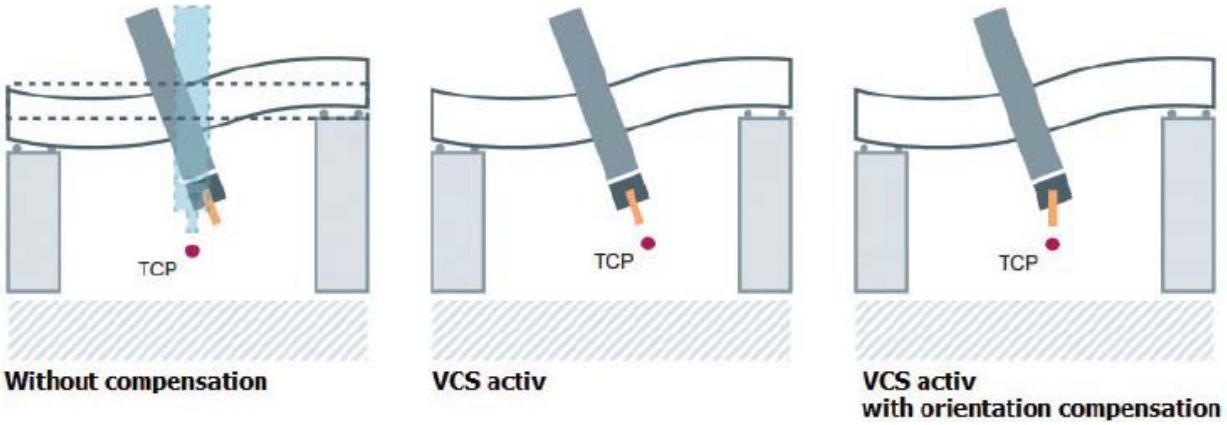

FIGURE 4.42 How volumetric compensation works for three- and five-axis machines. On five-axis machines, the orientation error also can

be compensated for.

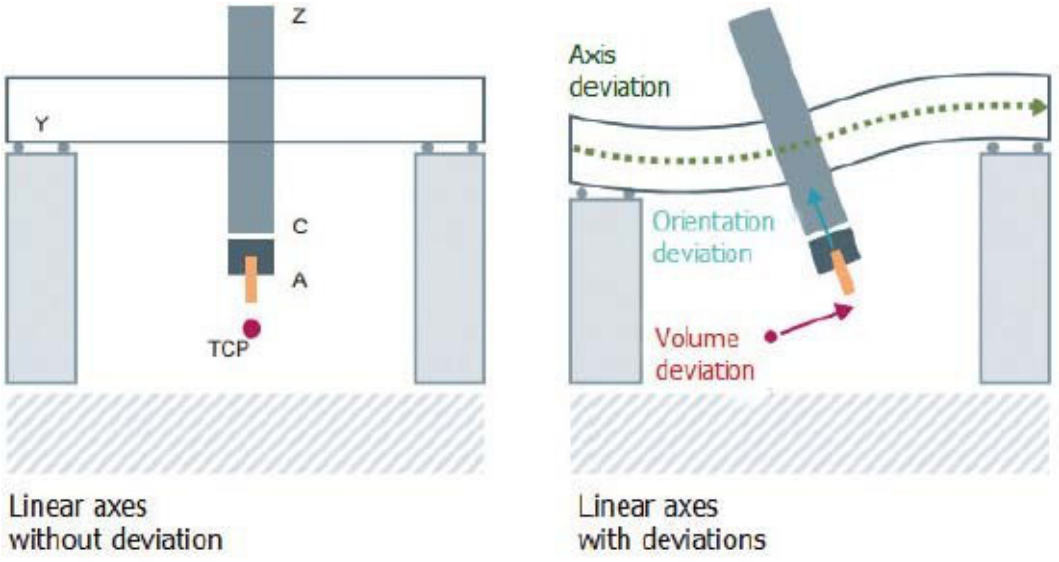

FIGURE 4.43 Volumetric errors at the TCP depend on the position of the linear axes.

In large machines, this error can amount to several tenths of a millimeter given an unfavorable constellations of the axes positions. The causes are large lever effects, for instance, on large portal type milling machines.

The possibility that errors of this magnitude are impacting the quality of the workpieces necessitates extensive and time-consuming countermeasures. This is where CNC integrated compensation becomes relevant.

Volumetric errors can be measured with laser measurement systems with optical measurements for position, rotation, translation, and circularity. For this, all machine errors in the entire work area must be measured. It does not suffice to measure single machine errors. The tests capture entire measurement graphs because the

individual errors depend on the position of the appropriate feed axis and on the measurement location. For instance, an error of the on one particular differs if the and take a different position.

A laser interferometer is used to capture the total geometric error with the transformation turned on and turned off. A compensation table with the acquired values is generated for the CNC system Axis measurement with a laser interferometer can be performed with various optical aids in sequence, meaning measurement of path characteristics such as pitching, yawing, and rolling or saving time synchronously with a multiaxis laser.

FIGURE 4.44 Test of position accuracy using a laser interferometer. Renishaw.)

Multiaxis measurement is based on a combination of interferometric way measurements for position, pitch, and swerve; horizontal and vertical straightness; and rolling via a laser

diode/position-sensitive diode (PSD) arrangement. The multiaxis measurement captures all degrees of freedom

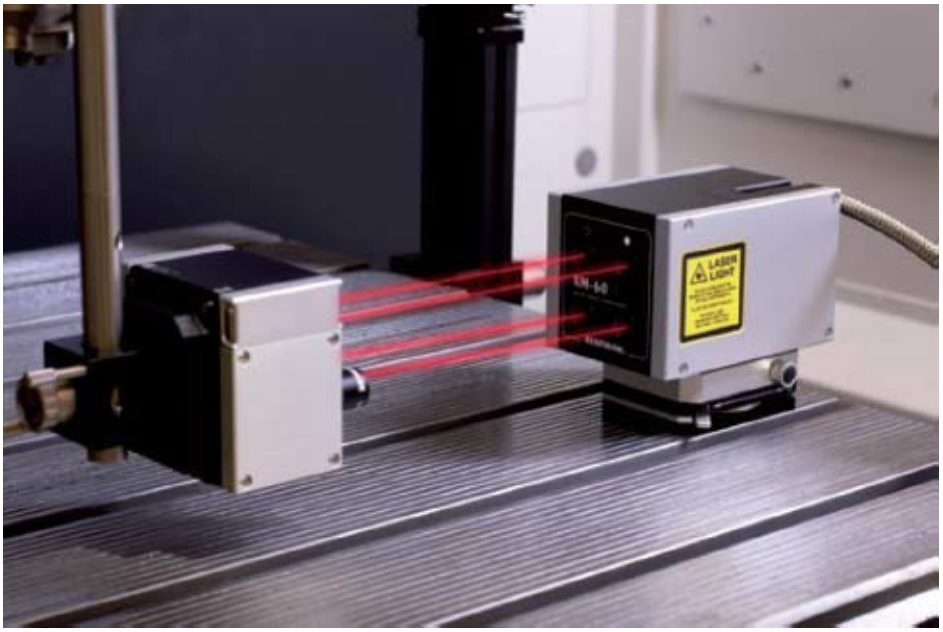

FIGURE 4.45 Multiaxis laser interferometer XM-60 for synchronized capturing of six degrees of freedom. Renishaw.)

The acquired data can be, without further processing, directly written into the VCS file. It is only necessary to record the position of the measurement beam relative to the TCP. The designations of the deviations in the volume compensation model are made according to Table

TABLE 4.2 Designation of Deviations in the Volume Compensation Model

Model

Model
Model
Model

Volume compensation can only identify systematic errors; any random errors, such as backlash, are not considered. Successful volume compensation requires that all axes have the best possible geometric alignment and that backlash, both translational and lateral, is at a minimum. Ideally, the success of volume compensation will be confirmed by independent means, such as a volumetric circular test.

With the activation of volume compensation and the appropriate transformations in the CNC system, for instance five-axis transformation, the machine will have noticeably smaller translational and perpendicularity errors. This is so even if previously linear compensations have been ascertained exactly 4.46 and

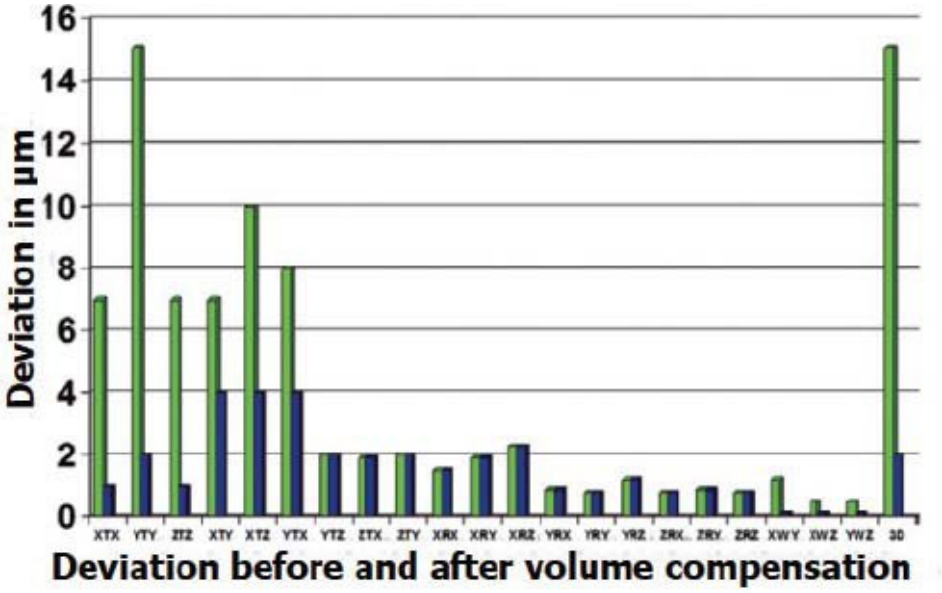

FIGURE 4.46 Measuring results of a volumetric machine compensation with individual data before and after VCS.

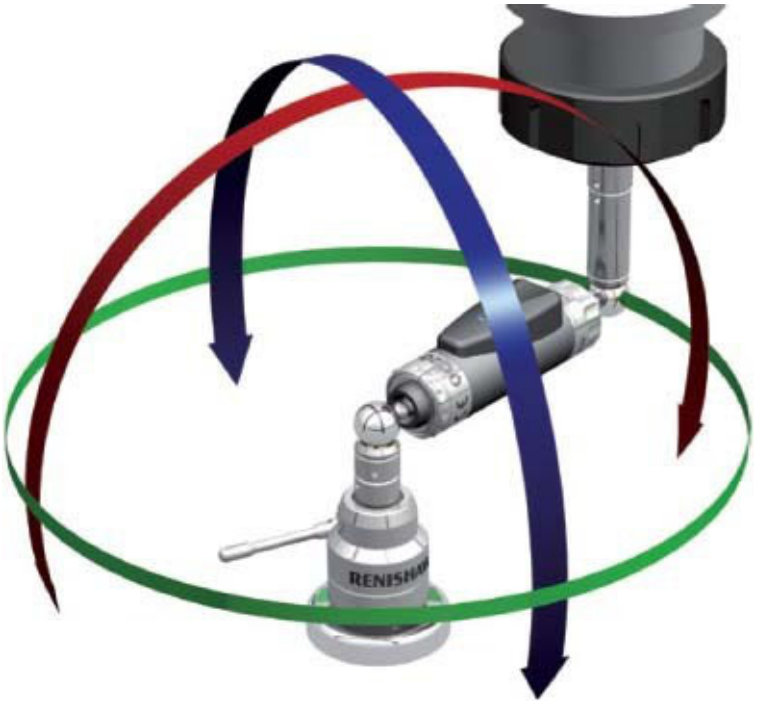

FIGURE 4.47 Principle of a volumetric machine measurement using the circular form measurement system QC20-W. Renishaw.)

Deviation Error Compensation

Deviation error is the term for residual system deviation of the position when moving a machine axis, also called *axis lag* or *following* The axial deviation error is the difference between the nominal and actual positions of the machine axis. The deviation error becomes manifest in the form of undesired speed-dependent contour distortions, especially at positive and negative accelerations, for instance, on circles and corners.

Deviation error compensation can reduce axial contouring errors to nearly zero. The machine manufacturer must determine the contouring error during commissioning of the machine with a CNC-integrated trace function or via external means. The errors are then entered in the appropriate machine compensation data memory in the CNC system.

With velocity precontrol of the deviation error compensation, a target velocity value is applied to the rotary encoder. Thus, given a constant velocity, the deviation error can be eliminated nearly entirely.

If several axes that are interpolated with each other have different timing of the axial control circuits, the dynamic adaptation of the deviation error compensation can be used to achieve synchronous timing. In this way, the best possible contour accuracy can be achieved without loss of performance.

Electronic Weight Balance

In the operation of loaded axes without load balance, the hanging axis can possibly drop after the break has been deactivated and before the CNC system takes over. In extreme cases, this can lead to damage to the tool, workpiece, or even the machine. Dropping of a hanging axis can nearly completely be eliminated with electronic

weight balancing. Electronic balancing prevents dropping of loaded axes when the CNC system takes over. After the break has been deactivated, the engaged constant-weight balancing moment holds the position of the hanging axis. Electronic weight balancing must be set up by the machine manufacturer, and the drives of the affected axes must be optimized.

Disadvantage: During operation, the axis servo motor has to continuously provide the torque; this creates more heat and can possibly overload the motor. Therefore, the servo motor must be dimensioned accordingly.

Compensation for Dynamic Deviations

Causes of poor surface quality and inaccuracies are often found in dynamic deviations resulting from the machining itself. Among these are short-term position and angular deviations and vibrations at the tool center. They result from acceleration and deceleration of the feed axes and increase the faster the NC program works. The drive spindle is also not entirely stiff, and its elasticity can also cause vibrations.

Dynamic deviations change during the machine lifetime because frictional forces in the guides change as a result of wear. Dynamic deviations are also affected by the weight of the workpiece.

Evidence of dynamic deviations consists of chatter marks, shadows, and contrast variations on the workpiece surface. Dynamic deviations also have a negative mechanical impact on tools and machine, resulting in excessive tool wear and breakdown and machine damage.

Drive control cannot completely compensate for these dynamic deviations. Yet today various control functions have become available that reduce dynamic deviations in drive axes of machine tools and thus largely improve path accuracy even at high feed rates and complex paths.

Chattering is a dynamic instability during the cutting process caused by incipient vibrations. It is one of the factors that limit the chip removal volume during machining. Visible evidence is the well-known chatter marks. At the same time, the tool wears faster and more unevenly; unfavorable circumstances can lead to tool failure. Chattering also puts an undue strain on the machine tool.

Chattering can be actively suppressed to increase the cutting performance. This allows larger infeed and thus up to 20% more material removal. Also, the tool lasts longer because of reduced load; in addition, the process reliability increases 4.48 and

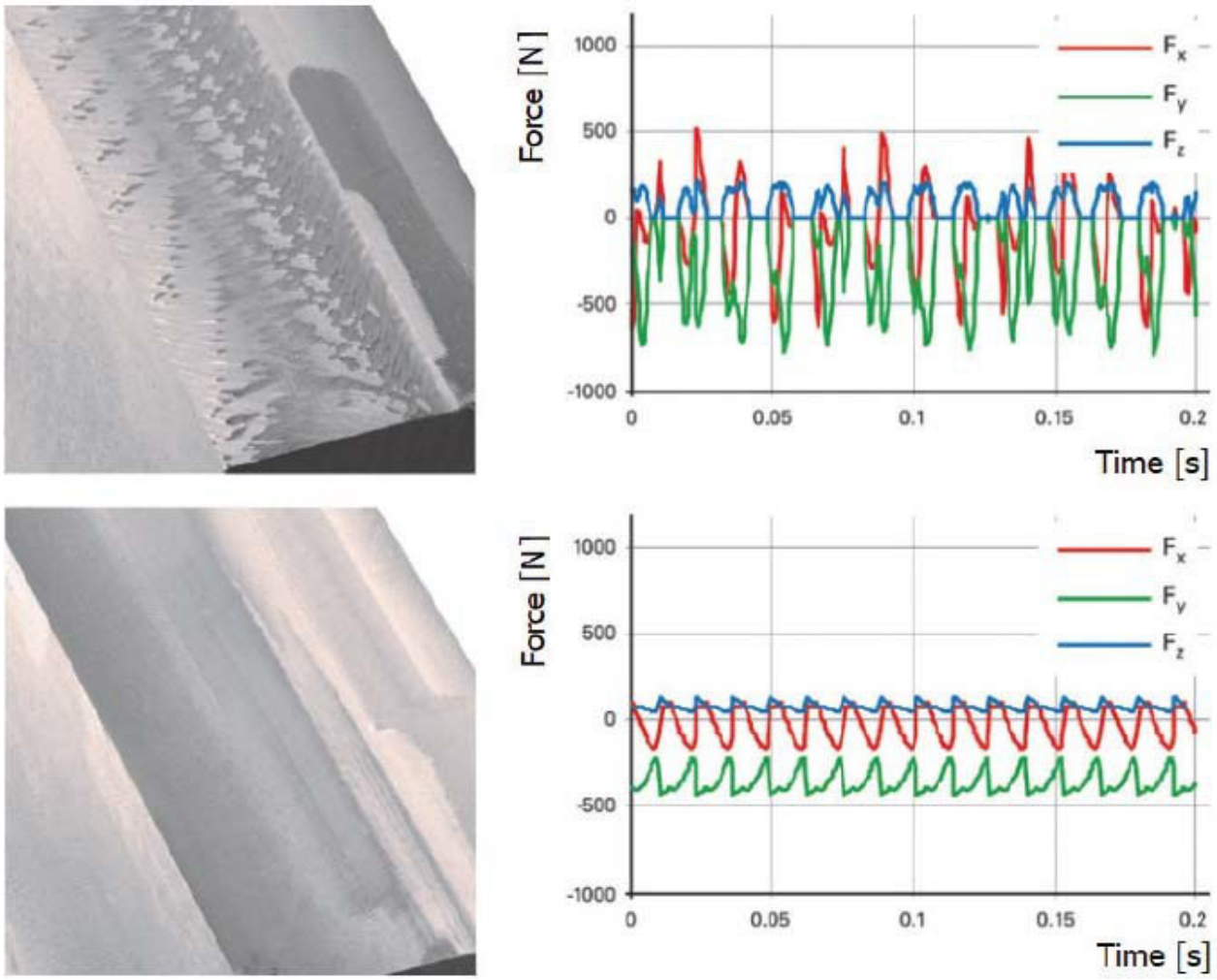

FIGURE 4.48 Workpiece surface and cutting forces when chattering (above) and with added chatter suppression (below).

FIGURE 4.49 Surface machined without active chatter suppression (above) shows visible shading. Active chatter suppression yields a noticeable improved surface quality (below).

Shadows and contrast variations are often signs of a fabrication process that has been tilted in favor of speed at the expense of surface quality and accuracy. Modern CNC systems have functions that take advantage of the machine's capabilities in terms of process speed and better surface quality and accuracy. These functions use

various machine parameters and allow increasing the that is the duration of the buildup of acceleration for a more dynamic behavior, and they suppress vibrations and position deviations to obtain more precision.

One of the functions is the compensation of acceleration-dependent position deviations. Dynamic accelerations release force that can lead to short-term deformations of the machine. As a consequence, the TCP might drift in or across the direction of acceleration. The results are pitching motions or dynamic feathering that cannot be captured by encoders. Thus control of the feed axes cannot react to it. Compensation for acceleration-dependent position deviations at the TCP allows more quality in the production or remarkably reduced cycle times because of the increase in the jolt.

Tilted and curved surfaces often display clear chatter marks of contrast variations. Two frequent causes are elasticity in the drive mechanism and vibrations as a result of poor placement of the machine. Functions in the CNC system can be employed to actively suppress these causative, mostly low-frequency vibrations. The result is quick and vibration-free milling. At the same time, said functions can create high jolt values and therefore higher accelerations, reducing process time without sacrificing surface quality.

Axis positions, workpiece mounting, and speeds of the machine also have a direct impact on the cutting result. CNC functions are available to adjust feed adaptation and reduce these disruptions. These measures:

■ Alter the machine parameters depending on the axis positions. This allows greater contour accuracy within the entire traversing path

of the feed axes.

■ Adapt the parameters continually to the actual mass linear axes or mass inertia at rotary axes and frictional forces. This can also occur during machining. The machine operator cannot decide for himself or herself the loading conditions; thus operator errors can be excluded.

■ Can adapt machine parameters in terms of a speed-and acceleration-based altered friction signature. These measures also can help suppress vibrations and allow a higher acceleration at fast motions of master/slave axes.

All these functions are adapted in the CNC system with high clock frequency to the motions and loads of the machine tool. There is no change in the machine's mechanics. In addition, many of the functions complement each other for still more improved processing results.

IMPORTANT POINTS TO REMEMBER

■ The essential characteristic of NC machines is the input of path information in digital or numerical form and the automatic execution in the machine.

■ Each NC axis is controlled by a closed-loop position control. A positioning-measuring device constantly measures the actual axis position, compares it with the command position, and corrects the difference toward zero.

■ Highly accurate graduated glass scales with optical scanning are used for position measurement. These devices are rotary, linear, or angular encoders and are highly accurate.

■ Absolute encoders are zero-voltage safe; after a power outage, they recognize the absolute position at once.

■ With each motion of an NC axis, there is a lag (axis lag), following error (deviation error, contouring error); it is proportional to the speed of the motion.

■ The size of the axis lag is determined by the factor. It indicates the speed in meters per minute with which an axis can move until a following error of 1 mm has been reached.

■ Closed-loop operation is the term for the measuring of the axis position with a length-measuring device (linear encoder) or the angle of a rotary axis with an attached rotary encoder.

■ Semi-closed-loop operation for linear feed drives is the term for measuring the axis position via a ball screw and encoder.

■ A 1-m-long feed axis has a maximum position error of up to 0.2 mm in semiclosed-loop operation at an average temperature change of the ball screw from 20 to 40°C.

■ Temperature changes and mechanical forces can lead to loss of precision. These systematic deviations can be measured during commissioning of the machine and be partially compensated for via CNC functions. The CNC system offers a selection of compensation functions. Yet these functions are aids for corrections with a limited scope. The precision of a machine tool is primarily determined by its mechanical construction.

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1 "Precision of Feed Axes," HEIDENHAIN Technical Information, March 2006, Dr. Johannes Heidenhain GmbH,

EXPLANATIONS

The terms *switching switching additional* and *auxiliary function* are all identical and refer to the commands that are programmed in an NC program following the M-address.

■ Switching functions are all functions for CNC machines that can be programmed during operation to be on or off, for example, coolant, clamping, and tool change.

■ Technical data can be the tool number (T) with dedicated tool offset values (D), spindle speed (S), and feed rate (F).

M-addresses are a collection of maximal 99 functions governed according to DIN 66026/ISO 6938, part The processing of these signals takes place in the interface controller. More information and a table of M-functions can be found in Chapter "Miscellaneous (M) Functions."

As a result of the early setting of standards, only switching functions for cutting machine tools were created. Therefore, the original two-digit commands M00 – M99 had to be extended to three to four digits (up to M9999) to make commands available for newer generations of CNC machines. In this way, the existing standards did not have to be changed.

Automatic machine functions have been used before in conventionally automated machine tools. With the maturing of

switching machine functions and the integration with automatic processing on CNC machines, it became possible to complete one workpiece at a time. This, at least, was the objective for the development of modern manufacturing centers.

With so many types of machine tools and their diverse variants, the result has been a multitude of designs and functional principles. This account discusses only automatic tool and workpiece change and feed and speed change.

TOOL CHANGE

To machine a workpiece, most CNC machines require the use of a number of tools in a sequence defined by the process plan. In order to extend the automatic work sequence to completely machine a workpiece, automated tool changing is indispensable.

Long before the appearance of CNC machines, tool turrets were used, especially in drilling machines and lathes. In these systems, each tool has a fixed position. After each operation, the turret automatically advances by one position, thus bringing the next tool into the working position.

The first CNC machines naturally made use of this proven technology for the automation of tool changing. It soon became clear, however, that the limited number of tools that could be accommodated in a turret meant that other tool-changing solutions were required. In 1960, the Milwaukee-Matic from Kearney & Trecker, the first machining center developed for use in normal mechanical engineering applications, was presented. As the forerunner of all subsequent machining centers, it had a tool magazine with a double gripper and coded tools and even automatic workpiece changing with pallets. Because the company had patented these innovations, this newly developed technology was unavailable to the market for many years, but it nevertheless led to the development of many other solutions.

The decisive criteria for evaluating a tool-changing system are as follows:

■ Number of tools available

■ Limitations with regard to the dimensions and weight of the tools being used

■ Tool-changing time, generally indicated as the *chip-to-chip time*

■ Costs of any additional tool holders or tool cassettes that may be required

TOOL CHANGING AT MILLING MACHINES AND MACHINING CENTERS

In these machines, the number of tools required is generally significantly higher than with lathes because many tools, such as drills, countersinks, reamers, and tapping tools, are specific to a particular shape or dimension. Therefore, the use of various types of tool magazines has become standard. Machine, tool magazine, and tool-changing system represent one single design element. A distinction is made between chain, disk, circular, and cassette-type magazines depending on the storage element 5.1 and

FIGURE 5.1 Disk magazine as an add-on unit. Miksch.)

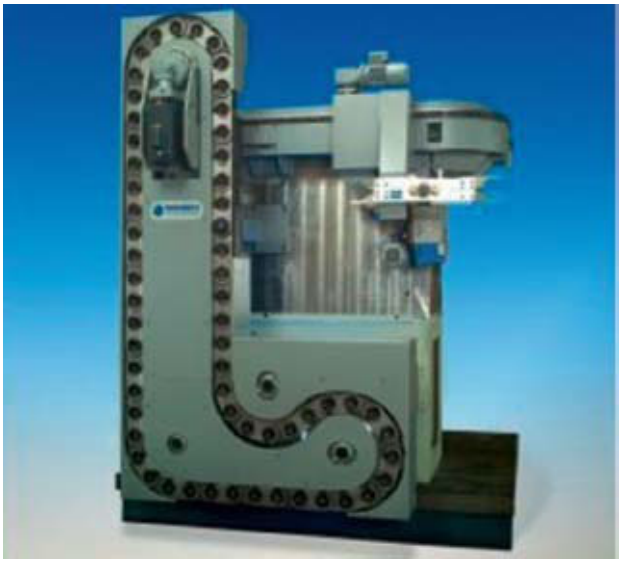

FIGURE 5.2 Chain magazine. Miksch.)

Programming of a tool change happens in two steps for these magazines:

1. The next tool using a T-address is called up for subsequent use.

2. Once the the tool had been readied, the NC program will, at the appropriate time, start the tool change with the M06 command.

The tool-related correction values are either stored together with the tool or are activated separately with a D-address.

In some instances, a machine's magazine can hold more than 100 tools. However, such a large number of tools cannot be accommodated in magazines with a simple one-dimensional arrangement, such as circular magazines with a chain-type or annular configuration. One reason for this is that it takes too long to locate and fetch a new tool. Circular magazines are limited first of all by

their dimensions. Such magazines have been designed for up to 32 tools. Chain magazines are also limited because of the weight of the chain with the tools and the resulting power that is required to advance the chain. Therefore, chain magazines have become available with two separate but shorter chains. Also, the motion of the chain creates mechanical vibrations that have a negative effect on the precision of the machining while the chain is in motion.

To hold a large number of tools, another solution was to equip machines with two or more magazines installed to the left and right of the machine base. There were even designs for tool-changing systems that had four magazine disks offset by 90 degrees on a rotary table that could be brought to the working position in sequence. Another approach was to arrange the tools in a 2D system, for example, by placing them in two or three concentric rings or on a number of disks located coaxially one above another. Yet this created a problem when the tool gripper had to reach across the outer rings to access a tool in the inner ring.

The best solution found so far is linear magazines, where the tools are placed or suspended next to each other in a number of rows. In each of these arrangements, space must be provided for moving in a second dimension.

A favorite way to hold a large number of tools was found in the principle of swappable cassette magazines. Four to six such cassette-type magazines can be incorporated into a single machine. Each of these magazines can house 20 to 30 tools within a rectangular area. The cassette-type magazines are loaded outside the machine and therefore can be exchanged and reconfigured while the machine is still in operation. This makes it possible to quickly prepare new tools

and to remove tools that are worn or no longer needed. Sorting of the tools and transport within the machine are accomplished by a floor-mounted robot that covers the entire range of magazines. It picks up the tools from the cassette that has been called up, delivers them to the changing position for the gripper, and also picks them up again.

Various systems also have been developed for the tool change between the magazine and the spindle. These systems basically have to perform the following set of functions, possibly in a different sequence, depending on the system:

- Moving the spindle and magazine to the changing position
- Making the new tool available
- Removing the old tool from the main spindle
- Dropping the old tool into the magazine
- Picking up the new tool from the magazine
- Inserting the new tool into the main spindle
- Moving the main spindle and magazine back to the working position

The sequence for this changing process is defined in the CNC system or the *programmable-logic controller* (PLC). Its duration is an

important factor for the cost-effectiveness of the machine. It is indicated by the so-called chip-to-chip time.

If it is foreseeable that a limited number of tools will be sufficient, a pickup magazine is the most economical method. As shown in Figure the tool magazine with the readied tool is located in the range of the of the main spindle. Tool change takes longer than the situation shown in Figure 5.4 when the main spindle drops the used tool with the into the tool magazine and advances the tool changer, and the spindle picks up the new tool.

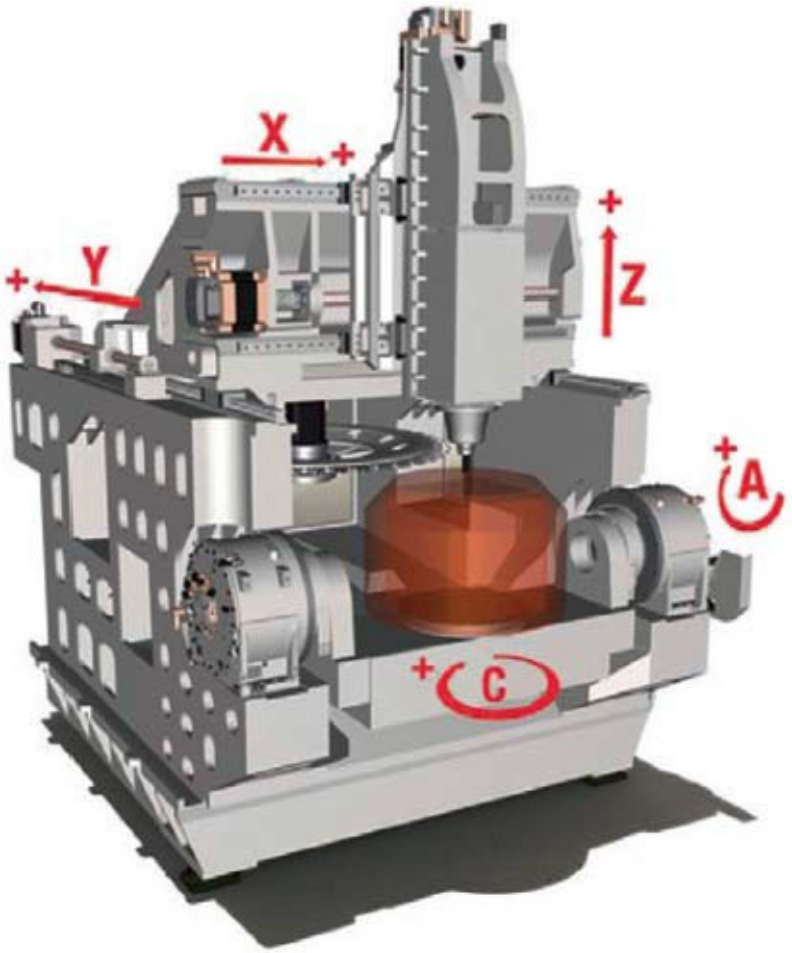

FIGURE 5.3 Pickup tool changer in machining center. MAG IAS.)

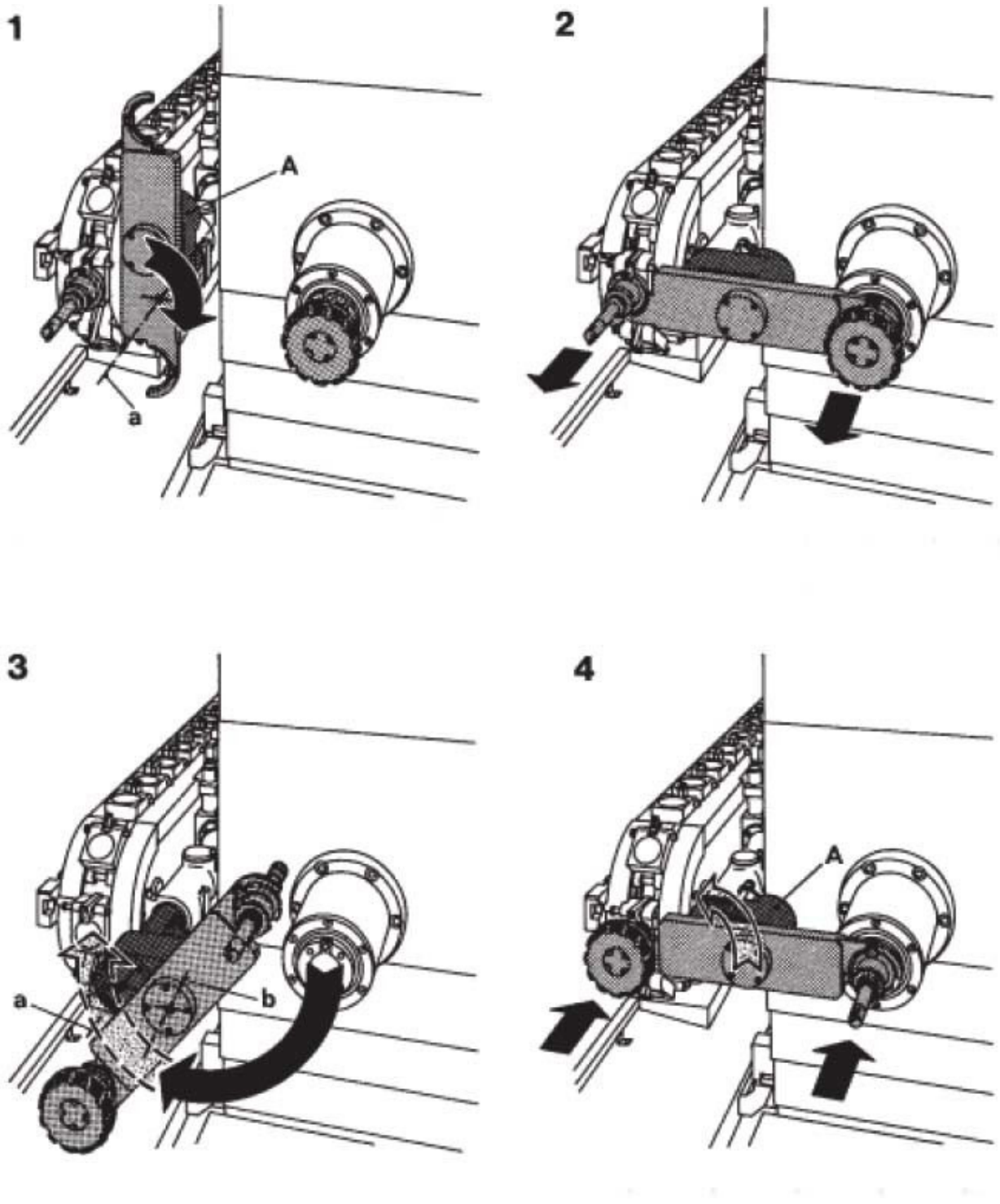

FIGURE 5.4 Tool change with double gripper and chain magazine.

Systems work faster that employ a single- or double-armed gripper. Of the two, the double-armed gripper works fastest because old and

new tools are swapped in one operation. The following tool will be readied during the machining time, that is, while the machine is working.

All magazines have limits when it comes to the dimensions and weights of the tools that can be stored and handled. This means that especially large or heavy tools may have to be exchanged manually. In exceptional cases, in addition to their normal magazine, machining centers sometimes are equipped with changing devices for such special tools, for example, large surfacing heads or drill heads.

TOOL CHANGING ON THE LATHE

On lathes, many tools are not specific to a particular shape or dimension. Thus the number of tools required is also smaller. This means that even today tool turrets are still the predominant solution. Modern lathes can have two or three turrets, and the number of tools per turret can be as high as 18.

For a tool change in a turret lathe, often not the tool number but the position of the revolver, for instance, T1–T8, is programmed. Thus a direct connection between the programmed tool and its position in the turret is created. The machine operator must be aware that with a new job on the lathe, a completely new set of tools must be loaded on the T1 to T8 positions. As the case might be, descriptive designations such as "end mill_63," for instance, might be used.

In modern turrets, the swivel motion is automatically clockwise or counterclockwise in order to bring the next tool into the working position using the shortest path. Inclining the axis of the turret by 45 or 90 degrees produces various types of turrets, such as star, crown, or disk turrets. In addition to stationary turning and drilling tools, all kinds of driven tools can be integrated into the revolver.

Although tool turrets do have a limited capacity, they also are more economical because they do not require additional tool-changing grippers. Because tools always stay in their dedicated holders, dimensional deviations on the workpiece are avoided. The

tool change also happens faster because each turret position needs only a short clearance for the change and must not return to a predetermined changing position. The essential advantage of tool turrets it the low collision risk.

TOOL LOCATION CODING

Various coding methods are available for tool identification. Each of these has its own specific advantages and disadvantages. The following distinctions are made.

Location Coding

Location coding can be used with two options. For option 1, the magazine locations are numbered, and the part program does not indicate the tool number *T* but rather the location number.

For option 2, the particular tool number is always addressed with a dedicated magazine location. After use, each tool must be dropped at the determined position.

Advantages

- Standard commercial tools or tool holders can be used.
- Search for locations is accomplished using the shortest path.
- Locations are easy to recognize via unique coding cams or electronic location detection (Therefore, short tool pickup and dropdown times are seen.)
- Oversized tools can be accommodated by leaving adjacent slots empty to avoid collision.

Disadvantages

■ During setup for a new program, the tools must be placed exactly as defined by the programmer in the program.

■ It must be ascertained that with each new workpiece to be processed, the appropriate set of tools must be placed in the magazine.

■ Configuring the magazine with very similar or twin tools is problematic and may require the use of “tricks” in the CNC system.

Variable Location Coding

Here the operator places the tools in random slots in the magazine and enters the tool number in the CNC system. The system will administer the ensuing data administration. With each tool change, the tool can be dropped at a different location because the CNC keeps track of where each tool is located at any given time. The tool number is entered in the program, and the machine’s internal tool management will determine the actual location of the tool. This method tends to prevail these days because it provides the described advantages and avoids the disadvantages.

Advantages

■ Uncoded or electronically coded tools can be used.

■ Reliable location coding of the magazine can be achieved.

■ The tool number is programmed in the system.

■ Short tool pickup paths are employed.

■ Quick tool change is possible with with double grippers. Two tools always change place in the magazine and spindle.

The condition for variable tool location coding is a CNC machine that has the required system software. This software must:

■ Ensure the correct correlation between tool and location and securely store the tool.

■ Provide the data interface for the read/write unit and tool data management.

■ Support manual tool change by advancing the magazine and indicate the tool number accordingly.

■ Provide dedicated locations for oversized tools and keep the adjacent slots unoccupied.

WORKPIECE CHANGE

Automatic workpiece changing is an additional step toward automated manufacturing. It makes it possible to avoid nonproductive time for the clamping and unloading the workpieces. The benefit is an increase in the productivity of the machine tool and possibly no need for human intervention—with the prospect of unmanned production. Apart from being able to store a large number of machining programs in the CNC system, under certain conditions, it is even possible to implement unmanned, demand-driven machining of various parts of a group of related parts in one-piece or small-series production. Moreover, automatic workpiece changing is an essential requirement for the integration of CNC machines into *flexible manufacturing systems* The change can be programmed and executed with an M-command, for instance, M60.

Automatic workpiece change has already been realized at conventional automatic lathes. These machines have magazines that are automatically restocked with bar stock and can work without human interaction for a long time.

Depending on the kind of workpieces and the way they are clamped, various systems for automatic workpiece change are used:

- Production from bar stock

- The pickup method

■ Changing of an unclamped workpiece by a loading device, for example, a standard commercial industrial robot

■ Changing of a clamped workpiece with a clamping device, for instance, a pallet retrieving the workpiece with a catching device

FIGURE 5.5 Workpiece change by means of a standard industrial robot. Chiron.)

The decision in favor of one of these systems depends on the nature and size of the workpiece and the type of machining. Production from bar stock is only practical for relatively small workpieces. It is thus used mostly with lathes, although it is also

employed with machining centers and milling/turning centers. Because the workpiece has to be cut off or sawed off at the end of the machining process, a removal device or robot is often used to pick it up, especially if it has to be passed on to further machining steps. In turning, producing from bar stock is disadvantageous because it limits the revolutions of the spindle. In combination with the performance of modern cutting materials, this would result in a significant increase in machining time. This has led to a different mode of operation with bar stock, in which the CNC program cuts the material to the correct length before machining, only after which the trimmed part is clamped.

In the pickup method, the gripper picks up the workpiece directly from a designated surface and advances it directly for machining. It is therefore used primarily in lathes because the chuck can serve excellently as a gripper. Because the workpiece is fed in an unclamped state, it has to lie on a horizontal surface and therefore can be gripped and clamped only from above. In lathes with a vertically arranged spindle, this is no problem. For this, the spindle has to be able to move from a working position to the pickup position and, after processing, possibly to another release position. This can easily be accomplished if the motion is performed by the X-axis of the CNC machine. For supply of the unmachined part and removal of the machined part, a simple conveyor belt is necessary. These kinds of systems are applicable only for medium-sized, stably resting, and mostly round parts.

Automatic changing of the unclamped workpiece by a loading device assumes that the clamping operation is simple and safely reproducible. The round part is held between centers or in the chuck of a lathe. In a milling operation, the part is inserted, for

example into the zero-point clamping system and held hydraulically or pneumatically.

Here, too, a distinction is made between systems with one or two grippers. Just as with tool changing, systems with two grippers have a significantly shorter changing time. Systems with a single gripper first have to remove the finished part; only then can they retrieve the new part and bring it to the loading position. Systems with two grippers, on the other hand, can exchange the finished part for the new part directly.

Such systems are used for the handling of shafts, as well as for chucked components of lathes and grinding machines, especially when these machines are combined with others via a special transport system. Such systems generally involve gantry systems that introduce the workpieces to the workspace from above. Industrial robots are often used when various complementary CNC machines form an FMS, and the robot can feed a number of machines in succession.

The changing of a workpiece that is already clamped, for instance on a pallet, is used when the workpiece lends itself to be held in such a holder, for large lots, or for large processing times. A pallet is a parts carrier that is appropriately designed on the bottom surface to be exactly received and clamped on the work surface of a machining center. The use of tool pallets allows the preparation of the next workpiece or pieces for the ensuing processing. Single-pallet changers have become an option offered by many machine manufacturers and are used increasingly. Depending

on the situation, a pallet changer can be expanded to handle several pallets; this arrangement is called a *pallet*

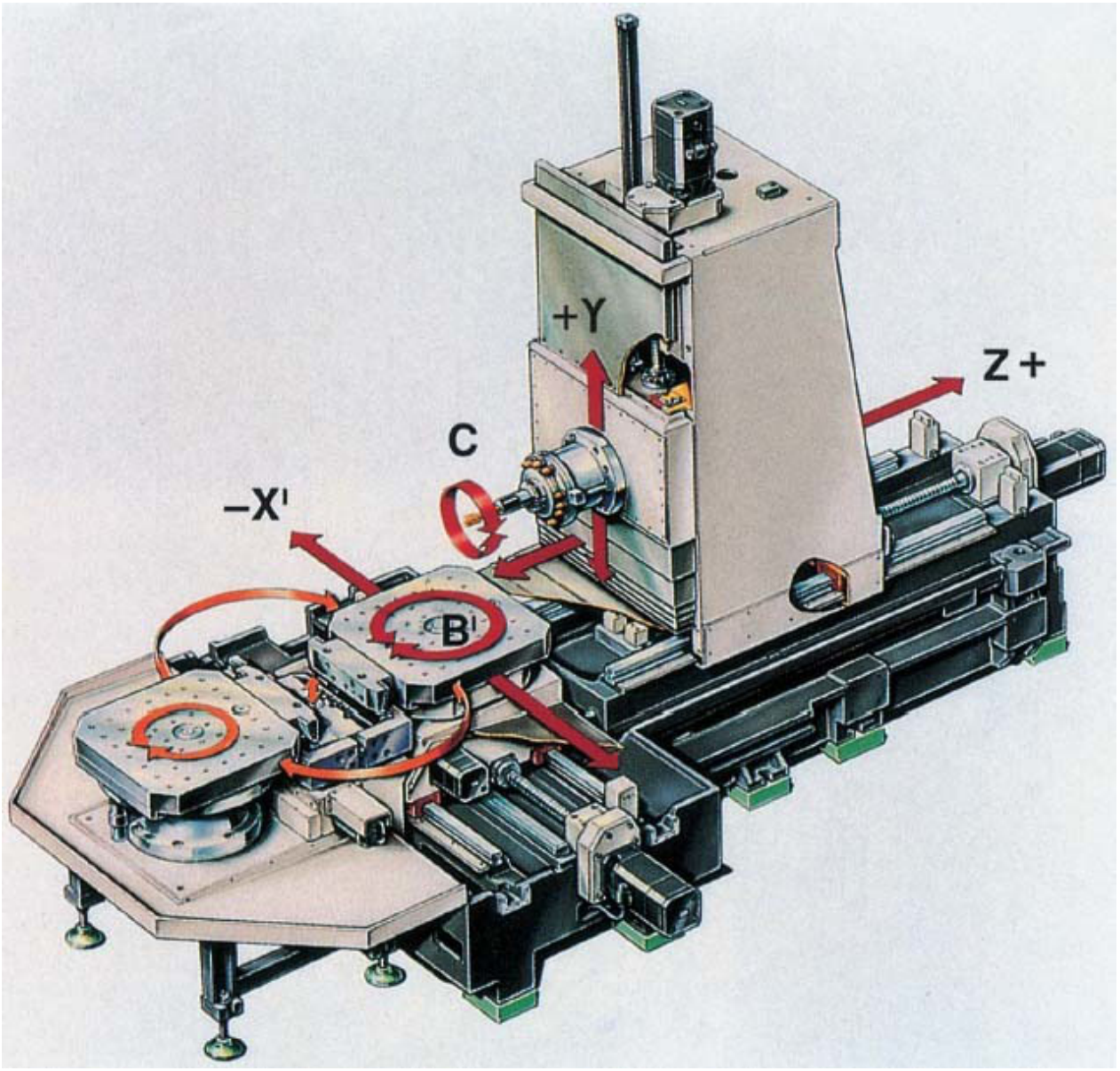

FIGURE 5.6 Machining center with pallet changer. Heckert.)

In installations with flexible manufacturing cells or systems, additional pallet pools or linking systems automatically supply new pallets with workpieces to the machines and transport processed

pallets to the central clamping station. This allows automatic workpiece changing within a given manufacturing time. With individual machines, a pallet pool offers a number of specific advantages relative to an interlinked system. Given a processing volume of four to eight pallets per shift, a pallet pool is a cost-effective alternative that allows unmanned production over several hours. The price advantage is particularly evident when operation is begun with a single machine, and additional machines have to be added later. In such cases, the expense for the interlinked system has to be paid only when the second machine is acquired.

Pallets are monitored and controlled in most cases with a coding system. This system allows the automatic identification of a pallet and the workpieces that are mounted to it and that activates the appropriate NC program in the CNC. When used with flexible manufacturing cells, the coding system must be automated; that is, it must be able to assign workpiece number, machine number, and possible sequence of successive machining operations on several CNC machines. Thus the coding system must be able to answer what machine of the FMS performed which operation. This information should help to troubleshoot in cases of operator error, tolerances not having been held, and bad parts being produced.

The same result can also be achieved with pallets with fixed coding. Then, updating and storing of fabrication data are performed in the CNC system under the function *workpiece*

SPINDLE SPEED CHANGE

Revolutions and orientation of the main spindle also have to be changed repeatedly during machining of the workpiece. In lathe operations with a given cutting speed, every change in diameter requires a different rpm value of the main spindle. In machines in which the workpiece rotates, at least every tool change requires a different speed. Therefore, automatic machine operations necessitate automation of required spindle revolutions.

The spindle speed is a technical function. It is programmed with the S-address directly in 1/min or mm/min, and the orientation of the spindle is determined with the switching functions M03 and M04. M05 causes a spindle stop (see Chapter

In conventional machine tools equipped with a normal three-phase asynchronous motor, the different speeds are produced primarily by means of stepped-gear units and less often via continuously variable, or stepless, transmissions. But positive-fit sliding-gear units are not very suitable for automation. More suitable are clutch transmissions that can be shifted under load. Accordingly, these are often used in lathes. These transmissions are very large and heavy, however, and they cannot be used in driven spindles mounted in machining heads, such as in boring machines or machining centers. In such cases, hydraulic drives are used frequently.

This problem became much easier to solve with the advent of continuously adjustable electric motors. For this reason, these motors gained very rapid acceptance despite their very high purchase prices. However, the adjustment range was still inadequate and a downstream stepped transmission often was necessary to produce the required speed range. If the stepped transmission is designed as a positive-locking gear unit, that is, as a sliding-gear unit or with claw clutch, then the drive has to be stopped to allow shifting; as it was done by means of a subprogram stored in the CNC. This is why the preferred solution was to switch such stepped transmissions using electromagnetic multiple-disk clutches, allowing speed changes while the drive is still running.

Today the adjustment ranges of continuously variable electric motors have advanced to such a degree that downstream stepped transmissions have became largely unnecessary. For more information on this, see Chapter

FEED RATE

Because of the great number of tools in CNC machines, it became necessary to use programmable and continuously variable feed rates. The programming, the steadiness of operation motions, and in many cases automated adaption of feed rates also apply for laser or water-jet cutting machines. At interpolating axes, for instance, for linear interpolation when machining of freeform, circular, and coiled surfaces, all axes must have the same feed rates so that the programmed cutting speed will remain constant (see also Chapter

Feed is a technical function and is programmed with the F-address. With direct feed programming, the feed rate, following the F-address, is given in mm/min (G94) or in mm/revolution (G95). The CNC system converts this value into the nominal rpm value of the appropriate axis drive, passes it on to the drive amplifier, and as needed, automatically adapts it to the machining process. Rapid traverse, for quick motion of the axes without tool engagement, is programmed G00. The G-functions define how the axes approach the programmed point (see Chapter "Preparatory (G) Functions.").

SUMMARY

Programmable switching functions are indispensable for the automatic work process of NC machine tools. They make it possible to almost completely process a workpiece on a machine without human interference. The most important functions for CNC machines are automatic changes of tools, workpieces, and spindle revolutions plus the tool- and workpiece-related feed rates.

Automatic tool changing is necessary for the use of several tools to completely machine a workpiece. Depending on the number and size of the tools used, the appropriate magazines are used. For a lathe, there are typically fewer tools. Therefore, tool turrets are used; the predominant turrets are star, crown, and disk turrets. A turret can also have driven tools for drilling or milling work.

For milling machines and machining centers, the requirement for tools is greater because many tools are dimension or shape bound. The tools are held in magazines and changing devices in various designs. It is distinguished between chain, plate, and disk magazines. For use with 100 or more tools, flat cassette magazines can be employed to achieve higher flexibility.

The simplest tool change is the pickup process, but it has the disadvantage of a longer changing time. Faster systems use gripper systems, mostly with a single gripper or, more economically, double grippers.

Identifying the tools is important for execution of the tool change and thus also for magazines. There is a distinction between tool coding, the location coding, and variable place coding, also called *random tool* Given a sufficiently large tool magazine and automatic workpiece change, the fully automated fabrication of part families without manual intervention is possible. Lathes can mass produce fully automatically using bar stock. Simpler workpieces often can be handled with the pickup method or with loading robots. If the workpiece must be fastened to a dedicated clamping tool, this tool, and possibly several others, can be mounted on a pallet.

On lathes, because of a wide range of diameters and the requirement for constant cutting speed, the spindle speed must always be automatically adapted via a stepless servo drive. In case the workpiece is clamped to the main spindle, each tool change requires a change of speed and feed rate. On modern machines, speed can be set with continuously variable digitally controlled servo motors.

IMPORTANT POINTS TO REMEMBER

■ With switching functions, a distinction is made between M-functions (on/off, left/right, spindle stop) and technical functions: *T* = tool, *S* = spindle, *F* = feed rate, *D* = diameter, *H* = height (length).

■ Decisive criteria for evaluating automatic tool change include:

- Number of tools available
- Limits in terms of dimensions and weight
- Tool-change time, also called *chip-to-chip time*
- Cost of additional holders, cassettes, and chucks

■ On lathes, mostly tool changers in the form of a star, crown, and disk turrets are used.

■ On milling and manufacturing centers, the possible tool magazines include:

- Chain magazines
- Plate and disk magazines

- Shelf and cassette magazines

- Pickup magazines, for instance, for large tools

■ Identification of the tools in the magazine is critical. It affects the pickup time and tool change, as well as the effort to reload the magazine for a new job. There is a distinction between:

- Location coding, and

- Variable coding, meaning programming of tool number but searching for a location number on the shortest path.

■ Various systems are available for automatic workpiece changes:

- Use of bar stock, mostly for lathes

- Pickup method

- Changing pallets, with individual or multiple clamping arrangements

■ Pallet depositories are used for changing workpieces that are clamped on a pallet in special clamping devices.

■ It is always required for lathes to program the speed (S) of the main spindle. On milling machines and processing centers, each tool change needs a speed change.

■ Switching functions are programmed with an M-address and typically a two-digit number according to DIN 66026/ISO 6938.

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DEFINITION

CNC refers to numerical control systems containing one or more microprocessors for the execution of control functions. The external characteristics of a CNC system are a display and a keyboard The operating system of a CNC system, also called the *CNC operating* comprises all the necessary functions, such as interpolation, position feedback control, velocity control, displays and editors, data storage, and data processing. Also required is an interface program for the machine being controlled. This program is created by the machine manufacturer and is integrated in the programmable logic controller (PLC). All the machine-related links and interlocks for special functions are defined there, such as those for tool change, workpiece change, and axis limitations.

The workpiece-specific control of the machine motions during machining is performed by the parts programs. These are created by the machine user and are not a part of the CNC operating software.

BASIC FUNCTIONS OF CNC

The typical task of NC systems, that is, to precisely control the relative motions of the tool and workpiece in a machine tool, is being augmented by more and more tasks and functions. Whereas some of these functions run in the for example, to monitor safety, others demand attention and occasional intervention on the part of the operator. For this reason, it is important for the CNC system to be clearly organized and easy to operate—all the more so because CNC has turned control systems that could understand simple numerical input into complex computing systems with completely new functions. These will be introduced and briefly explained.

Today, a basic CNC system includes the following:

■ A color graphics monitor with an 8- to 21-inch diagonal for display, programming simulation, operation, and diagnostic functions

■ Operator prompting with interactive dialogs and the ability to switch between at least two languages

■ A program memory for a number of parts programs, compensation values, tool data, zero-point tables, and cycles

■ A bus-coupled or integrated PLC with high processing speed for controlling the switching functions

■ Programmable software limit switches for the NC axes, thus replacing mechanical limit switches and their associated wiring

■ *Manufacturing data acquisition production data acquisition* and an automatic logbook for documentation of operating errors, error messages, function sequences, warnings, and manual interventions

FIGURE 6.1 Sinumeric 840D si, 19-inch CNC display and operator input panel; 3D simulation on display. Siemens.)

Added to these are some of the functions that make the machines more precise, reliable, and user friendly, such as:

■ Temperature error compensation to counter machine inaccuracies resulting from thermal effects

■ Random tool coding to accelerate the search and changing operations

■ Tool failure and tool life monitoring in automatic operation

■ Automatic storage of tool data in designated compensation-value memory

■ Simultaneous control of synchronous main axes and asynchronous auxiliary axes with no wait times

■ Input of machine parameters via keyboard instead of tedious adjusting during commissioning

The CNC system performs a large number of additional functions and tasks in automatic production. Today, these functions are considered routine.

Some of these special functions will be enumerated and explained below. Control systems from different manufacturers, however, may have different names for the same functions or may have different operational sequences or performance ranges.

Asynchronous Axes

These are auxiliary or secondary axes that are not interpolated with the main axes and move independently, such as tool or workpiece handling devices in a machine.

Automatic Return to the Contour

After a tool failure or emergency stop during machining, the tool has to reenter the interrupted program before the point where the problem occurred, thus resuming operation without leaving any marks on the workpiece. The new tool compensation values also have to be taken into account here

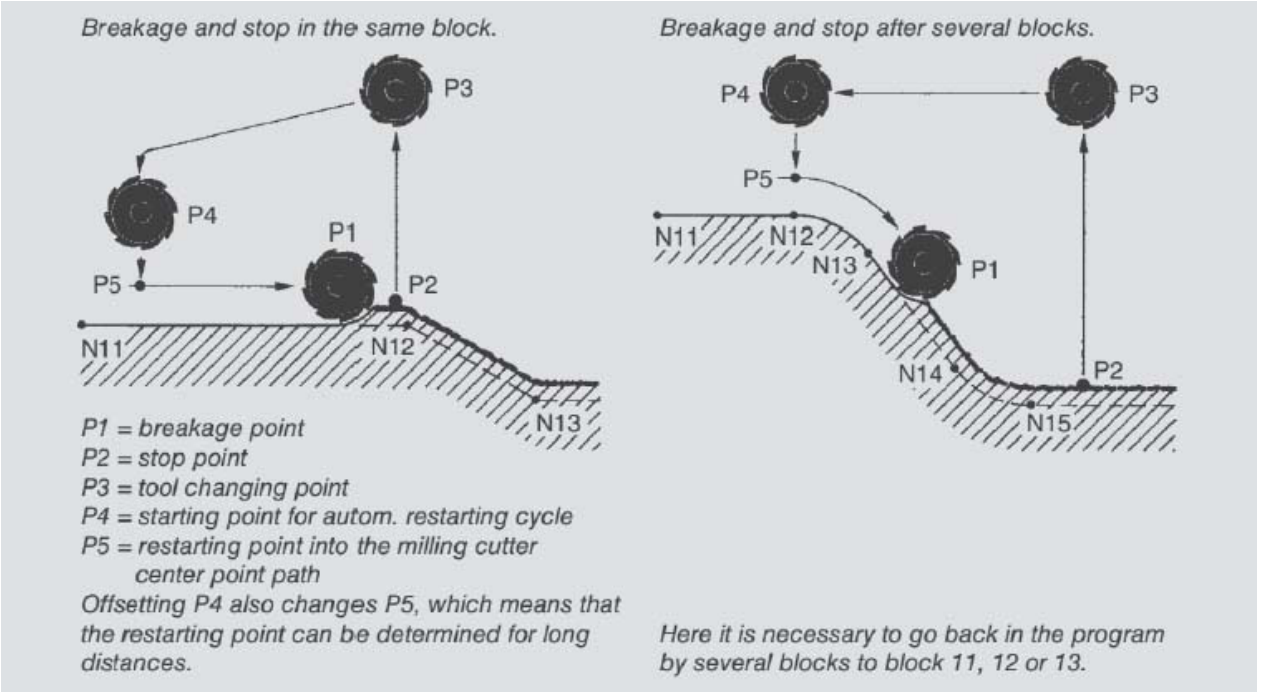

FIGURE 6.2 Resuming contour cutting: automatic resumption of cycle after tool failure.

Cutting the Tool Free

At the end of a machining operation, the feed stops for a set time while the spindle continues to spin, only after which the tool is retracted.

Block Delete, Skip Block

When a program is processed, blocks that have a slash in front of the block number, for example, /N147 X... Y..., can be executed or skipped depending on the switch setting. This can be used to activate programmed probing cycles or a machine stop. If this function is switched off, the marked blocks are skipped, and the usual processing of the workpieces continues.

Block Number Search

This is a time-saving option after a program interruption. It lets the program quickly find a selected block without performing any machine motion. On reentry into the program, the correct tool is available together with all compensation values and the correct feed rate and spindle speed.

Compensation Values

These are current tool data that have been entered and saved for each tool used in the machine (e.g., diameter, length, radius, and time of service). These data are taken into account during program execution. Compensation values also include error compensation, zero-point offset, clamping tolerance, and wear value; they are kept available for use in dedicated places in memory.

Data Interfaces

These connect CNC systems to higher-level computers to allow data exchange (direct numerical control [DNC]) or execution of remote-control functions. Such interfaces are also required for automatic workpiece and tool identification

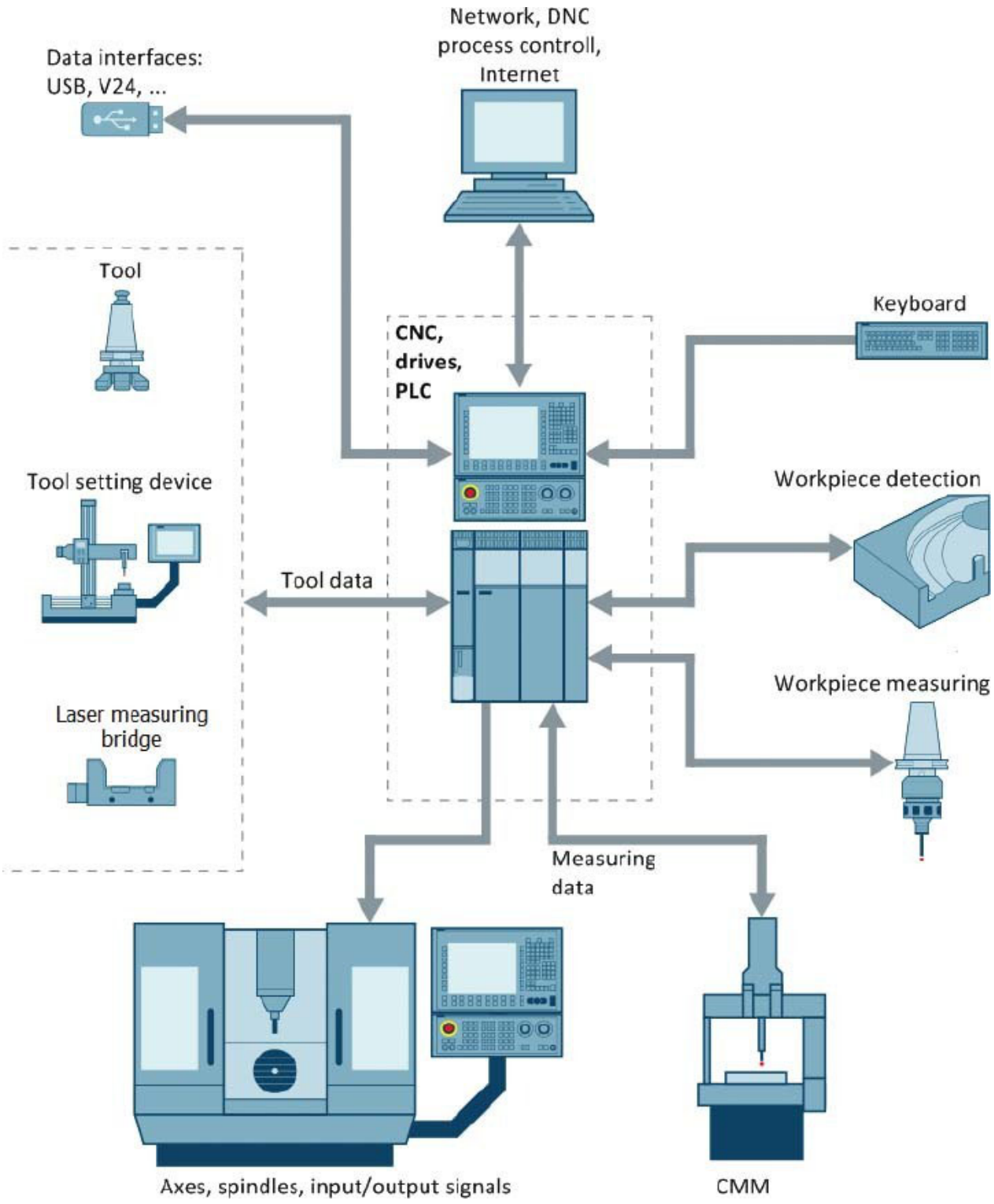

FIGURE 6.3 Data interfaces of a CNC/PLC for the transmission of various production-related data.

Deactivating Axes

The selective stopping of some or all CNC axes allows quick testing of a CNC program for programming errors without moving the axes in question. To save time, it is also possible to deactivate tool changing, pallet changing, coolant, and the main spindle.

Diagnostic Software

This refers to functions that can be activated permanently or via a program to monitor machine and control performance for the purpose of automatic documentation of errors and their causes. The CNC system facilitates this by depicting the measured values on the screen in the form of curves or diagrams or in digital format. All data also can be put out via a data interface.

In addition to error diagnosis, CNC manufacturers also offer special diagnostic software that supports the user in optimizing part programs. Thus it is possible to reduce the processing time, or *cycle* significantly. *Example:* If the PLC detects a broken tool, tool-changing motions can be performed using an asynchronous subprogram. The damaged tool is exchanged for a new one, and machining is continued from the last position.

Driven or Live Tools

These are terms for tools on a lathe such as drills and milling tools that perform operations on the standing part; therefore, they need to be driven. For this, the main spindle must be path controlled.

Energy Efficiency

Some current CNC systems have programs for analyzing energy consumption. For example, the switching times of the supply modules can be used to determine and record their energy

consumption. This can help the machine manufacturer in designing supply modules so that they are dimensioned properly for a specific application. The user has the opportunity to optimize work sequences and part programs to save energy. This especially pays off in largescale production.

High-Level Language Elements (Queries, Loops, Variables)

Today's CNC systems feature languages similar to BASIC or C for programming and calculating complex sequences. It is thus possible to implement queries such as IF . . THEN . . ELSE . . END-IF and loops such as FOR . . TO ... NEXT, WHILE . . DO . . END. In some cases, it is even possible to write access requests to the file system in this high-level language, for example, to save a log file.

Note that these high-level language elements are manufacturer specific and are not standardized. It is therefore not allowed to exchange programs containing such elements between CNC systems from different manufacturers.

Jolt Suppression

Setting of the acceleration and deceleration behavior of the CNC axes maintains the integrity of the hardware by preventing jolts. It is important to set the same value for all axes in order to prevent path deviations.

Macros

Macros can be used to summarize and redefine elements of the programming language. For example, hard to understand G-codes can be replaced with easy-to-read text, or existing language elements can be overlaid. In this manner, it is possible, for example, to implement a whole series of switching operations by programming a single G-code.

Manual Input

This refers to activities from entering and correcting a CNC program manually via the CNC system's keyboard to *shop-floor programming* using the graphical displays and interactive dialogs.

Mirror Imaging, Rotating, Shifting

The programmed path data can be mirrored on a specified axis, rotated, and/or shifted by a defined distance. This makes it easier to program parts with repeating geometries.

Offset

This refers to electronic compensation for clamping tolerances for a workpiece or tool in order to eliminate the need for precise mechanical alignment or adjustment.

Polar Coordinates

These are set by a 2D or 3D coordinate system for depicting angle-dependent functions or angle-related drawings. For processing on machines with linear axes, the programmed polar coordinates have to be converted into Cartesian coordinate dimensions, either during programming or in the CNC system.

Position Setup

Using a dial indicator or other aid, the operator aligns the spindle center point with a fixed point on the workpiece or the fixture and references the axis position to the values indicated in the drawing or the CNC program. Today, a switching indicator is standard.

Program Test

This refers to sped-up execution of a CNC program with increased feed rates or in fast-forward motion to check for major programming errors, possible collisions, or other errors. The material used is not metal but rather a dedicated plastic material that machines easily.

Reset

Pushing the Reset button on the CNC machine interrupts execution of the current program. The CNC system remains synchronous with the machine. It is in the starting position for a new program run from the beginning. Possible NC programming errors will be deleted.

Simulation

This is the graphical depiction of the machining operation, that is, travel paths of the tools and the final workpiece, taking into account the tool compensation data and the geometry of the unfinished part. Depending on the type of control system, it may be possible to simulate the entire work sequence and display it as a three-layer view or as a solid model. By calculating the complete program, it is possible to detect error sources and estimate the machining time in advance. The simulation is executed directly on the machine with the CNC system.

Subprograms, Cycles

These include permanently stored programs such as hole patterns and drilling, tapping, and milling cycles, including the necessary data (parameters). These programs, also called *parametric* can be called up and executed as often as desired.

Synchronous Axes

These are all CNC axes of a machine whose movements are interpolated and coordinated simultaneously. As a rule, these include all the main axes of a machine. The opposite are asynchronous axes.

A detailed description of any of these functions can be found in the documentation of the specific CNC system in question.

SPECIAL FUNCTIONS OF CNC SYSTEMS

As a general rule, the performance and expandability of a CNC system are defined by the manufacturer during the initial concept and development of the system. In addition, new CNC concepts have an open-software interface for the CNC system software. This gives the machine manufacturer and user the capability to integrate their own special functions or know-how at a later time. For this purpose, the CNC system includes special programming software that can be used to integrate custom solutions. With this software, it is even possible to access the control system's graphics in order to visualize user help systems, selection menus, or dynamic simulations. It is, for instance, possible to reconfigure a CNC system for machine tools as a master CNC system for a pallet-transport system. What is more, this makes it possible for the machine manufacturer to test newly developed machines at an early stage without having to inform the CNC system manufacturer.

What follows is a selection of some custom solutions that can be implemented with modern CNC systems.

Automatic System Diagnosis

This refers to a customized software that switches the CNC monitor to oscilloscope operation.

This can be used as a convenient method for testing NC programs and finding any errors that may stem from programming or during processing.

System diagnosis answers some of the following questions:

- Where in the program did the error appear for the first time?

- What effects does the error have on the program?

- What are the effects on other variables or program sections?

- How important is the error for the program?

Automatic Tool Length Measurement

After a new tool is inserted, a measuring cycle is executed that moves the tool to a measuring probe to determine and save the absolute tool length

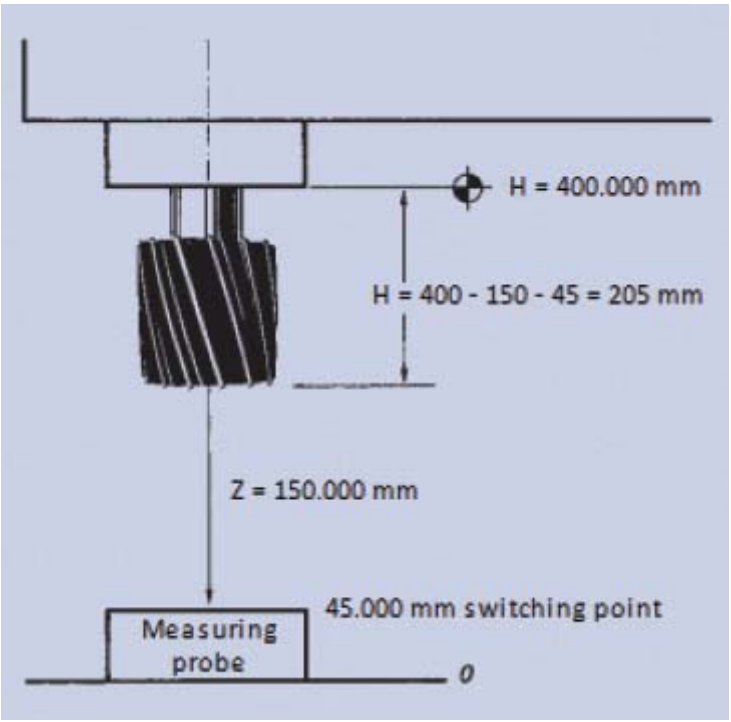

FIGURE 6.4 Automatic tool length measurement with an encapsulated switching measuring probe.

Asynchronous Subprograms

It is possible to define a (small) subprogram in the CNC system to interrupt the normal execution and perform custom functions. This subprogram can be triggered via the PLC or another channel. *Example 1:* Two work units of a machine have an overlapping workspace. If one unit has to move into the workspace of the other unit, then it can use an asynchronous subprogram to interrupt its work and move out of the way. Once the first unit has exited its workspace, it then can continue from its last position. *Example 2:* If the PLC detects a broken tool, tool-changing motions can be performed using an asynchronous subprogram. The damaged tool is exchanged for a new one, and machining is resumed from the last position.

Axis Swapping

Axis change makes it possible to convert CNC programs created for milling machines with a vertical spindle for use on machines with a horizontal spindle and an angle head mounted in front by swapping the and

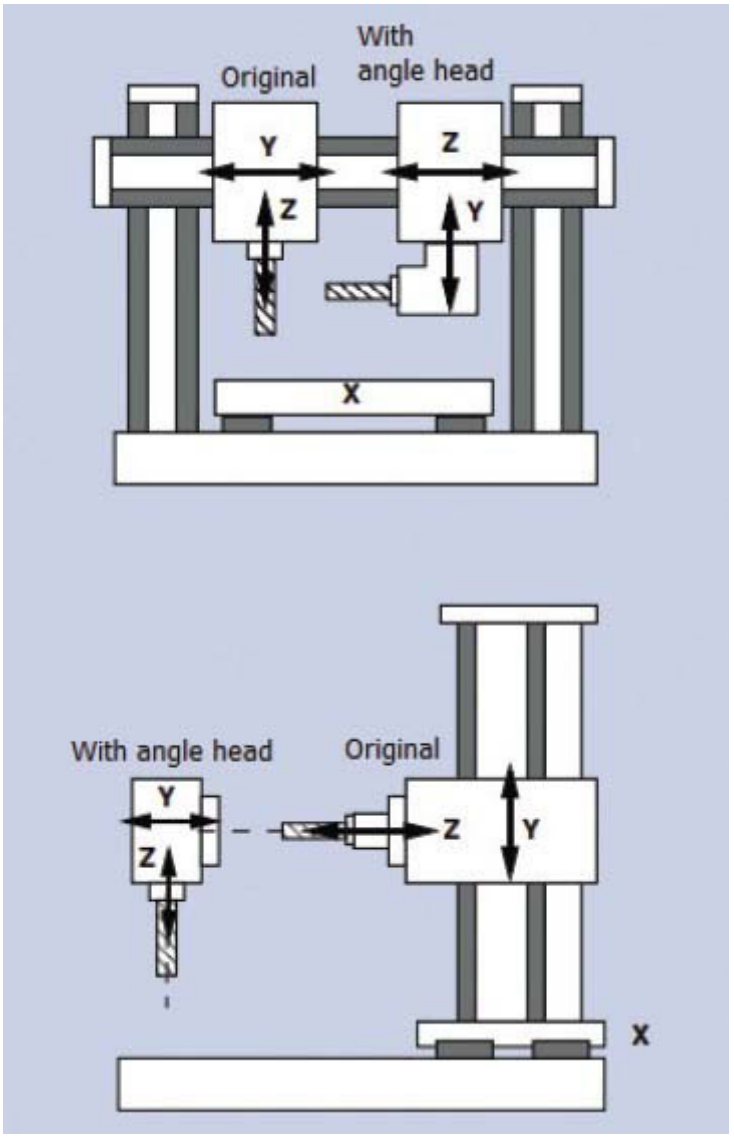

FIGURE 6.5 Axis swap. With an attached angle head, can be swapped to use NC programs that were created for a vertical

Block Cycle Time

In order to achieve high surface quality and contour accuracy, the CNC system has to execute the CNC program very quickly and without feed rate fluctuations. If the execution time of one block is shorter than the preparation time for the following block, then the feed rate will be reduced. For this reason, the CNC system must have a high computing speed and a constant supply of

prepared blocks. A dynamic buffer that is constantly refilled will keep an adequate number of prepared blocks at hand, thus preventing *stuttering axes*

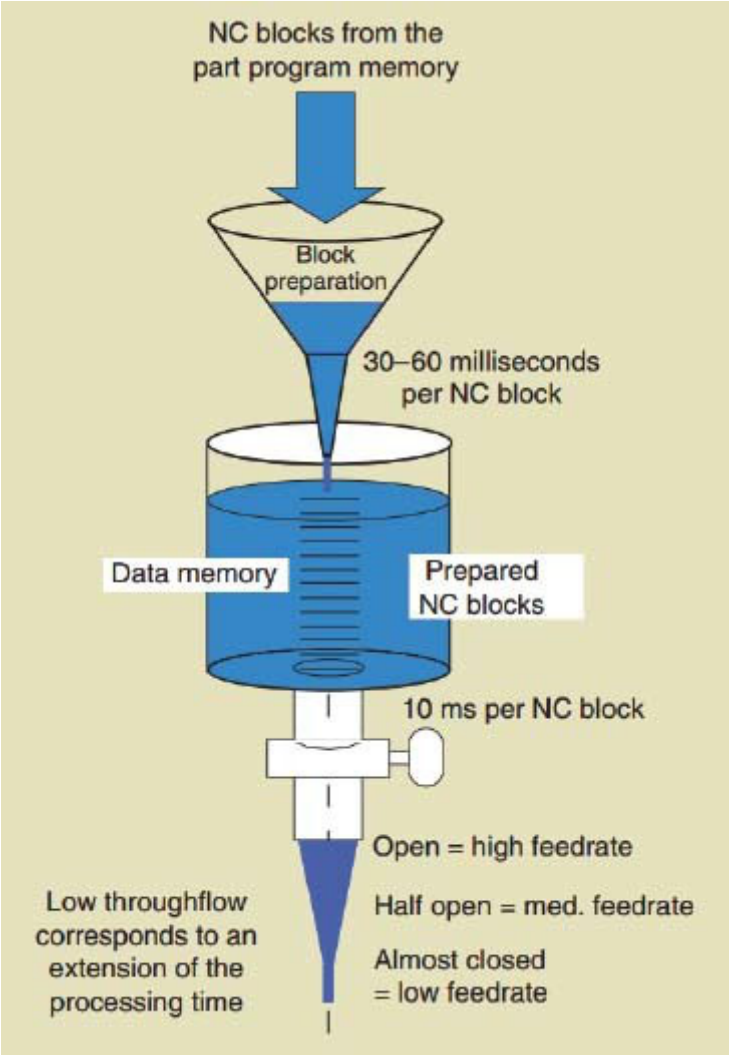

FIGURE 6.6 Dynamic data buffer with short transmission times to ensure short block cycle times.

If this supply is still not adequate, then the feed rate has to be reduced until the axis moves continuously. The interrelationships among the block cycle time, polygon length, and

feed rate are shown in Figure *Example:* For a polygon length of 0.1 mm and a block cycle time t = 2 ms, the maximum feed rate = 4 m/min.

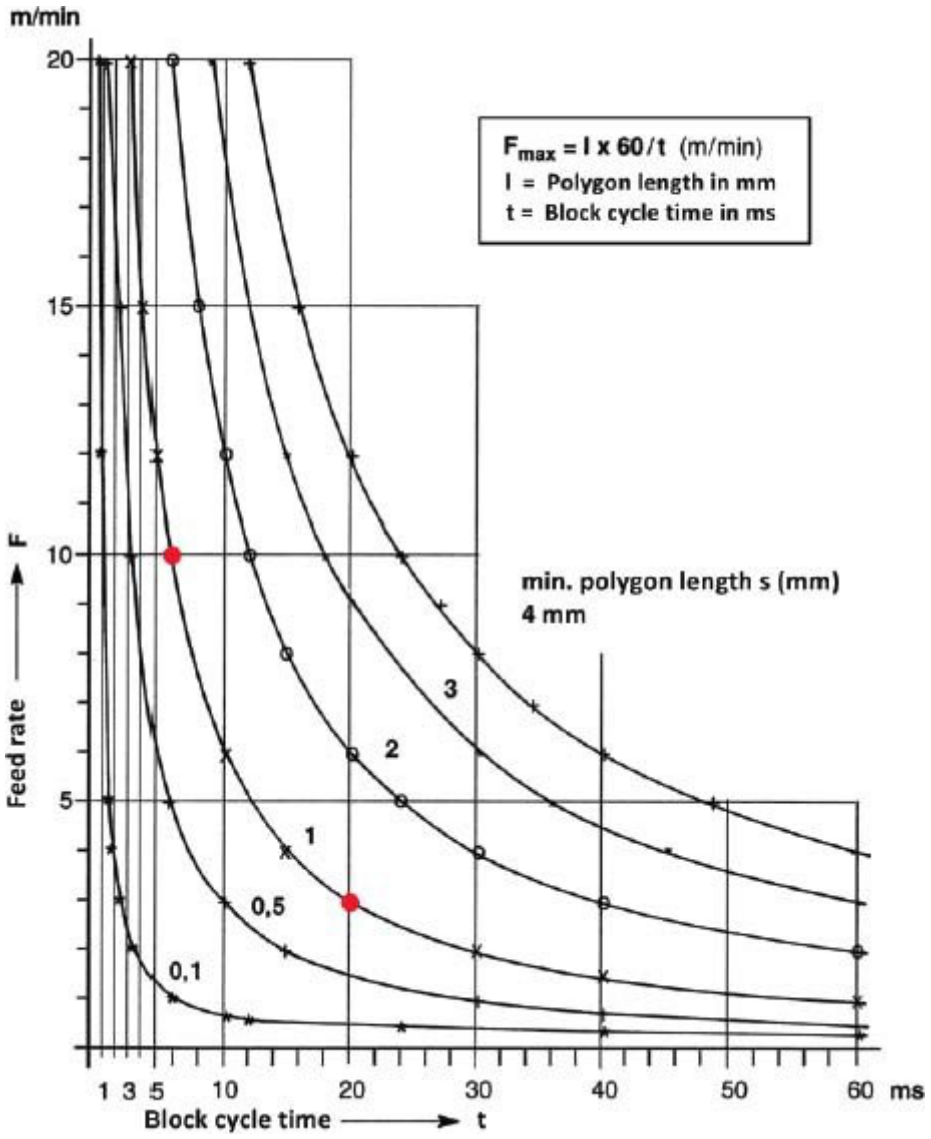

FIGURE 6.7 Interrelationship of maximum achievable feed rate polygon length S of a graph, and block cycle time t of the CNC system.

DNC Interface

The CNC system must have suitable data interfaces for automatic reading in and out of part programs, tool compensation data, PLC data, status and error messages, and so on (see Figure High-performance DNC interfaces also allow computerized remote control of the machine, for example, when moving to the zero point, deleting individual programs, sorting tools in the magazine, and so on (see Chapter

Work Area Limit

The free work area of a CNC machine can be limited temporarily by programming the upper and lower limit values for each axis. When instructing an axis to move to a position that lies outside these *software* it generates an error message, and the machine stops immediately. *Example:* N1 G25 X100 Y255 Z70 $ = lower-limit values for the and *Z* axes; N2 G26 X440 Y321 Z129 $ = upper-limit values for the and *Z* axes.

DYNAMIC COLLISION MONITORING

Modern machine tools are dynamic, precise, and productive. In order to maintain precision and productivity for a long time, collisions in the work area must be absolutely avoided. Because CNC machines are completely enclosed due to health and safety regulations, and because of the high feed rates and component motions, a manual intervention is impossible in the case of a malfunction. Thus, collision checking is of extreme importance during setup. CNC systems offer various safety functions in order to do so.

Simulation

Today, most CNC systems have high-quality graphics with scaled representation of machine, tool, and workpiece Before an actual run, it is possible to display a virtual run of the entire program with tools and zero-point offsets on the monitor. The display is usually dynamic, the workpiece is shown in three dimensions, and feed-in is depicted in multiple colors. Similar to CAD/CAM software programs, zooming in on sensitive areas is possible, and sections through the workpiece allow the examination of hidden contours and holes. Visualizing the program reveals possible collisions and allows for the preparation of remedies. If the program simulation does not take into account the actual tool lengths but only depicts the tool engagement point, the danger of a collision is still real.

Simulation alone does not relieve the operator of a CNC machine tool from the responsibility of avoiding damage to machine, tool, and workpiece resulting from collisions during an automatic machine run.

There are more setup functions that help to avoid collisions besides measuring of the tool and setting the tool reference point.

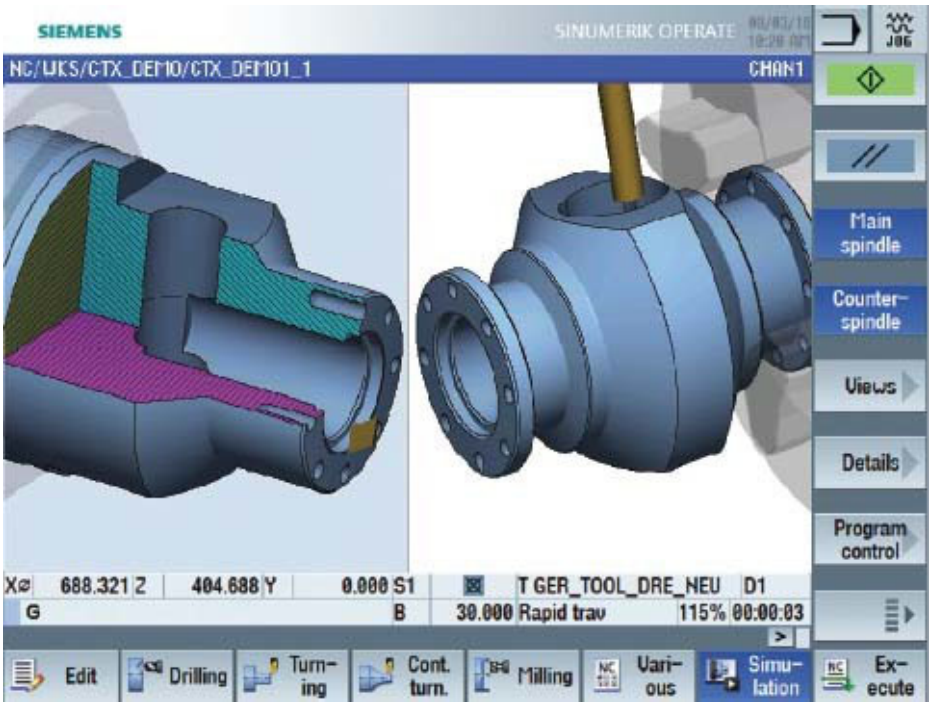

FIGURE 6.8 3D simulation of a turning operation on a turning-milling machine helps to detect collisions during program creation. With the aid of the sectional view of the machining on the main spindle, it is also possible to detect contour violations of the internal features. Milling operation on the counter spindle. Siemens.)

Setup Functions

An NC program is typically not started without testing, even if the simulation of the CNC system, and possibly also the CAD/CAM system, has indicated a problem-free run. Therefore, CNC systems allow a test run without tool engagement. Before machining a part, the program can be tested directly in the machine to detect possible programming errors. For this, a test run feed rate must be activated in the CNC system. The process speeds that have been programmed

in relation to G1, G2, G3, etc. are substituted with a determined test run feed rate. This value also applies to the programmed feed rate and should be quite high, possibly as high as the rapid traverse speed. The workpiece or blank should either not be clamped, or an appropriate zero-point offset in positive feed-in direction should be activated at the beginning of the program. When executing a *test run feed* there must be no tool engagement because the high feed rate values would exceed safe cutting speeds of the tools, and serious damage to tool or machine could result. A dry run can only test the trouble-free execution of the NC program. It cannot test whether an incorrect feed-in may result in a collision or not.

Another aid to detect possible collisions is the use of a dry run and the program test via the simulation; that is, the machine does not perform the programmed axis motions; it only executes the programmed auxiliary functions, dwell times, and tool changes. The complete machining of the workpiece takes place virtually on the display of the CNC system with depiction of the tool geometry. The operator thus checks for the correct run of the program. Another test to check the integrity of an NC program is the single block operation. Before starting the NC program, it is advisable to set the select "Automatic" and "Single Block" and carefully monitor the changes from one block to the next. The operation takes place one cut at a time, and the operator can interrupt the sequence at any time. When using cycles, macros, or subprograms, it must be considered that these are read by the CNC system as one block, and when pressing Start, several consecutive machine motions will be triggered.

Protected Areas

Protective areas can be used to protect different elements of the machine, the equipment, and the workpiece from wrong motions. Tool-related protective areas relate to the tool and the tool holder. Workpiece-related protective areas relate to machine parts that belong to the workpiece, for instance, workpiece, clamping surface, clamping claws, chuck, and tail stock

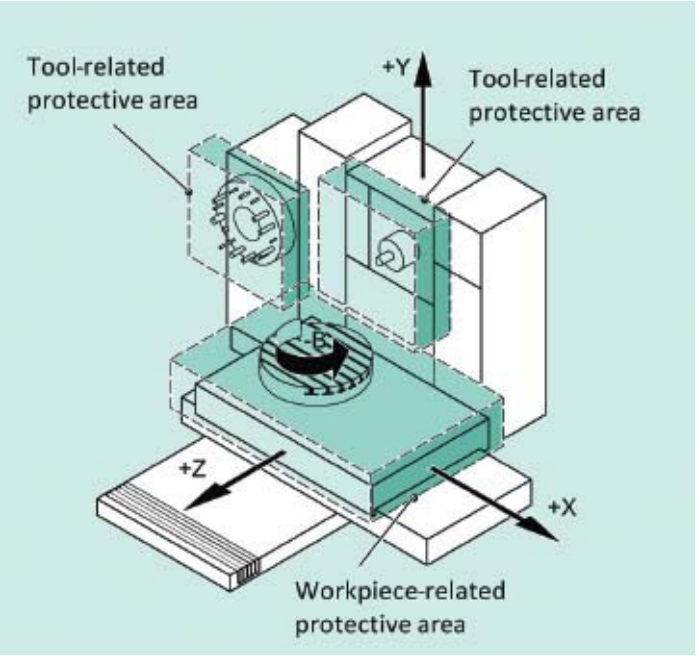

FIGURE 6.9 By defining protective areas, the operator can prevent collisions of machine parts.

Depending on the type and particularity of the CNC system, these protective areas can:

- Prevent the motion of the axis into a protective area
- Reduce the feed rate
- Display a collision warning

Protective areas also can be:

■ Related to the tool and tool holder

■ Related to the part, such as workpiece, clamping surface, clamping claws, chuck, or tail stock depending on the type and particularity of the CNC system

Often the operator can define such protective areas in the machine parameters via the input of coordinate points, thus preventing collisions of, for instance, the tool changer or the parts table. Yet these protective areas do not operate dynamically; that is, multiaxis kinematics can only provide limited protection from collisions.

Dynamic Collision Monitoring Online in the CNC System

In many situations, collisions can only be prevented in a limited fashion with the measures just described. Thus dynamic collision monitoring in the CNC becomes necessary.

The actual clamping position and location of the workpiece can be clearly defined only by setting a reference point and measuring the workpiece relative to this point. Sometimes these tasks can be taken over fully automatically by cycles, macros, and subprograms during execution of the NC program. In an unfavorable situation, the operator realizes a collision or the tripping of a software limit switch during the operation, particularly if the machine's work area is crowded. In these instances, CNC systems with dynamic monitoring provide the best possible collision protection.

In the global program settings, transformations can be defined, such as offsets, rotations, and axis swapping that can act additively and be superimposed on these transformations as they are defined in the NC program. The operator can define or cancel these transformations at any given time during the run. Consequently, they are only recognized by the CNC system and can be recognized by systems with dynamic collision monitoring.

Tool correction values sometimes deviate from the previously simulated values because only at the time of loading the tool changer are the actual values entered into the tool table of the CNC system; they become active when the tool is called up. Additionally, the operator can add more correction values, called *delta* It might also be that table probing system or laser measurements determine the actual correction values for length and radius during operation and write them into the correction tables of the CNC system. Just the same, these values are privy exclusively to the CNC system, so a possible collision can only be detected and prevented as the program is executed with dynamic collision monitoring.

A fully automated tool change can take place at the end of a tool's life anywhere in the program. In this case, the CNC system exchanges the tool with a comparable or twin tool, defined by the operator. Particularly with five-axis milling machines, a tool change necessitates complex machine movements that are controlled by macros and cannot be simulated. Systems with dynamic collision monitoring also check these processes.

Machine manufacturers and operators have many opportunities to individually adapt the behavior of the CNC system for very diverse

functions via the machine parameters. With these, for instance, different positions can be set within or at the end of cycles or the effects of coordinate transformations or pivoting behavior and so forth can be anticipated. These settings cannot be clearly simulated externally; also, they can be temporarily changed during the run of the NC program. In these cases, collisions can only be prevented with dynamic monitoring of the CNC system.

Operating Mode of Dynamic Collision Monitoring

Dynamic collision monitoring images actual machine objects in the CNC software. Based on these data, the DMC system monitors the machining processes for possible collisions in order to prevent damage to machine, tool, and/or workpiece. To use DCM, the machine manufacturer must define all collision-prone areas, such as spindle, table, machine parts, covers, probes, and so on during commissioning of the machine. This is done with the help of geometric objects such as planes, cuboids, and cylinders.

Modern CNC machines, with the help of special design software, can be configured via the machine kinematic from a PC or directly from the CNC system. The software simulates the machine motions within the work area and indicates possible collisions between machine components. These components can then be integrated into the CNC system via the concurrently running dynamic collision monitoring. The visualization of the machine components is also available on the CNC system. As collision potential between machine components is detected, dynamic collision monitoring stops all axes and highlights the affected machine components. Additionally, machine components with a recognized collision potential are named in a status window.

Machine components that are recognized by dynamic collision monitoring can be thought of as enveloped with a protective sleeve. The CNC system considers the spatial information combined with the actual tool data when calculating the axis motions and will thus definitely prevent possible collisions. While the machine program is executed, the last operation before an imminent collision with the defined protective sleeve will not; the machine will stop. One more level of process safety can be attained by factoring in the possible collisions during the setup instead of checking for collision potential before processing parts. Systems for dynamic collision monitoring, integrated into the CNC system, make these functions available in real time.

During setup, the machine operator moves the machine manually via the axis direction keys or the electronic hand wheel. In this manual mode, a collision cannot always be foreseen by the machine manufacturer. Systems for dynamic collision monitoring are therefore active during manual motions of the axes and prevent collisions by stopping the motions in time and putting out a warning 6.10 through

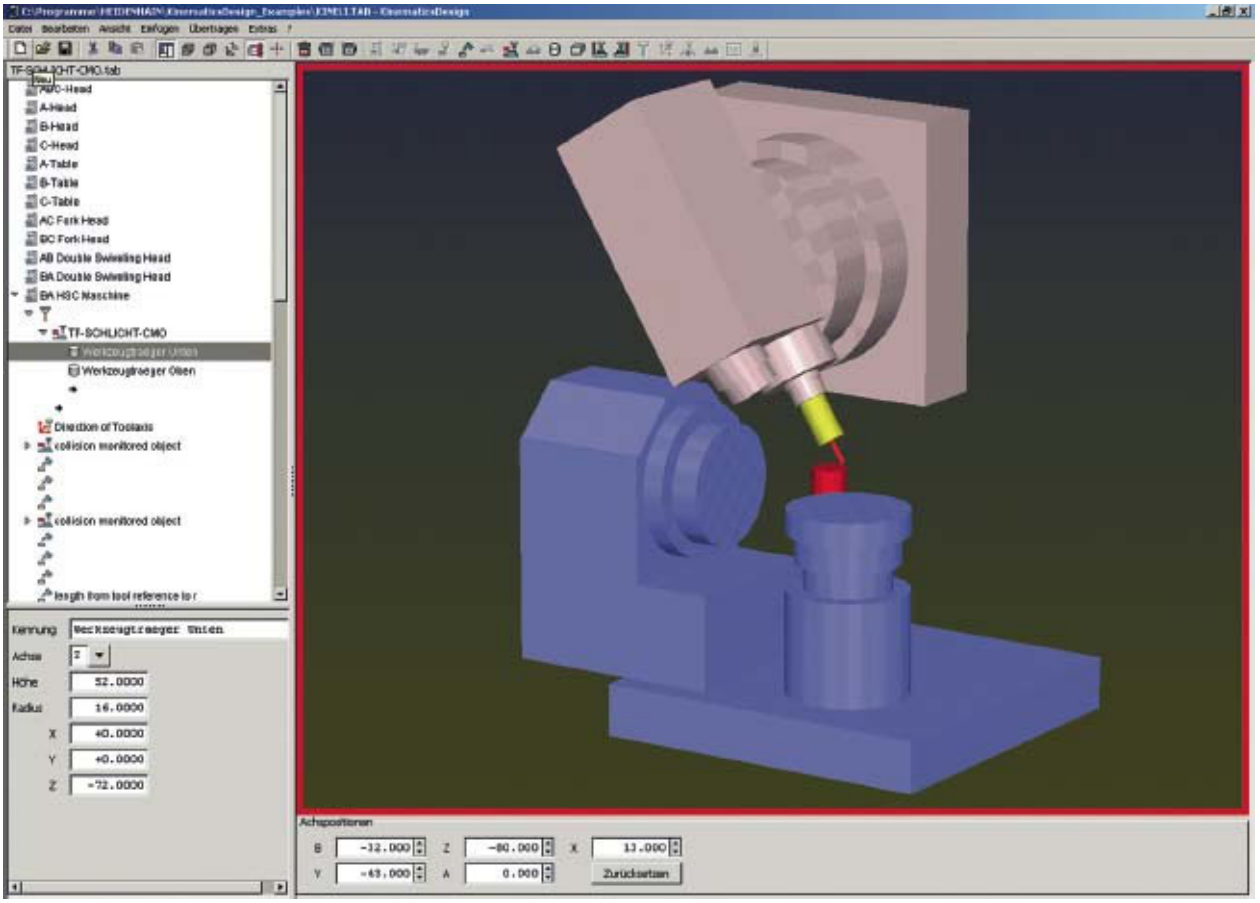

FIGURE 6.10 PC software tools such as KinematicsDesign make configuration of the DCM system particularly easy and comfortable. Heidenhain.)

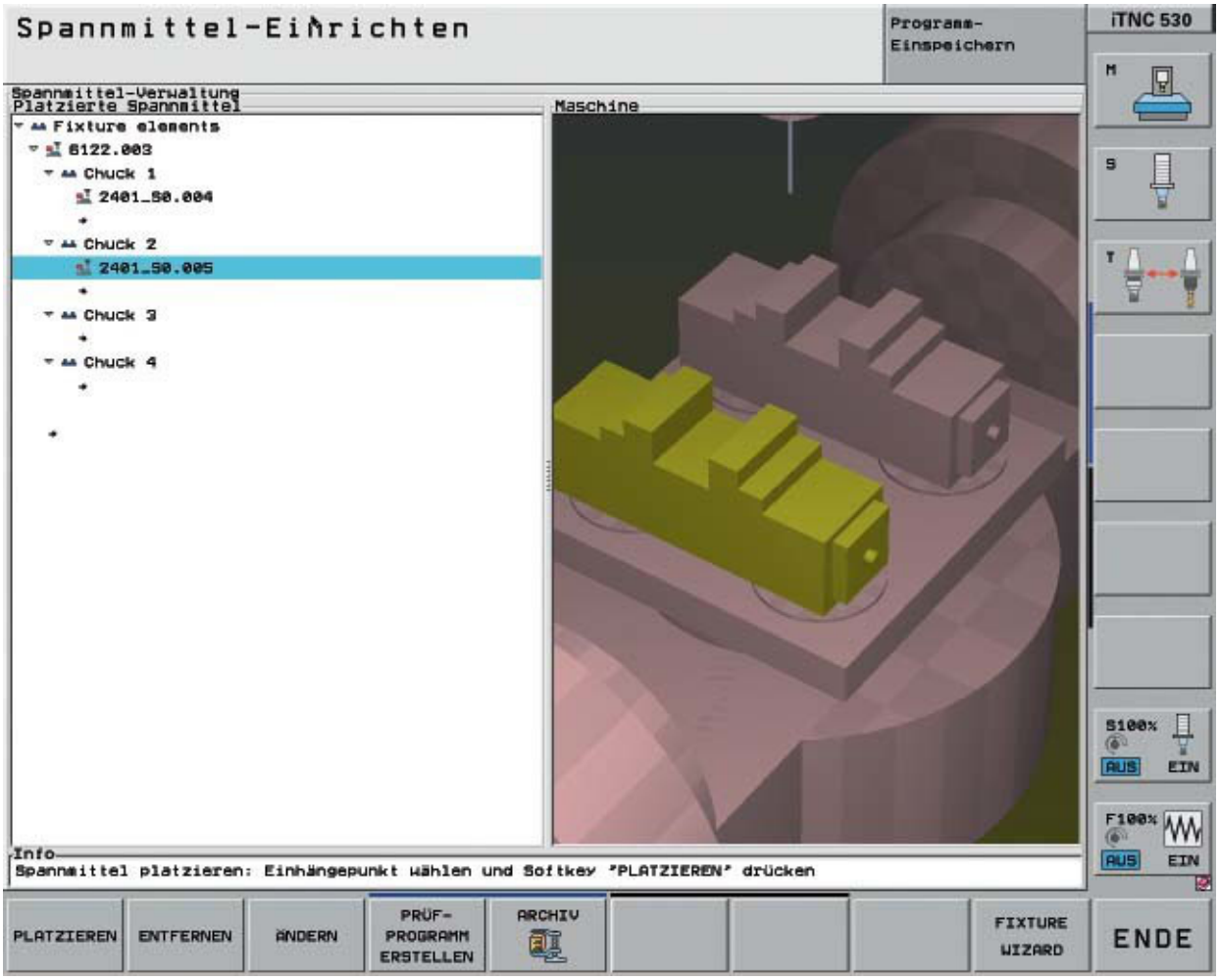

FIGURE 6.11 Configuration of the machine also includes an intelligent clamping tool administration, such as the DCM system. It allows registering clamping tools, here two vices, for collision monitoring. Heidenhain.)

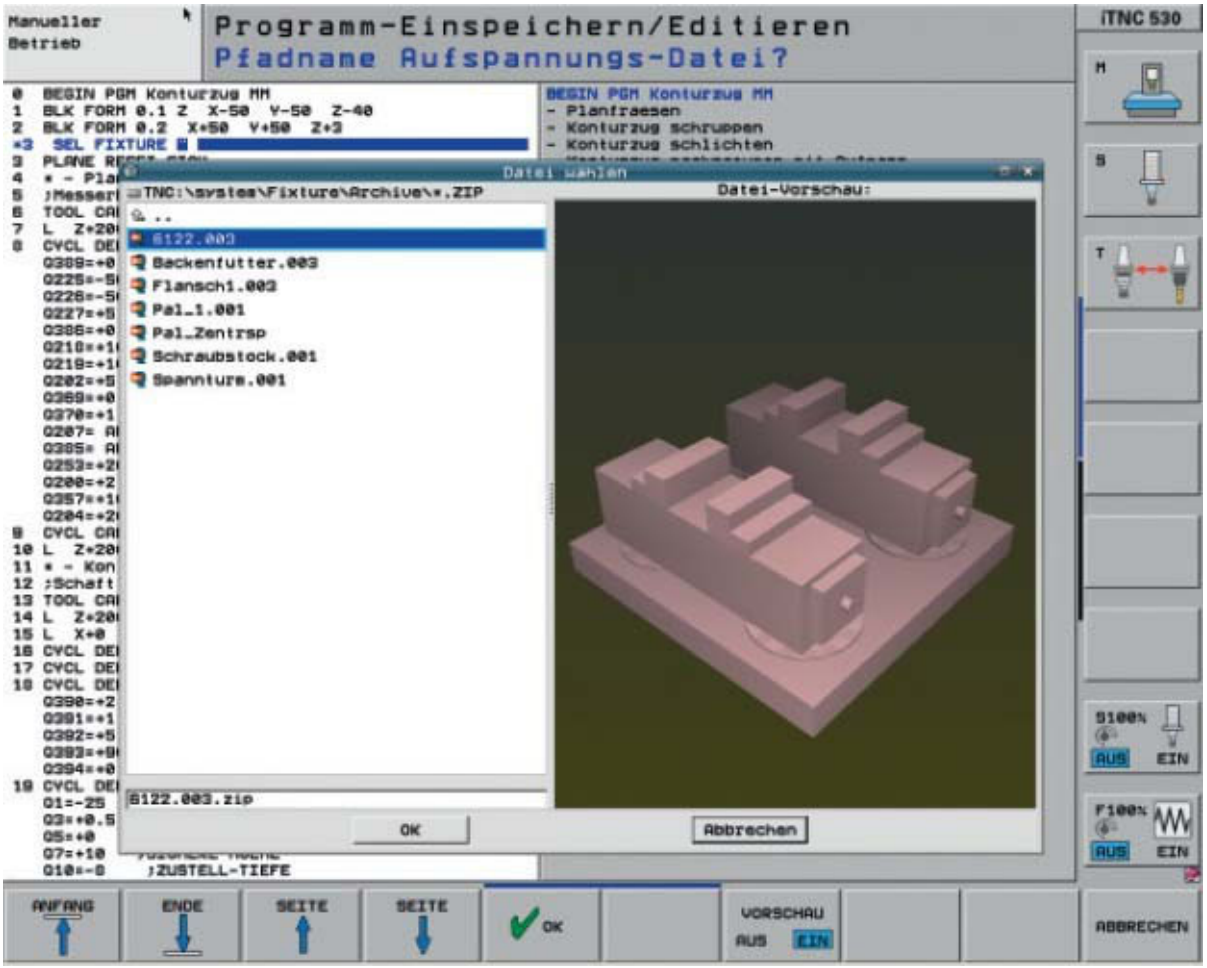

FIGURE 6.12 An archived clamping system can be called up in the NC program and enabled for collision monitoring. Heidenhain.)

FIGURE 6.13 The specific kinematics of the machine tool are displayed in real time on the CNC system. In the event of a possible collision, the DCM system will stop the machine and indicate on the monitor the problematic area. Heidenhain.)

FIGURE 6.14 DCM on a CNC machine also prevents collisions during setup while considering the actual machine-specific situation. Heidenhain.)

DCM effectively prevents imminent collisions by considering the actual situation during the operation of a machine tool, such as position and state of the spindle, table, machine elements, covers, probes, chucks, and tools. Additionally, DCM, when activated in the CNC system, provides important information to improve machining strategies in terms of general avoidance of collisions.

Automated Work Area Monitoring

In the case of automatic work area monitoring, a camera installed directly next to the spindle takes reference photographs of the first good parts of a run, such as a picture of a correctly clamped part before and after machining. Pictures can also be saved as reference photographs of known defects and other errors, for instance, typical clamping errors or a forgotten tool

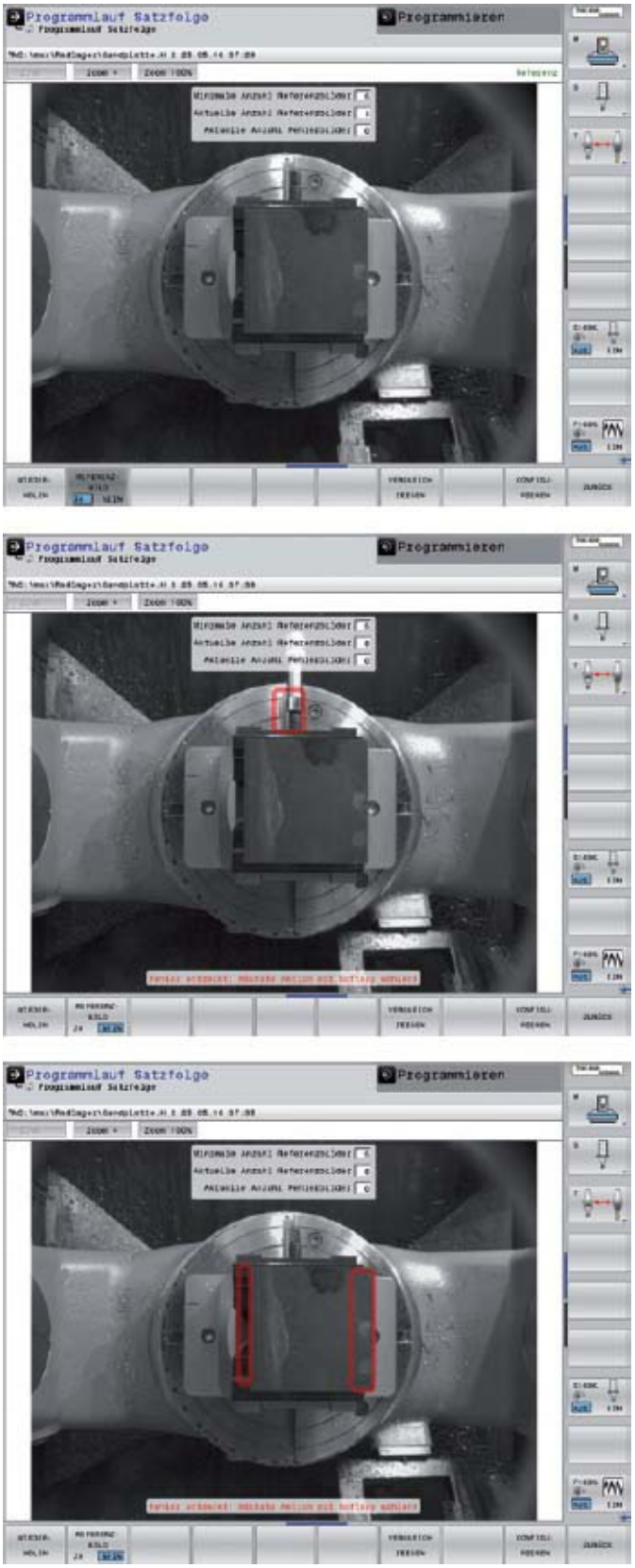

FIGURE 6.15 (a) With the help of workspace monitoring, the CNC system detects deviations from the correct situation. (b) A forgotten

wrench is highlighted. (c) An incorrectly clamped workpiece is highlighted. Heidenhain.)

In the ensuing series production, the CNC system automatically monitors whether the finished parts match the reference photographs of good parts; it learns to detect errors and, for instance, monitors clamping situations for documented errors. Thus automatic work area monitoring can detect, before machining starts, whether a part has been mounted wrongly. This can avoid expensive damage to tool, workpiece, and machine. After machining, automatic work area monitoring can, for instance, put out an alert that a process step, such as drilling a hole, has not been executed.

It is up to the machine operator to instruct the CNC program when and how often these checks should take place. He or she can also document complex clamping situations with own images and consult these at a later time.

The operator can define, with the use of reference photographs, special monitoring areas, such as workpiece features with particularly critical clamping situations or processing steps. This selective test has the advantage of a reliable result, the more so when chips and coolant are present on the workpiece. The closer a test area is defined, the better is the result via automatic work area monitoring. Also, the system can learn. A number or reference pictures can teach the system typical structures and contamination so that the presence of chips and coolant influence the detection of deviations less and less.

For protection from airborne chips and coolant, the camera and its optics are located in a protective encasement. The cover over the

lens opens only when photographs are taken. Next, an air curtain will protect the optics from moisture in the machining area.

INTEGRATED SAFETY CONCEPTS FOR CNC MACHINES

To protect people from dangerous machine movements, safety measures must be provided. These are used, for instance, when a door to the work area is kept open during setup to prevent dangerous machine movements. These safety features include monitoring of axle positions, for example, end positions; the monitoring speeds and stops; and, finally, lockdown in dangerous situations.

Modern CNC machine tools have axis accelerations that are three to four times the Earth's gravitational acceleration. This presents a significant safety risk. Therefore, the safety technology of modern machines is an essential part for an accident-free operation. Conventional safety technology, mainly based on electromechanical switching elements installed parallel to control and drive technology, cannot always sufficiently fulfill the requirements for safety, flexibility, and economy in today's automation technology. For this, it takes additional integrated technology that, when detecting a dangerous situation, will trigger a switch function in the main circuit and stop machine movements.

With the integration of safety functions, CNC and drive systems also perform safety functions, in addition to the regular functions. By virtue of short data paths, very short reaction times can be achieved from the capture of safety-relevant information (e.g., speed and position) for their evaluation. Systems with integrated safety technology react very quickly to permissible position or speed limits that are exceeded. This is of crucial importance for the desired safety

result. The integrated safety technology can act directly on the power semiconductors in the drive controller without using electromechanical switching devices in the power circuit. This results in reduced susceptibility to malfunctions and reduces machine wiring 6.16 and

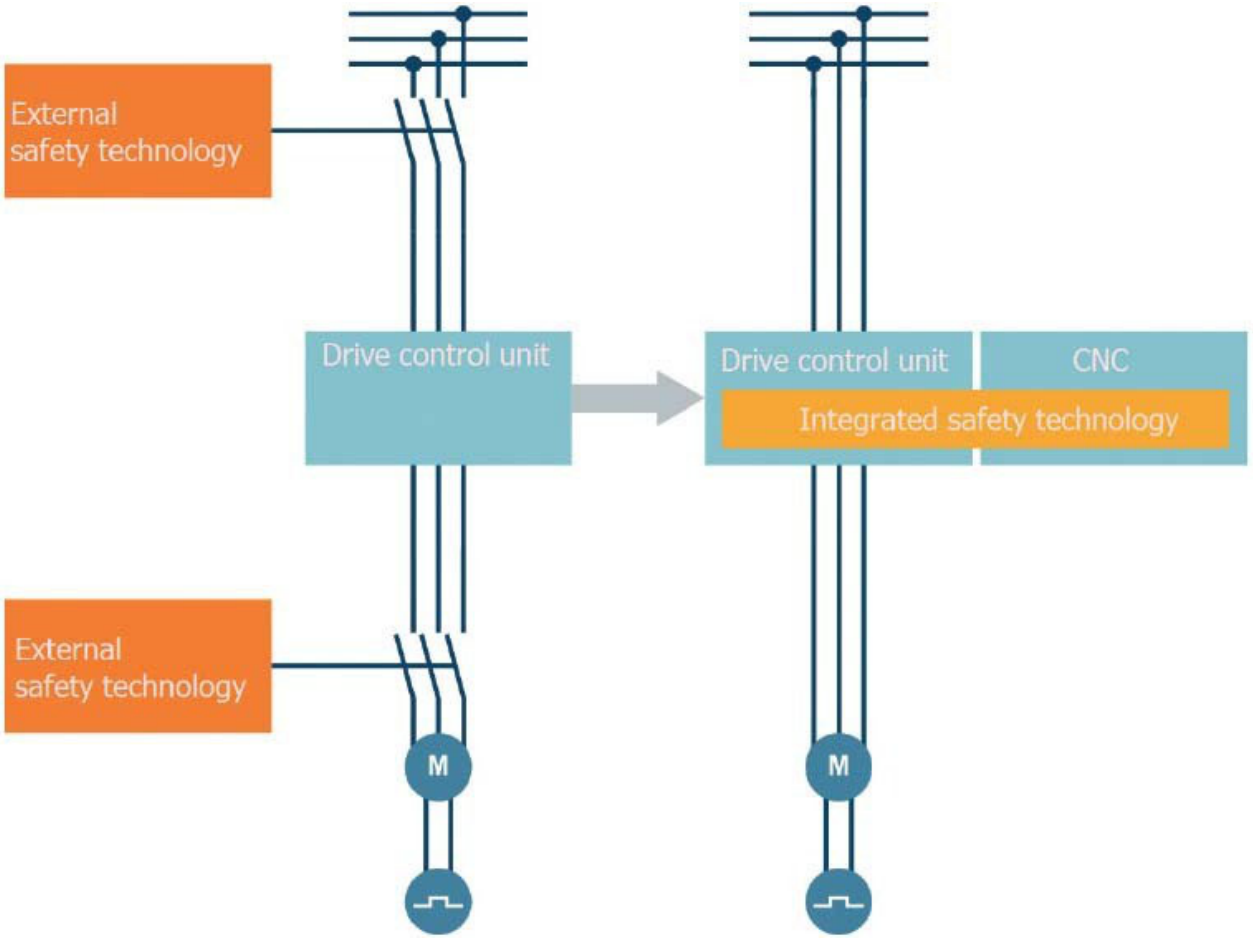

FIGURE 6.16 External versus integrated safety technology.

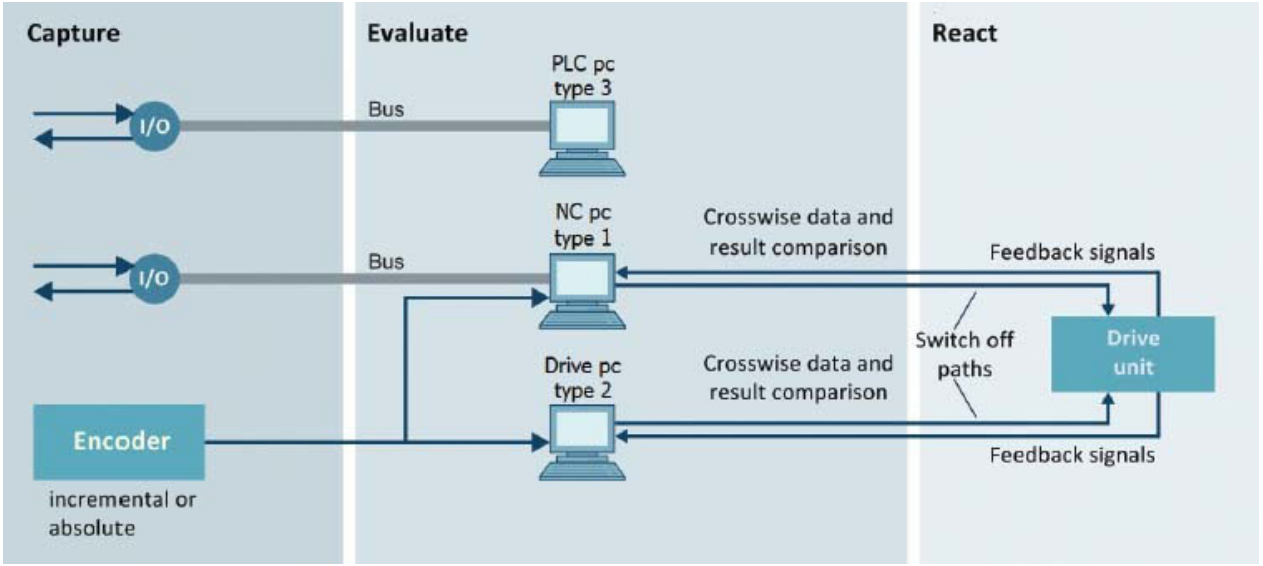

FIGURE 6.17 Reliable CNC-integrated safety functions thanks to multichannel system architecture. On detection of an error message, a necessary reaction of the control takes place, which immediately interrupts the drive power and sends corresponding information to the CNC system.

The encoder can use both a one- or two-encoder system. The encoder signals are provided both to the CNC computer and the drive computer. A crosswise comparison of data and results between these two computers is performed. If a discrepancy is detected, the drives are safely shut down.

Safety-related sensors and actuators are connected to the CNC system via ProfiBus or Profinet with two channels with the help of secure input or output modules. The CNC system will process these signals in an asynchronous subprogram (NCK) and in a standard PLC program (e.g., STEP 7) in two channels. The two computers (CNC and PLC) perform a crosswise data and result comparison. If a discrepancy is detected, the drives are safely shut down.

CNC systems and digital drives with integrated safety features have been available for several years. The integration of security functions into the basic system offers a hitherto unknown intelligent system penetration directly to the electric drives and measuring systems and thus leads to extremely fast and situational reactions. This is of utmost importance for the operational safety considering the highly dynamic drives of today's machines.

The security functions satisfy the requirements of category 3 as well as performance level (PL) d, according to DIN EN ISO 13849-1, and safety integrity level (SIL) 2, according to DIN EN 61508. They work specific to each axis and can be used both in setup and automatic modes. This means a high degree of protection for the personnel in setup mode and additional protection for machine, tool, and workpiece in automatic mode.

Integrated functions consist of, for instance, the monitoring of speed, standstill, and position. Safety-relevant peripheral signals, for example, of "EMERGENCY STOP" or optical sensors can be connected directly via secure input-output (I/O) modules. The signals are linked with an integrated, secure, and programmable logic.

In principle, all safety-relevant faults cause a controlled safe stop of dangerous machine movements or rapid energy cutoff of the motor. The energy cutoff between inverter and motor in case of a malfunction happens without contact and can be triggered for a specific axis with a very short response time. A direct-current (dc) link discharge in the drive is therefore not necessary. This behavior is gentle on the electronics, allows fast restart of the drives, and thus results in higher machine availability.

The shutdown of the drives is always optimal, meaning that it is adapted to the operating condition of the machine. Thus, when the safety door is opened, very short axis lag occurs, which significantly reduces the risk to the machine operator.

The integrated safety functions are configured and given parameters specifically for the machine and installation. The achievable safety optimizations are extremely diverse. The following examples provide a brief glimpse into the areas in which the integrated functions can be used:

■ *Machine* For each axis, spindle speed limits can be defined with the function “Safely reduced speed.” In combination with the “Safe software cams,” grinding machines, for example, can be operated with a safe peripheral grinding disk speed. Expensive and complicated external devices are eliminated. “Safe breaking management” can be employed for loading portals and machine tools to significantly reduce the risk of dropping hanging axes The integrated safety technology with its consistency provides completely new possibilities.

■ *Machine operating* In setup mode with the safety door open, for instance, when pressing “EMERGENCY STOP,” drives can be shut down very quickly. In automatic mode, it is possible to safely shut down the individual drive of each axis. Testing new programs with open safety doors is possible with additional safety devices, for instance, a “Permission” button and a “Safe nominal value limit” in automatic test mode.

■ *Machine* It is possible to move linear axes in setup mode with open safety doors and active speed monitoring with toggle switches and an additional “Permission” button. The spindle can be turned by

hand when the safety door is open while the other drives continue to be in position feedback control The operator can work with the tool magazine or prep station while machine operations take place in the processing room. A programmed tool change is blocked until it can be done safely.

● Through the thus realized simple and practical machine operation dangerous manipulations of safety devices will no longer be possible.

■ The coordinated safe shutdown in case of error or danger can eliminate or reduce consequential damage, such as a crash, and allows a quick and easy restart of the machine. The replacement of electromechanical devices and wiring with software and electronics also accounts for the elimination of a large portion of wear-prone technology.

● Drives of a defined safety area or part of a large machine can be shut down purposefully and safely, for instance, for unloading, retrofitting, or in case of an "EMERGENCY STOP." In other safety areas or parts of the installation, production can continue during this time. This minimizes downtime and increases machine availability.

■ *Installation* With the safe use of software limit switches and cams and the safe programmable logic, a number of mostly electromechanical components for processing safety information in the control cabinet and on the machine are eliminated. This means a significant saving in additional connection technology between the machine and control cabinet.

● In flexible manufacturing systems (FMSs), transfer lines, or chaining of individual machines, a continuous communication of

safety signals is achieved, resulting in significant advantages in the handling, operation, and availability of the installation.

TABLE 6.1 Scope of Functions

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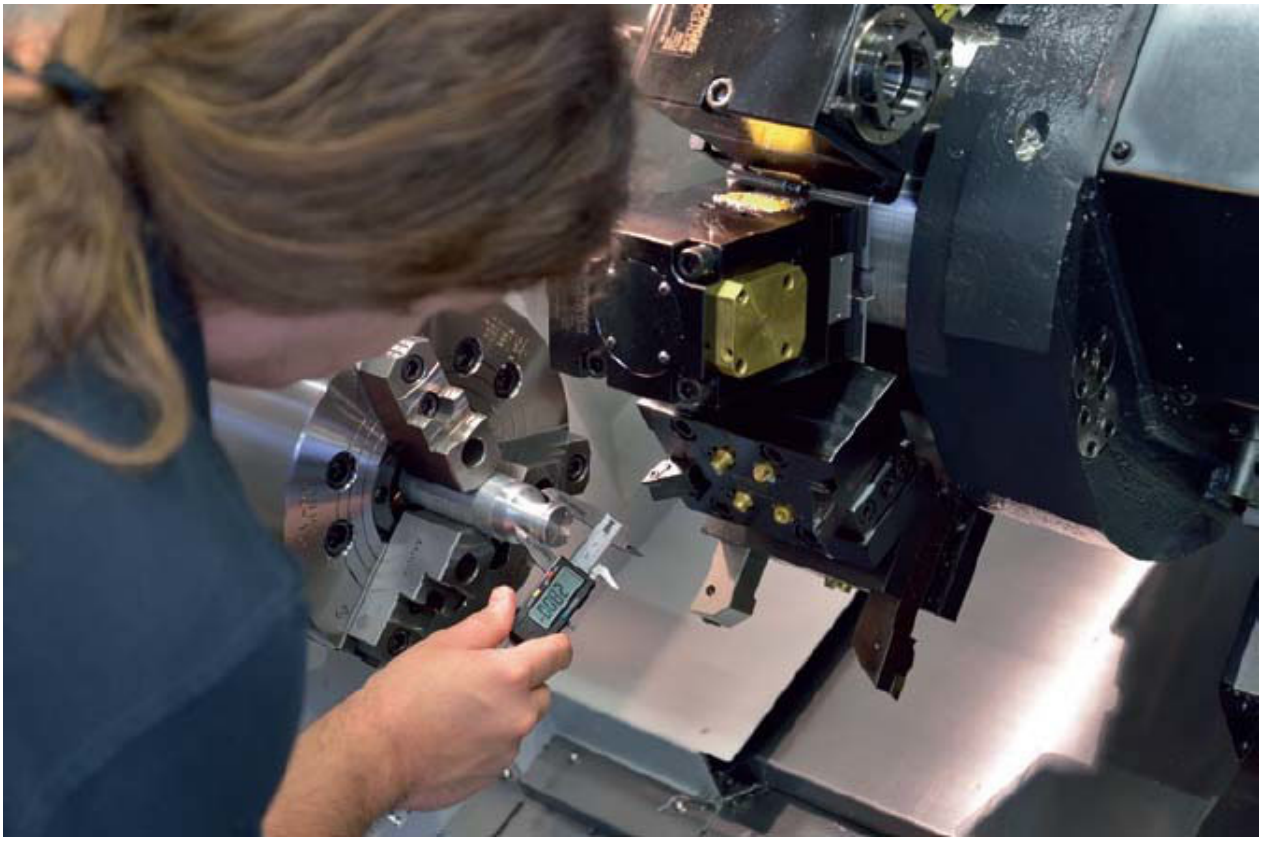


FIGURE 6.18 Setup mode, spindle in safe stop. In setup mode, the spindle can be turned by hand with the safety door open while the other drives are in position control.

Corner Delay

When milling a pocket, at every corner, when the cutter is immersing into the material, an overload is building up that can lead to damage to the tool and workpiece. Therefore, a corner slowdown is programmed, reducing the feed rate at each corner automatically and reducing cutter overload. *Example:* N123 G28 K15 F40 $; this means that the feed rate is reduced to 40% 15 mm in front of each corner. These values can also be entered manually; G29 turns off the corner slowdown

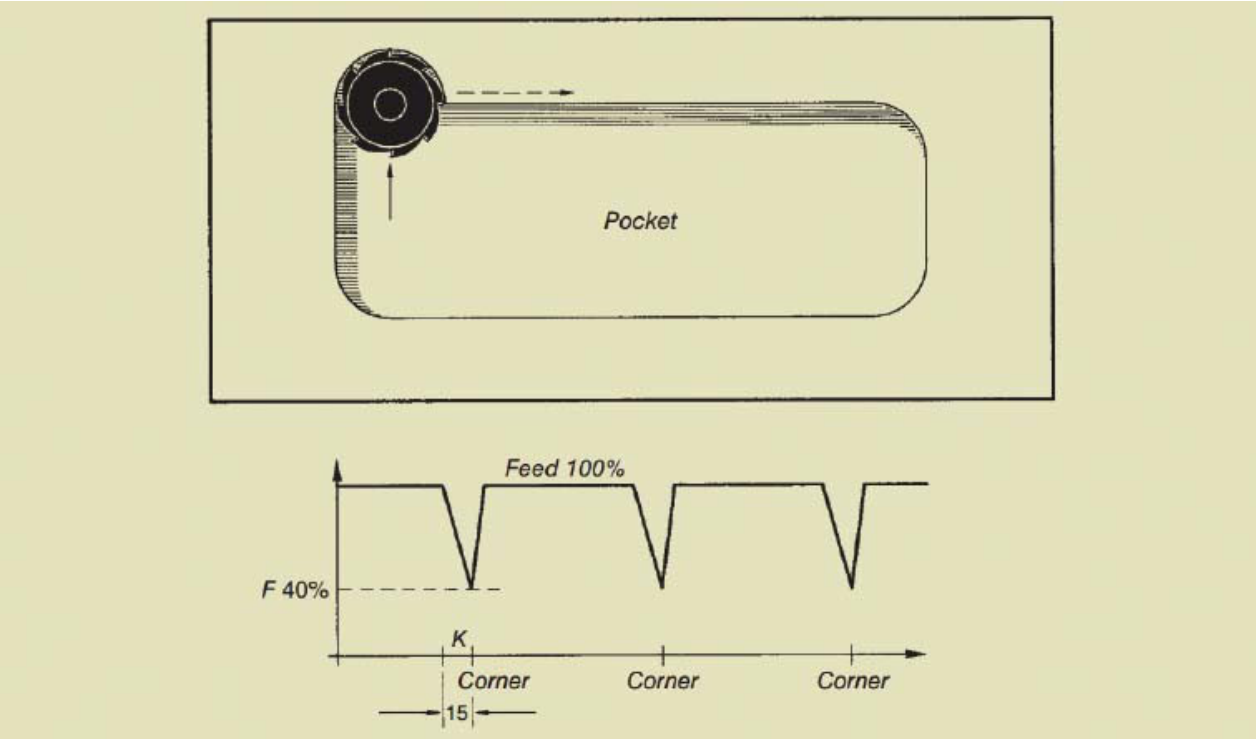


FIGURE 6.19 Corner delay, a modal G-function prevents tool overload, tool breakage, and workpiece damage during pocket milling.

Frame

Frame is the commonly used term for a coordinate transformation, such as offset and rotation. In order to machine sloped contours, it is either necessary to use appropriate fixtures to align the workpiece

parallel to the machine axes or, in the case of a five-axis machine, to create an appropriately modified coordinate system that is related to the workpiece.

The coordinate system can be shifted or rotated by means of a program using programmable frames These can be used:

■ To shift the zero point as desired

■ To rotate the coordinate axes and align them parallel to the desired working plane

■ To machine slanted surfaces, drill holes at various angles, and perform multisided machining, all in one single clamping operation

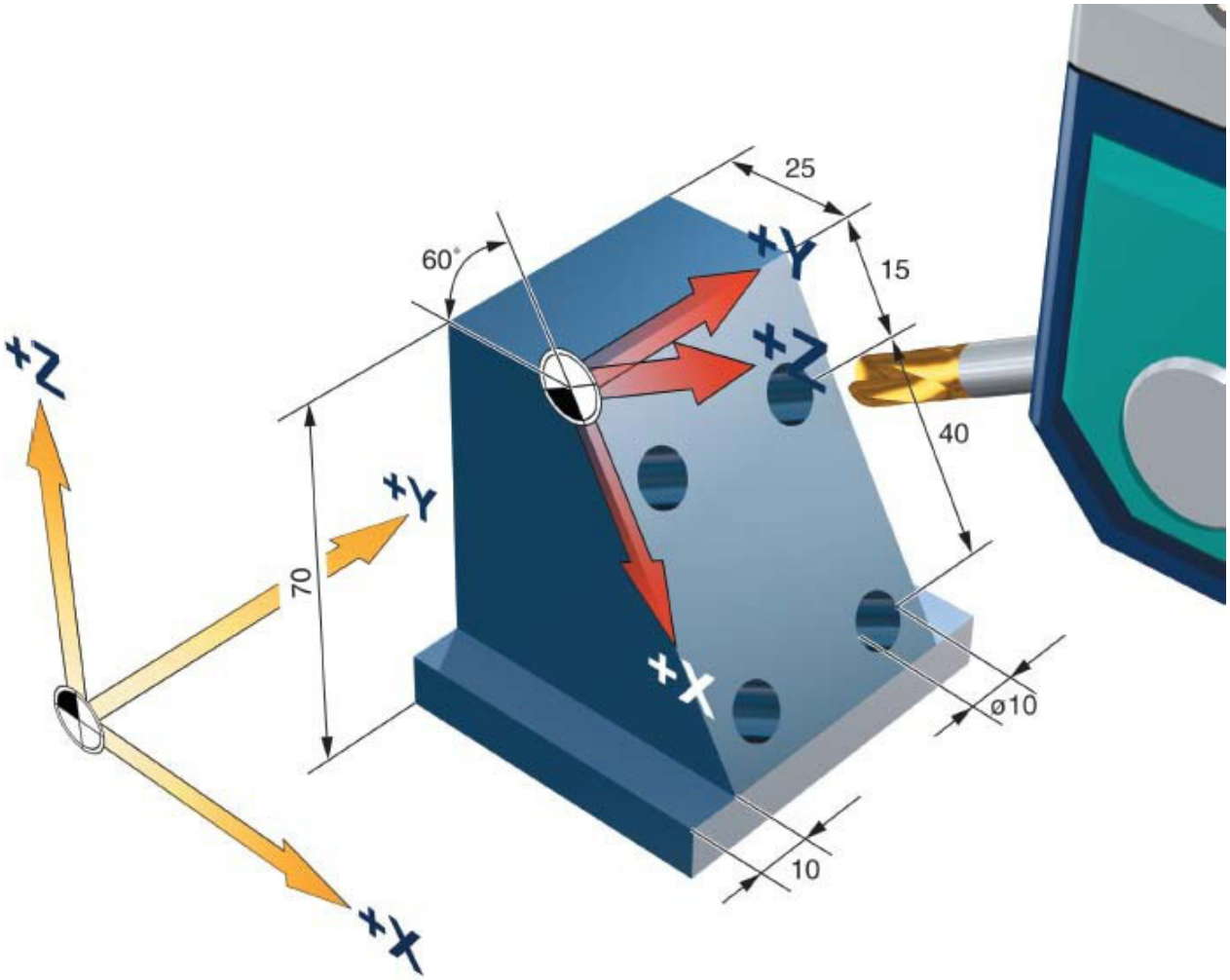


FIGURE 6.20 With high-performance CNC system the processing of sloped surfaces can be programmed directly on the machine.

Milling Strategy

Milling strategy refers to the generation of optimized milling paths for special machining tasks. Various milling strategies can be applied in CAM systems to achieve optimal cutting conditions. The service life of tools can be increased through the use of helical or trochoidal paths, improving the surface and allowing the machining of hard workpieces with up to 65 Rockwell C Scale Hardness (65 HRC).

For certain macros (cycles), it is possible to program these paths directly in the control system even without a CAD system.

Examples are macros for pocket milling with helical machining, slot milling with a trochoidal strategy, and plunge milling for large material removal.

Adaptive Feed Control

The feed rate for a milling operation is usually contingent on the material, cutter characteristics, cutting depth, and set for the respective milling process. If the cutting conditions change during the machining, for example, by tool wear, fluctuating cutting depths, or hardness of the material, this does not affect the feed rate. It could mean, for example, that with decreasing material thicknesses, the constant feed rate is lower than it needs to be. Thus the processing takes longer than necessary. A feed rate that is programmed too high, especially at increasing removal volume, can put excessive strain on the spindle and tool.

Adaptive feed control optimizes the feed rate depending on the spindle power and other process data. It is always based on the reading of the spindle power. Often, with the help of a series of test cuts, the maximum spindle power is approached and recorded. In a table in the CNC system, the maximum and minimum limit values of the spindle power are recorded. AFC then constantly compares the spindle power with the reference power and tries to maintain the reference power through adaption of the feed rate throughout the processing period.

AFC always provides for the maximum possible feed rate, thus increasing efficiency. This monitoring provides for a reduced feed rate if spindle power increases and prevents consequential damage caused

by cutter failure or wear. Thus the machine mechanics and spindle will be protected from overload 6.21 and

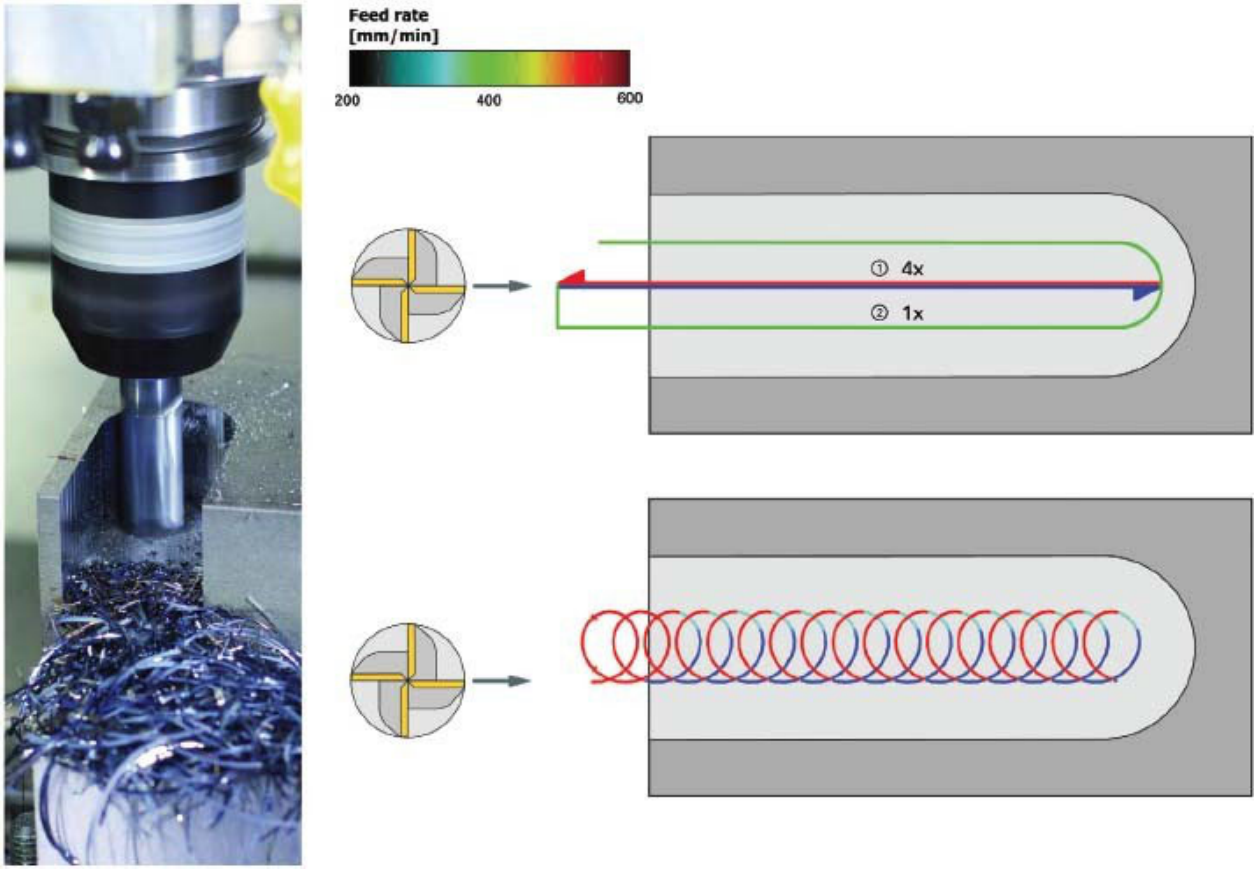


FIGURE 6.21 Conventional milling strategy: full cuts in four depths plus a partial cut. Whirl milling in combination with AFC: processing in one step. Heidenhain.)

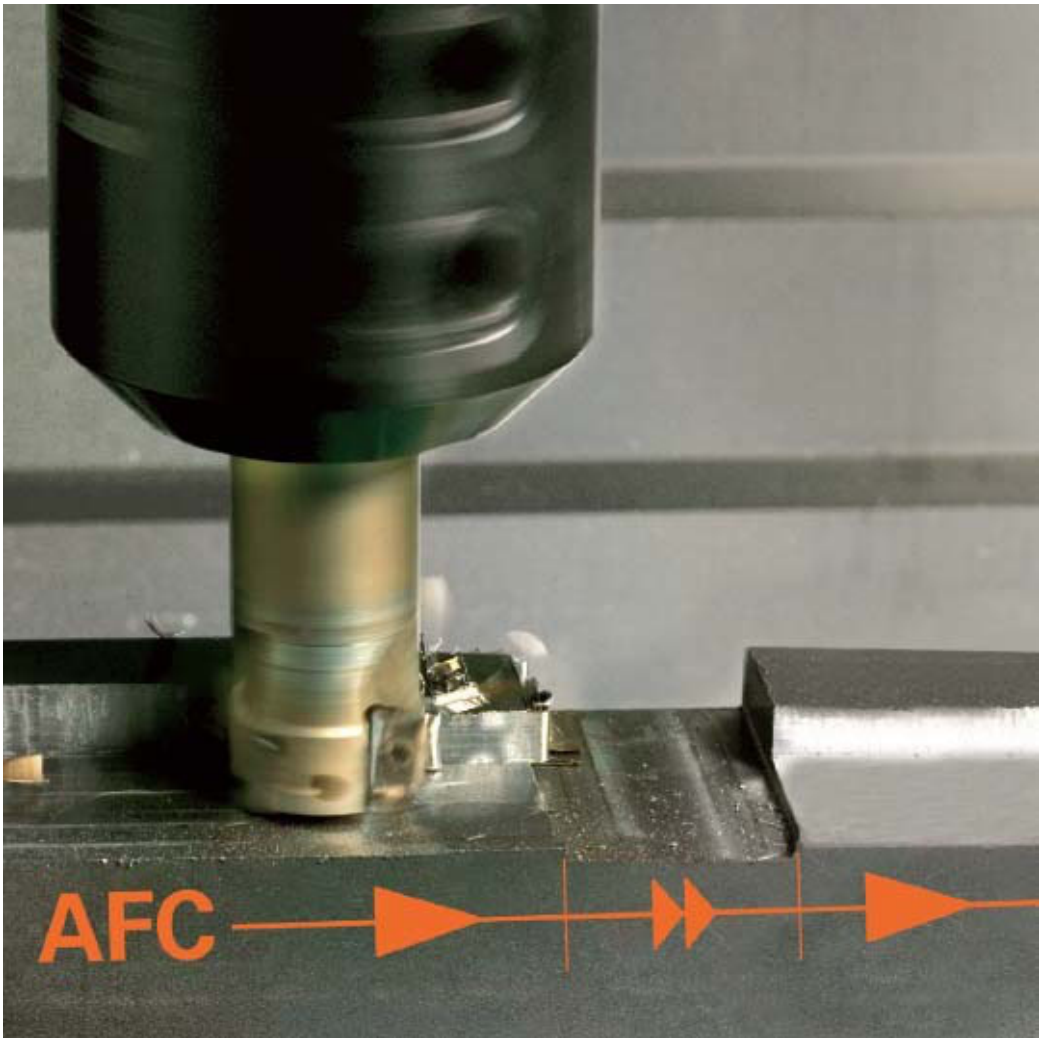


FIGURE 6.22 AFC adapts the feed rate to the different cutting conditions. Heidenhain.)

Tapping without Compensating Chucks

This function makes it no longer necessary to use compensating chucks that place unnecessary limits on the drilling range (i.e., the drilling depth that can be achieved). By advancing the with interpolation, depending on the thread pitch, it is possible to cut threads in blind holes precisely to the final drilling depth. Next, the direction of spindle rotation is reversed, and the tool retracts from the hole without exerting any compressive or tensile forces on the tap.

Thread Milling

When cutting inside and outside threads with form tools, helical interpolation is necessary. This consists of two motions: a circular motion in a plane and a linear motion perpendicular to this plane For this, the milling cutter's approach to the workpiece and the feed of the have to correspond to the thread pitch

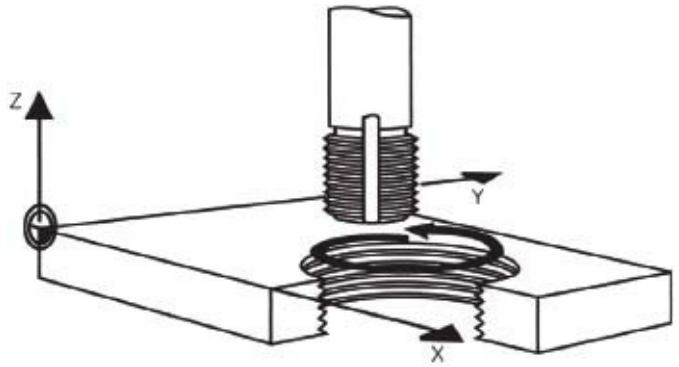


FIGURE 6.23 Thread milling with form cutter and helical interpolation.

Manual Retraction

The retract function supports manual retraction of the tool from the workpiece after a power failure or "NC Reset." This makes it possible, after interrupting a tapping process (G33/G331/G332) or a drilling job in general to retract the tool in jog mode in the tool direction without damaging the tool or workpiece. In this way, machining at the interrupted spot can resume, even if the affected axes are in swivel mode

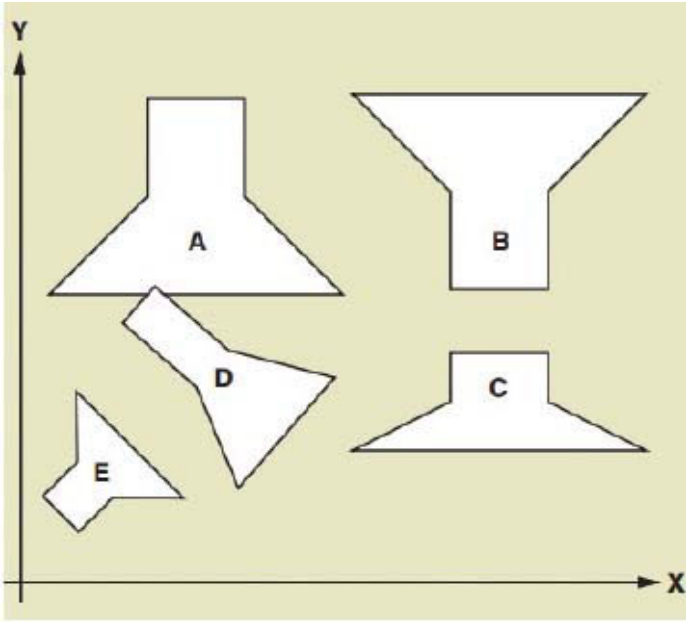
FIGURE 6.24 Manual retraction (image of Sinumerik 840D sl). After a power failure or machine reset, the tool can be moved out of the threaded hole without damage to the workpiece or tool. Siemens.)

Channel Structure

In complex machines with multiple synchronous work units, the CNC system's channel structure is used. Each separate unit, or channel, has a number of synchronous axes assigned to it. These axes are interpolated together. Each channel executes its own program and is independent of the other channels. If necessary, individual axes can be taken away from one channel and reassigned to another channel. It is thus possible to adapt the logical structure of the machine to the manufacturing job (see Section 6.5.13).

Scaling Factor

All programmed dimensions of a CNC program can be converted using any desired factor—even a different one for each axis. In this manner, it is possible to use a single CNC program to manufacture different geometrically similar parts. High-performance CNC systems allow an additional rotation by any desired angle α



A = Original shape
B = Mirrored on X-axis and moved,
C = Y-dimension halved (q = 0.5),
D = X-dimension halved (p = 0.5) and part rotated,
E = (X,Y) x 0.5 and part rotated.

FIGURE 6.25 Scale factor, for example, enlargement, reduction, or distortion of parts using programmable scale factors.

Scale Error Compensation

This is accomplished by measuring the natural error curves = for each CNC axis and entering the resulting compensation value in a compensation value memory. The CNC system automatically takes these compensation values into account when the axes are moved. The accuracy thus achieved is greater than the accuracy of the measuring system

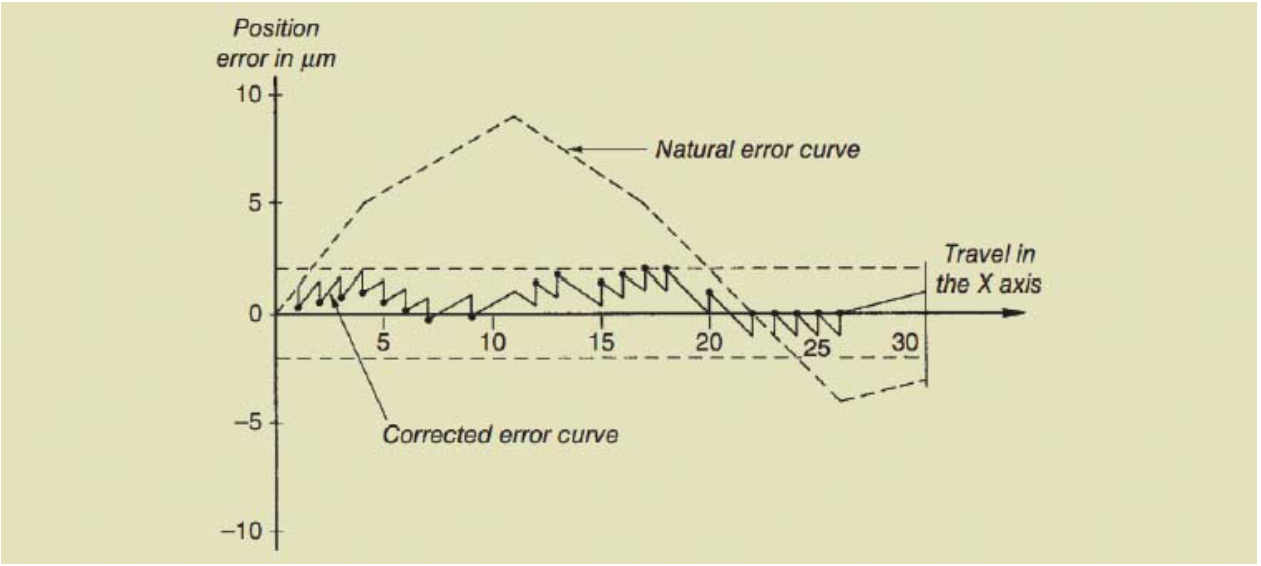


FIGURE 6.26 Scale error compensation. The natural error curve for each axis can be compensated for individually by means of stored compensation values that are taken into account automatically.

Probing Cycles

These are process cycles that are stored in the CNC system and used for automatic measurement of boreholes, grooves, or surfaces using a switching probe and for immediately calculating positions, machining accuracies, form and measurement deviations, centers of circles, center distances, or inclinations of the workpiece. The measured data thus determined can be output via the data interface. A measurement as part of execution of a CNC program, called *in-process* can be performed to ensure compliance of the workpiece with tolerances and, if necessary, to automatically correct the program or tool. The use of measuring probes requires special calibration and probing cycles in the CNC system to obtain precise measurement values

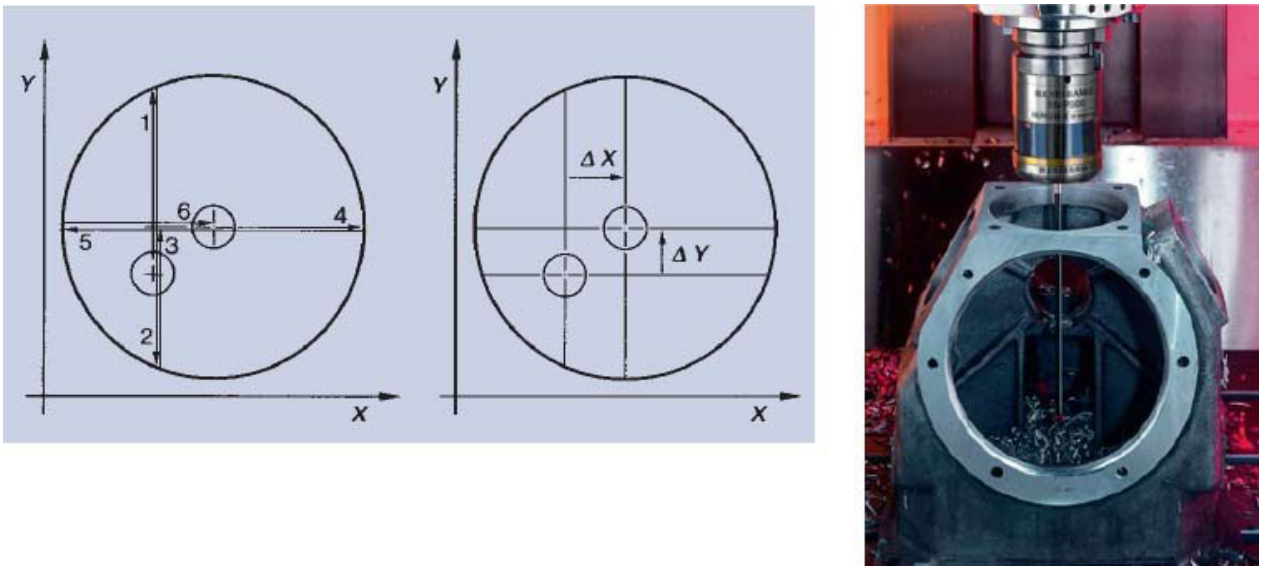


FIGURE 6.27 (a) Automatic measuring cycles for a probe to find the center of a hole. (b) A high-precision measuring probe for machining centers for workpiece compliance monitoring. Renishaw.)

Nano- and Picointerpolation

While in linear, circular, and spline interpolation, a distinction is made based on mathematically defined curves; in nano- and picointerpolation, a higher resolution during interpolation is involved. The reason for this is as follows: for drives with a digital interface, the nominal values of position, speed, and/or torque are exchanged between the CNC system and the drive control unit via the digital protocol (e.g., the SERCOS interface). Depending on the type of machine and accuracy requirements, the transmission accuracy of the data is between 0.01 and 10 µm (0.000,01–0.01 mm).

The transmission accuracy must not be confused with the axis resolution and the accuracy of the position measuring systems. The *transmission accuracy* is the accuracy or resolution with which the CNC system defines the interpolated command values and to which the drive control unit has to respond.

To achieve better drive control characteristics in modern systems, this transmission accuracy is elevated to the nanometer or picometer level. In nanointerpolation, the point specification is 1 × m (0.000.001 mm), whereas in picointerpolation, it can be 0.6 × m (0.000,000,006 mm), for example As a result, the CNC axes run much more smoothly in interpolated path execution, thus producing better surface quality on the workpiece.

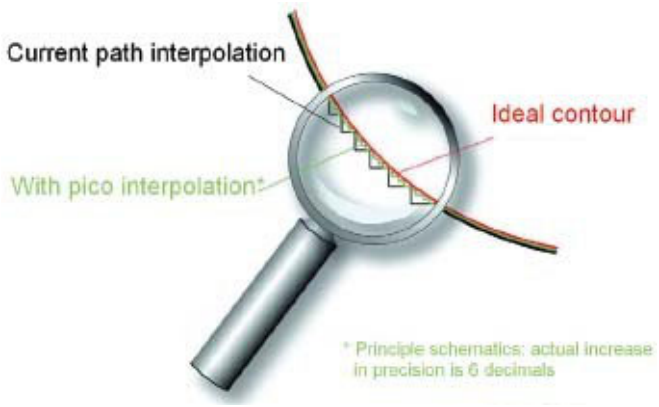


FIGURE 6.28 Principle of nano- or picointerpolation.

CNC Auxiliary Axes

Auxiliary axes have to operate completely independently of the main axes, for example, to change tools or workpieces independent of the machining sequence. While the main axes are machining the workpiece, the auxiliary axes execute motions according to a completely different program.

Spline Interpolation or Nonuniform Rational-Basis Splines

Nonuniform rational-basis splines are the result of concatenation of higher-order mathematical curves with tangential transitions. In this manner, it is possible to depict complex curves with fewer CNC blocks than is the case with approximation using traverses and linear

interpolation. The tangential transitions allow the axes to move more "smoothly." Splines can only be programmed using systems that have been configured for that purpose.

Spline interpolation also includes the capabilities of parabolic interpolation. For geometrically demanding surfaces with small tolerances, such as turbine blades, integral parts for aircraft, or casting molds, the linear interpolation primarily used in 3D machining leads to a number of problems. These involve mostly the long block cycle time of the CNC system, acceleration jumps of the axes, and the vibrations of the drives. Appropriate solutions have to be found here, especially for high-speed machining 6.29 and Below, some of these problems are described in detail.

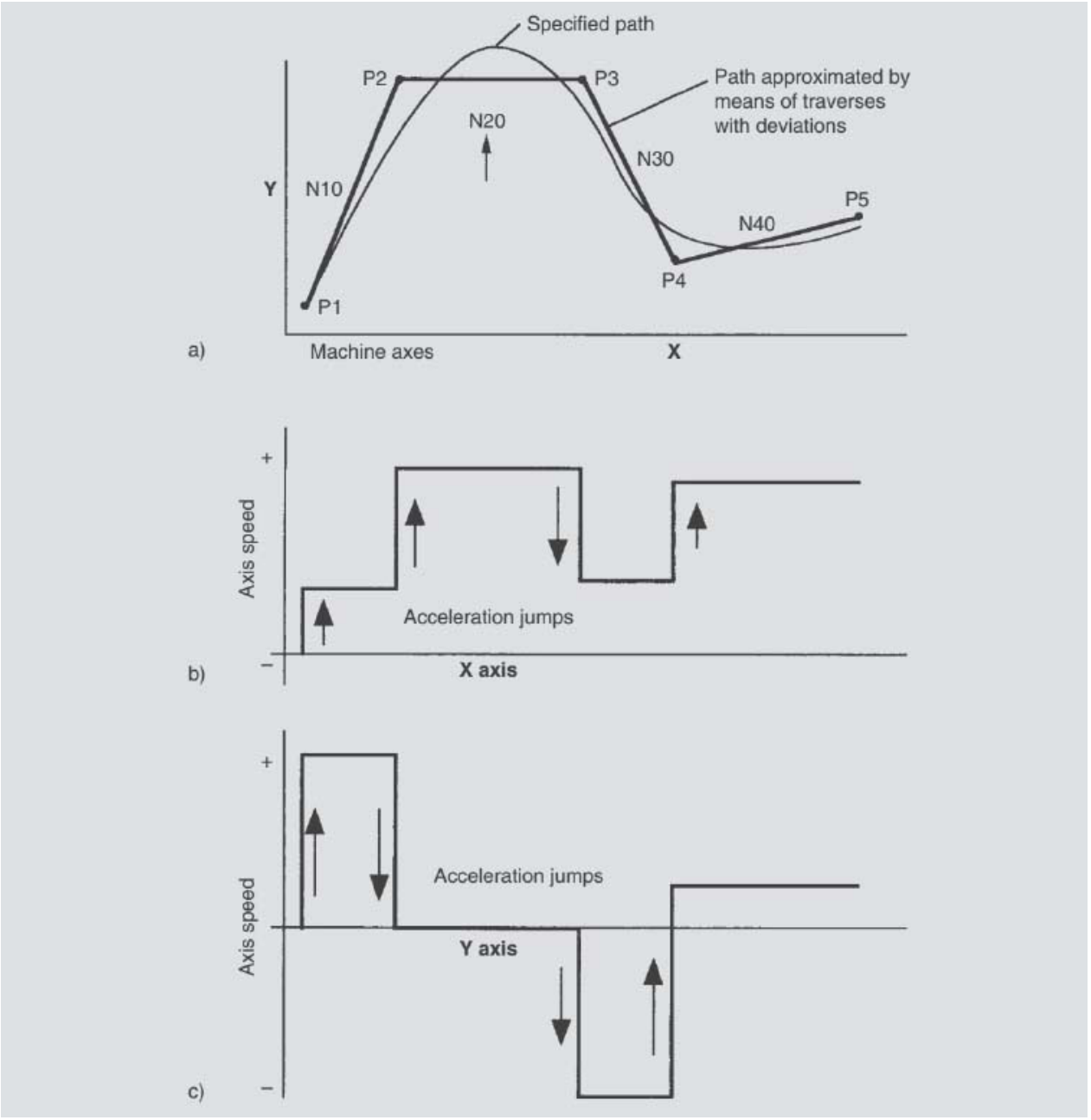


FIGURE 6.29 Path deviation and acceleration jumps in linear interpolation with constant path velocity.

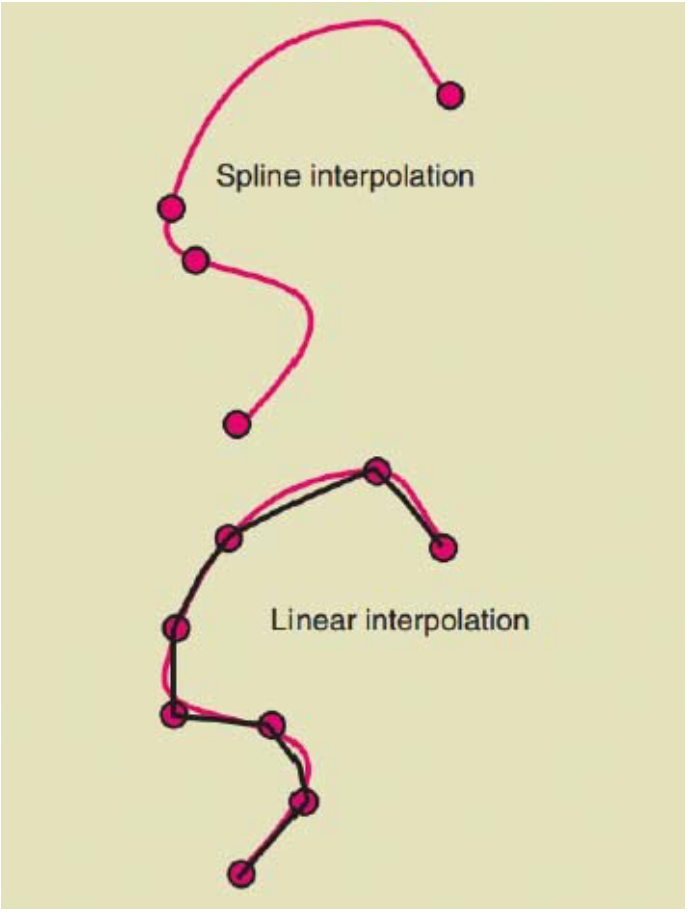


FIGURE 6.30 Programming of a path with splines and emulation with linear traverses.

Problem: Data Conversion

The mathematical depiction of curves and shapes in a CAD system differs fundamentally from the simple path description in CNC programs. To describe curves and surfaces, CAD systems employ spline mathematics or, more precisely, *nonuniform rational B-splines*

This is a mathematical method that has been used for years to describe curves and free-form surfaces using points and parameters. Regular surfaces such as cylinders, spheres, and tori also can be described precisely in this manner. As opposed to other splines, NURBS have the advantage of being able to represent precisely all

kinds of geometries, even sharp corners and edges. A number of CAD systems define their internal models for surfaces and bodies on this mathematical basis.

This type of depiction is also used in *standard for product model data exchange* ISO/IEC 10303) but not in CNC systems. Therefore, to generate linear blocks before processing in existing CNC systems, the high-precision CAD representation of surfaces has to be converted into traverses and approximated to the shape (see Figure This is one of the tasks of the postprocessor. To achieve high contour accuracy, a small chord error has to be selected for this approximation; this leads to a large number of very small individual steps, thus producing very large CNC programs.

Problem: Block Cycle Time

The processing of the many small traverses in the CNC system is very time-consuming. A CNC system is a clocked system that operates at the clock speed of the microprocessor being used. The *block cycle time* is the computing time needed to prepare the next processing step, or block, in the CNC system. In today's systems, this takes between 1 and 10 ms. If the computing time is longer than the time necessary to process the motion of a programmed block, rough and jerky machine movements result.

Result

The short linear blocks selected for reasons of quality not only lead to large quantities of data but also limit the feed rate. This conflicts with the requirement for high feed rates in high-speed cutting operations. With NURBS, it is possible to program significantly longer path segments; in such cases, the block cycle time is not critical anymore.

Problem: Vibrations in Linear Interpolation

Acceleration jumps at the traverse transitions in combination with lag-free drive controls result in vibrations and/or jolts in the machine. These, in turn, can put extreme stress on the machine axes. The consequences are evident in the form of characteristic facets and vibration patterns on the workpiece surface.

Solution: Spline Interpolation

As detailed earlier, the advantages of NURBS are lost when the CAD splines are converted into the CNC-appropriate *DIN* format. Therefore, it is advisable to design CNC systems in such a manner that they can accept and process NURBS directly from the CAD system. This provides three major advantages, especially for high-speed machining:

- Higher processing speed (by 30% to 50%)
- Higher accuracy
- Better surface quality

This also eliminates time-consuming rework of the workpiece. Furthermore, the machine moves more evenly, without abrupt acceleration peaks. This has a positive effect on the machine load, the workpiece surface, machine service life, and tool life.

This requires, however, a completely different CNC program format, which may look like this:

N29 Po[X] = (−3.525, 0.001) Po[Y] = (20, −0.014, 0.006)

N30 Po[X] = (−33, −26.371, 26.155) Po[Y]

= 20, 6.947, −3.367)

PO[Z] = (23.977, 25.953, −25.953)

N31 Po[X] = (−33, 0.265, 0.095) Po[Y] =

(20, −0.034, 0.012)

Po[Z] = (20.977, −0.847, 0.489)

N32 Po[X] = (−12.155, 36.816, −19.133)

PO[Y] = (20, −7.727, 6.775)

P[OZ] = (20.977, 39.746, −19.808)

Here the coefficients of a third-order polynomial are transferred for each axis, for example, for the

$= + + ct + d$

Switching between Languages

All output and dialogs of the CNC system are stored in two or more languages. This makes work easy for an operator or service

technician of a different tongue. A language with a different character set, for instance, Chinese, pose a particular challenge. In this case, the CNC system has to change not just the contents (text) but also the depiction (characters). Today's CNC systems should have the option for texts in part programs (e.g., comments or notices) to be in the local language.

Executing CNC Programs from Internal or External Storage

With *execution from external storage* CNC systems provide a solution for easy data management that is also independent of the storage location. The user has the option to process CNC programs directly from all connected storage media, such as CNC internal memory, local drive, PC, USB, and network

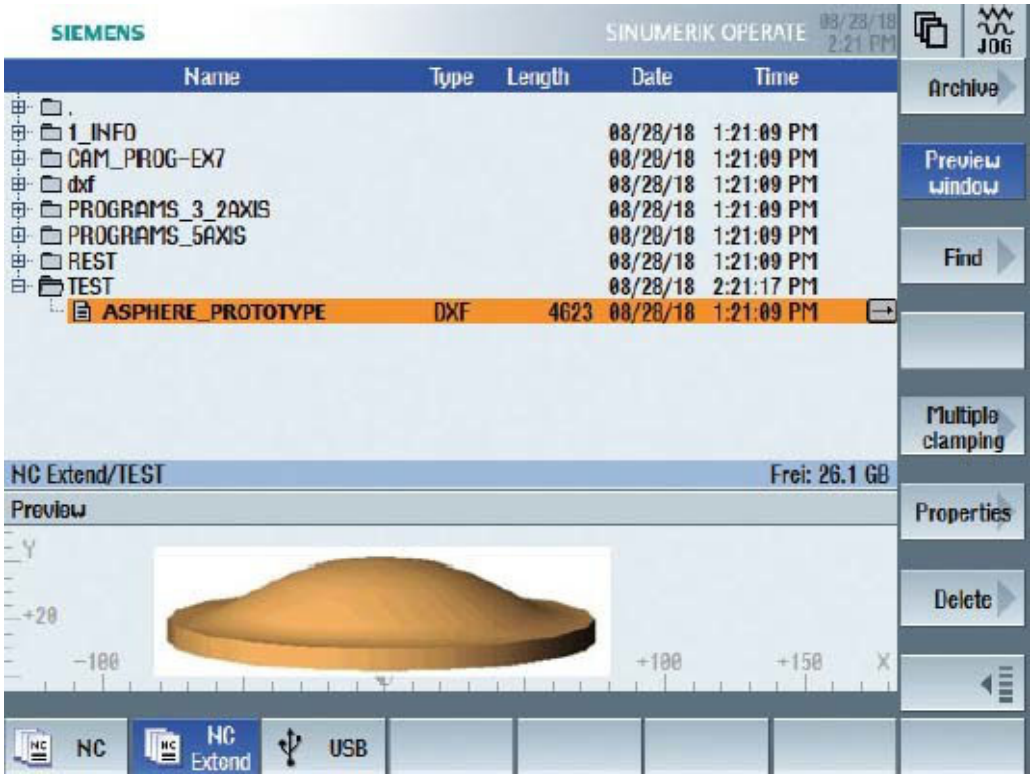


FIGURE 6.31 Program administration on external medium, function EES, with Sinumerik 840D sl. Siemens.)

The processing of the part programs can also be performed directly on the external medium. An external drive can be used as an extension of the integrated CNC storage, and it can accept main programs and subprograms in any folder on this drive. The main program can also be executed directly from the external memory. Thus, when a subprogram is called up from a main program, there will not be any restrictions such as jump forward, jump backward, or loop commands. Also, the call-up itself takes place only by specifying the subprogram name without special syntax or path information. Furthermore, the size of the program is no longer relevant because the storage capacity of CNC systems has been extended by the size of the external medium.

Virtual NC Kernel

The *virtual NC kernel* is used as the basis for calculations in simulation systems. The CNC manufacturer makes its CNC kernel available as a virtual environment for the machine space or machining simulations. In this way, the exact real control behavior can be simulated on a PC before production begins. The virtual CNC kernel tests the part programs for collisions, surface errors, and so on and makes important characteristics available for production planning. The time required to set up and test the machine can be shortened significantly.

Feed Limitation

Feed rates that are too high or too low can damage the tool and workpiece. For this reason, the permissible feed range can be specified in the program. If the CNC program is given values higher or lower than this, the limit values are automatically observed.

Feed Forward

The following error of the CNC axes results in contouring errors on the workpiece. Given the inertia in the system, the cutter has a tendency to leave the target contour (gray area in Figure and create an area (yellow/red) that deviates from the nominal contour. The size of the following error results from the system (e.g., analog position control) and the feed rate. By setting a high value and activating the function "Axes feed forward control" in the CNC system, the speed-dependent following error will be reduced toward zero, and the contour accuracy on the workpiece will improve.

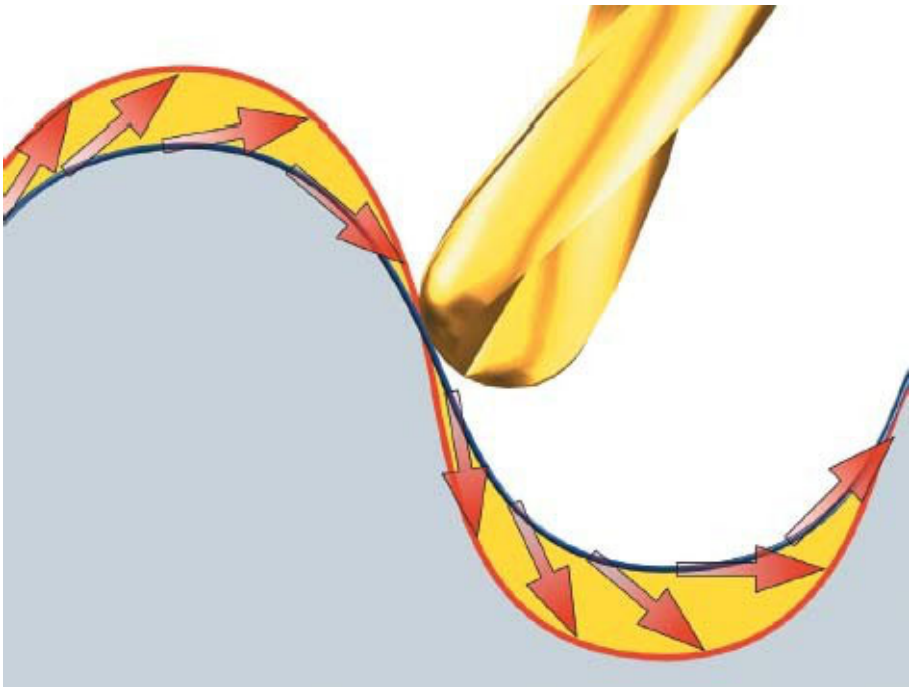


FIGURE 6.32 The function "feed forward" minimizes the following error of the CNC axes and improves the contour accuracy during path execution (blue: programmed path; red: path deviation caused by contouring error).

3D Tool Offset

This feature is required for CNC machines with four or five axes if the tool axis has one or two pivoting movements and tool length or

diameter must be correctable. In this case, neither the standard drilling cycles nor the tool corrections can be used. The approach alone to the drilling position requires complicated calculations, and for the drilling operation, two or three axes must interpolate linearly. Using 3D tool compensation, the operator can enter the part geometry and compensate as needed. The CNC calculates the resulting positions and movements automatically

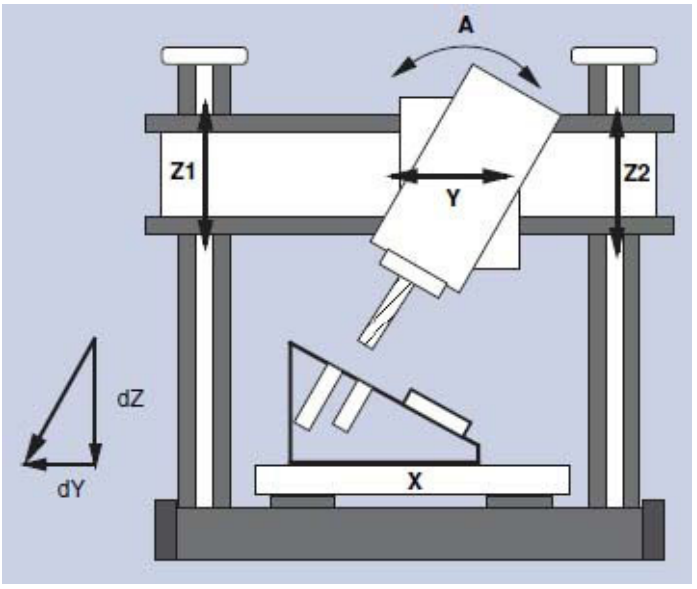


FIGURE 6.33 3D tool compensation allows machining inclined surfaces with tool compensations and the drilling of inclined holes with swivel-head machines in which the cannot be realized with the quill.

Remote Diagnostics

The specialist for troubleshooting a machine tool is often not locally present. Teleservice therefore offers a timely and cost-saving option. It connects the machine operator to the pertinent service centers of the machine or CNC system manufacturer for quick diagnostics. Typical service cases might be:

■ Diagnosis of incidents during operation, commissioning, or maintenance

■ Software updates

Prerequisite for this service is a direct data connection to the machine in question.

Teleservice functions can be subdivided into:

■ *Passive* These consist of only indicative and evaluative functions for rapid assessment of the machine condition and troubleshooting.

■ *Active and repair* For instance, these could involve interventions with the software of the CNC or PLC.

CONDITION MONITORING AND MACHINE DATA COLLECTION

Analysis of the cost structure of the use of machine tools reveals the fact that the cumulative secondary costs of a machine tool significantly exceed the purchase price. In order to minimize these costs, it is important to know which types of processing puts a greater or lesser strain on the machine. The careful study of machine problems resulting from daily operation provides information about the life expectancy of the components.

Therefore, automated, centralized, and comprehensive condition monitoring becomes a must. Mostly larger companies today have adopted permanent machine tool monitoring. Avoiding one single unplanned failure usually pays for the investment. Whereas remote diagnostics have been applied for many years in instances of actual machine problems, the use of condition monitoring is preemptive. It is the basis for efficient and automated remote service functions that come into effect before a problem occurs. The smart application prevents expensive repairs and downtimes, as in the case of an exchange of a defective low-cost bearing that would be costly to repair had it gone unnoticed. It is possible and rewarding to transition from reactive to condition-based maintenance.

The applications of condition monitoring are freely scalable. The company decides whether it only wants one machine monitored or an installation of several thousand machines. The topic is thus relevant for the machine manufacturer and machine operator. The tale of an automotive supplier may exemplify how worthwhile condition monitoring be can. Previously, the ball screws of its machine tools

were continuously used until they had worn out. The eventual forced exchange of a single ball screw took place in an ad hoc manner, and production loss and repair costs amounted to a five-digit dollar amount. With condition monitoring, the ball screws are used up to a certain predetermined mechanical condition and then sent for repair. The costs amounted to under $1,000, and the downtime could be coordinated within an overall maintenance schedule

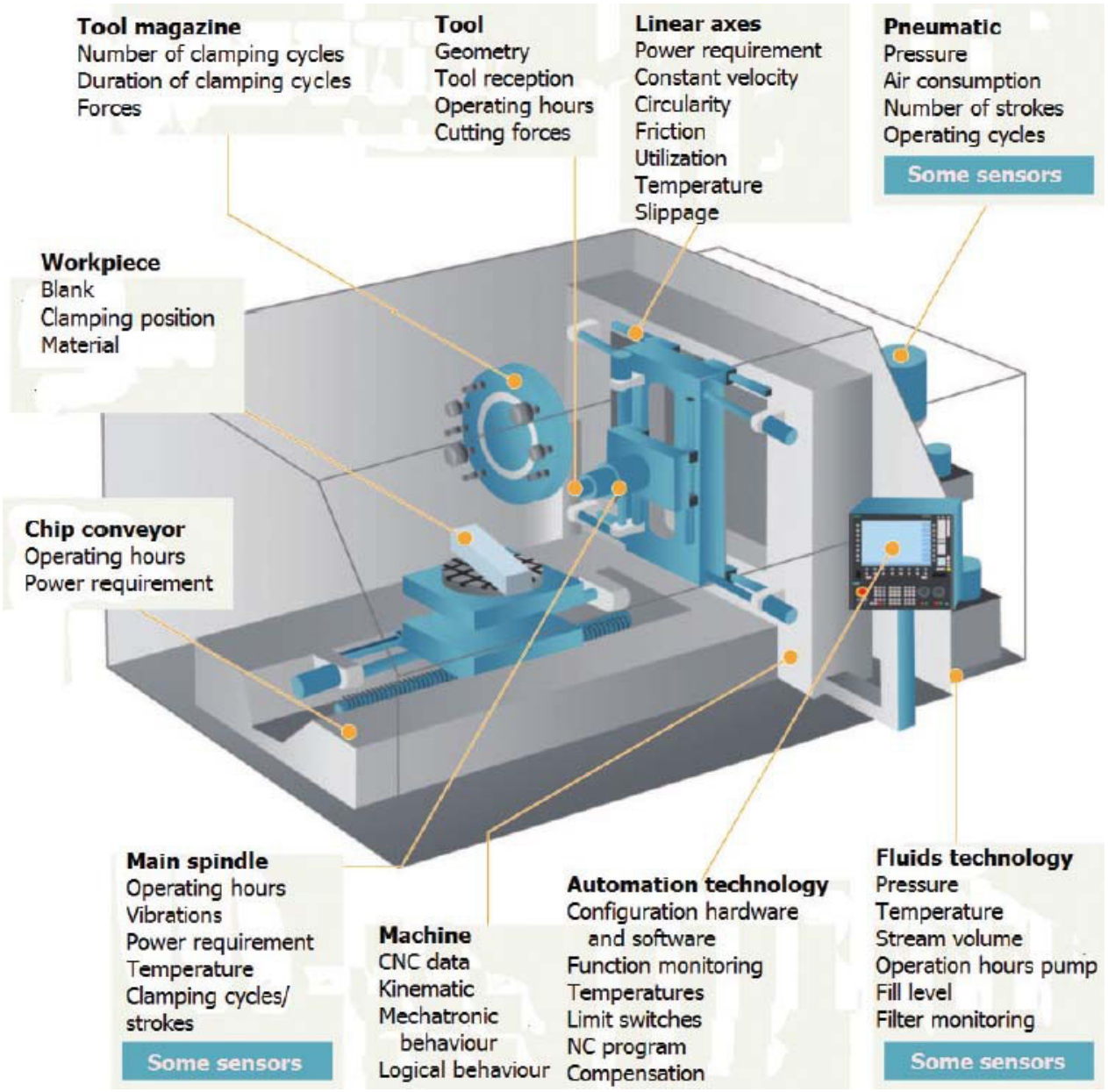


FIGURE 6.34 Examples of components of a machine tool that can be automatically and permanently monitored. The CNC system puts out a notice when a conspicuous machine condition occurs.

Machine tools with their moving parts are equipped with many sensors, such as proximity switches, pressure gauges, scales, and vibration and temperature sensors. These data are destined for machine monitoring. In addition, modern CNC systems can directly access all variables of the CNC system and PLC, such as PLC inputs and outputs, flags, and data on temperatures, lubricants, sealing air, movement times, torques, currents, temperatures, set points etc. Permanent monitoring and comparison with reference values provide the operator with the earliest possible knowledge of deviations. If necessary, external sensors, for instance, to monitor the spindle or an ancillary component, can be easily integrated.

It is an advantage of current client/server communication that access to these data does not require any interference in the CNC or PLC system but is accomplished with a generic client that is running on the CNC machine. In many new CNC systems, the client is included and just has to be activated. The actual configuration of the data-acquisition logic is done via *web user interfaces* that are made available to the machine through executable scripts. It is thus evident that even the subsequent introduction of condition monitoring in an existing infrastructure is uncomplicated. Machine and plant operators must not concern themselves with losing claims toward warranties granted by the machine manufacturers in case it comes to an interference with the CNC system. The required data are collected locally on the machine, in the corporate network, or in the cloud. Independent of the storage location, there is typically no need for additional software for accessing and processing the data; they run

on a server and are visualized via a browser. Visualization is becoming increasingly important. Many companies want an overview of the condition of a machine park and find out at one glance what maintenance work must be planned. The machine manufacturers also see the need to provide their customers with a standardized and open platform to make these views and information on their machines available. Equally important is the inclusion of machines or devices of other manufacturers because hardly any company has a homogeneous machine park.

A cloud data storage solution works for both the machine manufacturer and the machine operator and provides the additional advantage of worldwide and secure access to data, evaluations, and detection logic. Integration with the company network can provide access worldwide, relative to the organization, and also allow integration with other systems in the company network. These are usually supervisory control and data-acquisition (SCADA) systems, enterprise resource planning (ERP) systems, manufacturing execution systems (MES), and CAM systems.

Condition monitoring does not so much focus on malfunctions of the machine. Rather, the analysis starts much earlier. For instance, a particular temperature elevation in a short time from 70 to 80°C indicates that something might be wrong. Such changes must be recognized and recorded. In order to keep clean records, the focus is on intelligent data gathering instead of big data analysis.

A data set called a *fingerprint* can be used to define nominal and borderline values and what should happen if one of these values has been reached. The detection of an excessive value might trigger alerts via text message or email. An email alert may also contain historical

and present data pertaining to the speedy analysis of the problem. Email notifications are not only suitable for reporting problems but also are often used to automatically send out regular status reports to a number of addressees.

Figures 6.35 and 6.36 indicate an early problem with a ball screw. A weekly circularity test with a maximum circularity deviation of 10 µm will notify the maintenance department to address the problem.

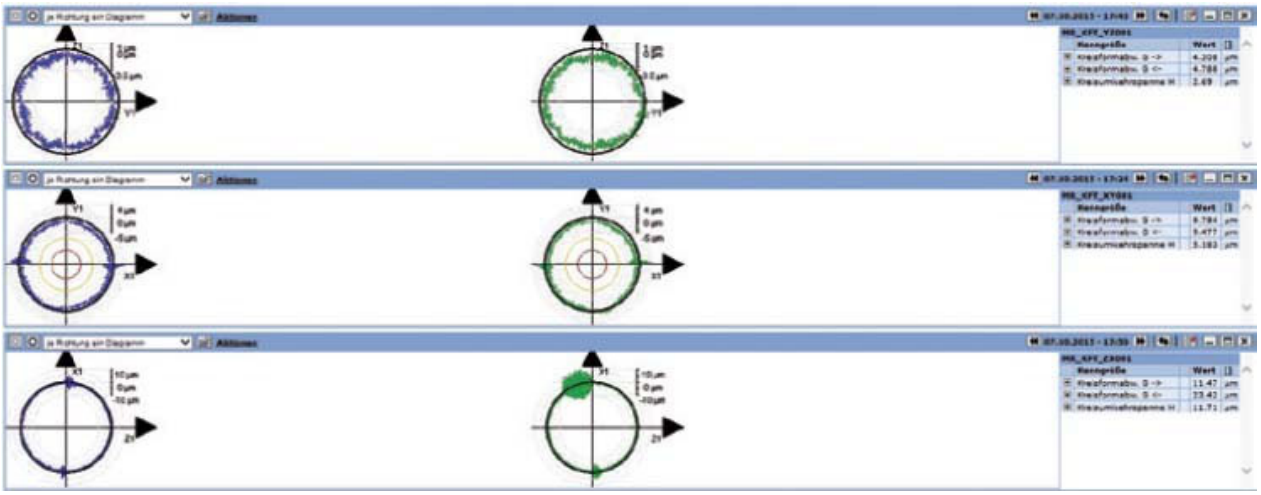


FIGURE 6.35 Automatically performed series of different circularity tests of various axis combinations.

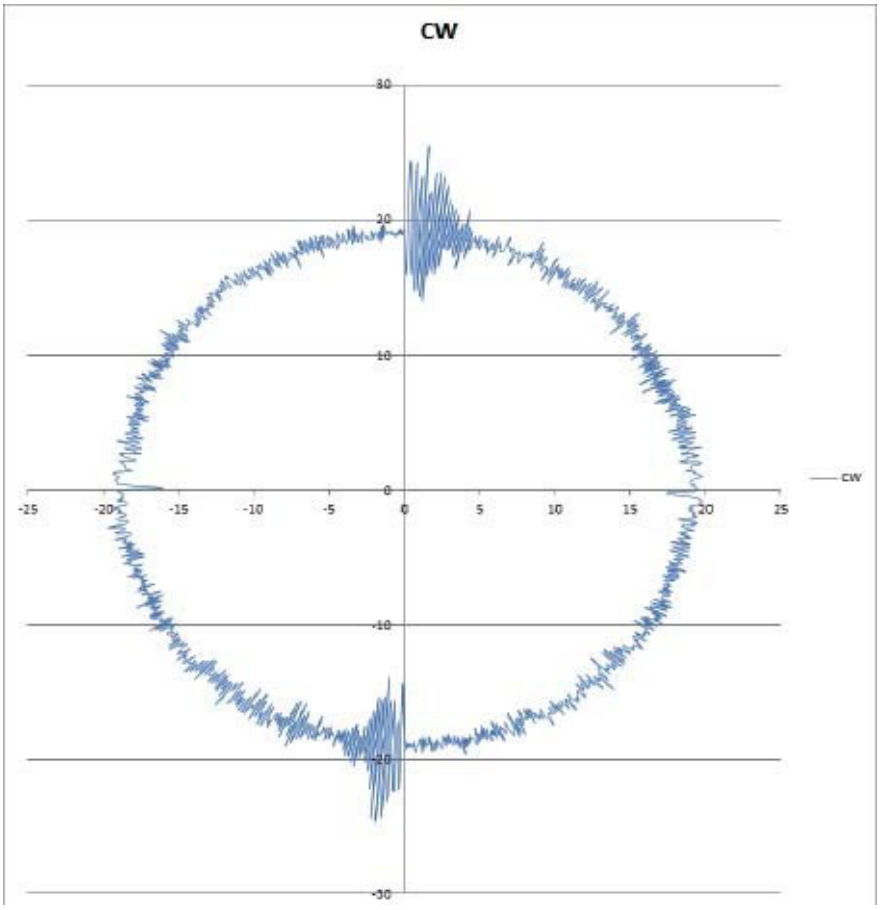


FIGURE 6.36 Close-up view of lower-left feature in Figure 6.35 of a problem detected by an automatic circularity test.

A constant-velocity test provides evidence of irregularities over the entire travel path. Stuck and difficult-to-open covers, worn ways and ball screws, distorted linear drives, and much more information can be read from the analysis of torque values and forces. The presence of a direct measuring system also allows evaluations of mechanical stiffness.

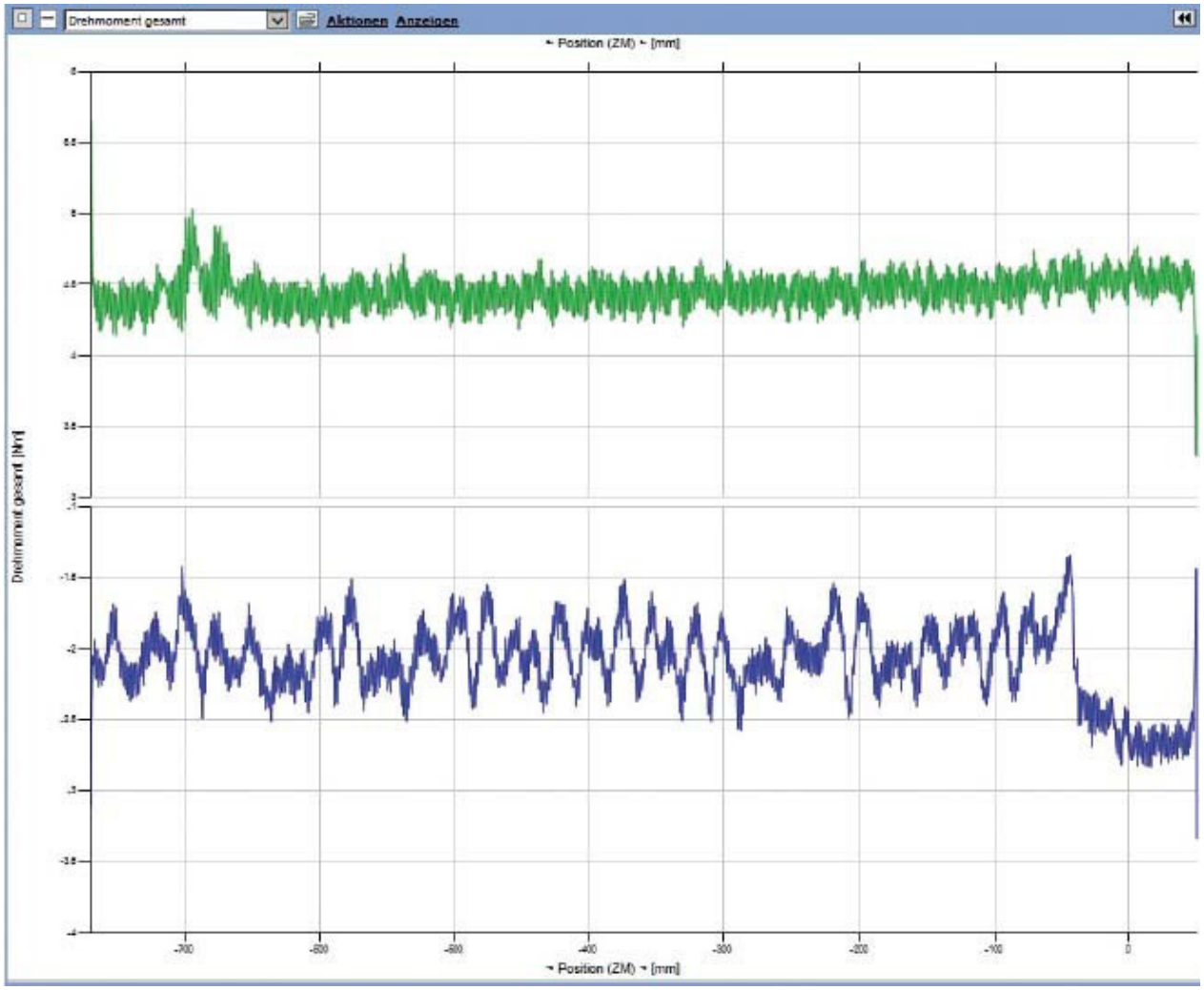


FIGURE 6.37 A constant-velocity test over the entire travel path. It provides information about average, maximum, or minimum torque along with the limits. The acceleration and deceleration ramps are intelligently hidden; the graph compensates for weight influences.

Remote Access

Remote access can provide the following accesses on a CNC machine:

■ *Remote* Remote control and monitoring of human-machine interface (HMI).

■ *File* Transferring files from and into the file system on a CNC system.

■ *Remote* Access to the PLC of the CNC system.

■ Conference call. Participation of several service technicians, for instance, control manufacturer, machine manufacturer, and service department.

■ *Session* Documentation of actions taken at a session.

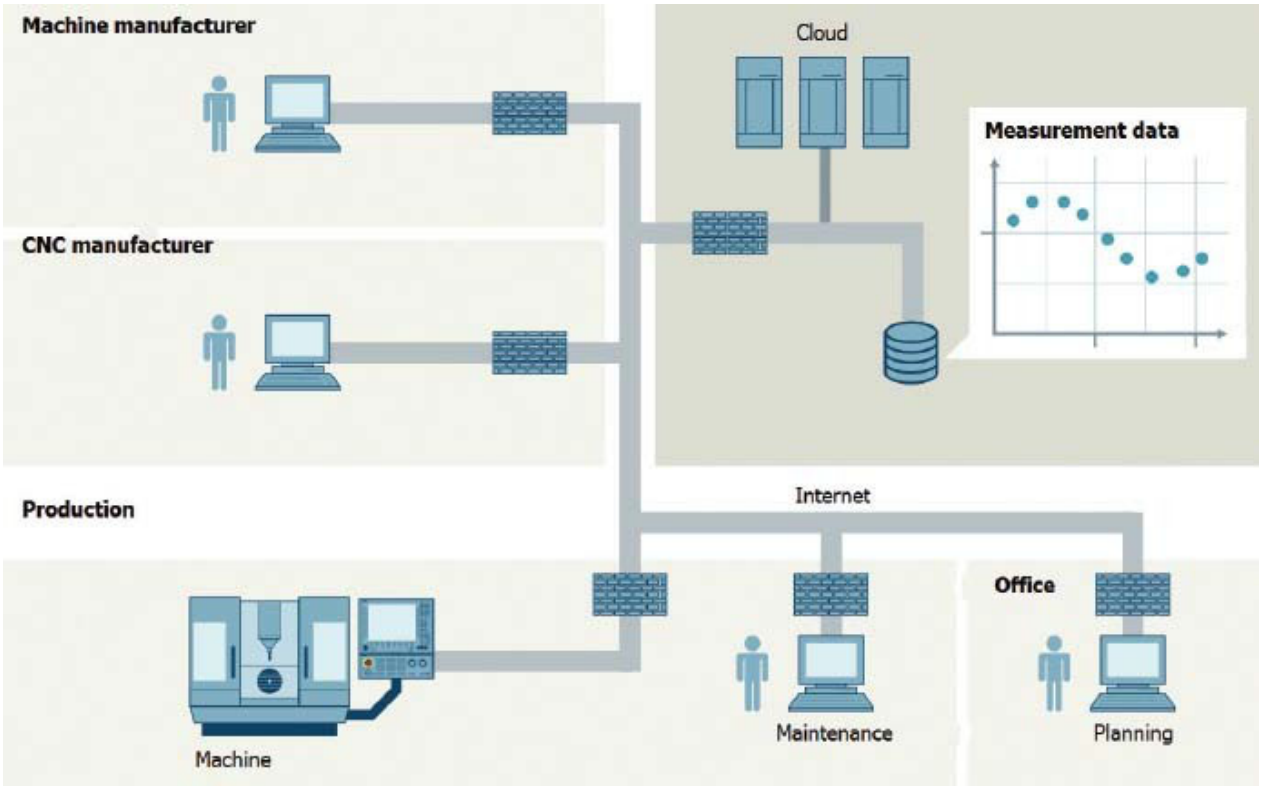


FIGURE 6.38 Remote access can be made secure without having the individual connections unlocked by the IT department of the customer via a VPN tunnel.

Secure remote access is realized via conference servers. Conference servers can be used by third parties; they also can be located directly at the customer or machine manufacturer. This arrangement secures a flexible availability for machines and service engineers. Access to machines and servers is secured with certificates and authentications.

With restriction of the outbound traffic from the machine to the server, the machine can be integrated in the information technology (IT) environment at the customer without setting up a virtual private network (VPN) tunnel.

Big Data versus Smart Data

Intelligent data acquisition is based on two principles:

1. *Time-based data* This is used for the cyclical tracking of values. It allows the scheduled evaluation of service performance of the machine.

2. *Event-based data* This can be made up from logical links of signals from the machine or cycle-accurate PLC trace records of several arbitrary signals.

In addition to the cycle-accurate recording of PLC signals, CNC data can be recorded with the servo trace or the trace server, respectively. The following applications are already possible:

■ Checking the synchronization of CNC axes. With this test, irregularities of the entire travel of an axis in each direction can be measured via torque/force.

■ Circularity tests with two CNC axes each show form deviation and backlash.

■ Universal axis tests analyze torque, rigidity, and friction conditions.

If the onboard tools of a CNC system are insufficient, modules, for instance, for high-frequency data acquisition, can be connected. These modules could be acceleration sensor systems that allow data buffering with up to 40 kHz and generate minimums, maximums, averages and also recognize peaks.

Summary

Condition monitoring is not just about detecting malfunctions; the analysis begins much earlier. Changes in the temperature of the spindle, the concentricity of the axes, and so on are detected by permanent comparison of actual data with the fingerprint file of the nominal values of the machine and transmitted via the company network to the maintenance department of the machine manufacturer. Thus actions can be initiated before the machine fails and unplanned downtime can be avoided.

DISPLAYS IN CNC SYSTEMS

Information output on a screen is the *interface* with the operator. For this reason good, solid and clear information on the monitor is an important prerequisite for trouble-free operation of a CNC machine. Today's CNC systems have flat *liquid-crystal displays* (LCDs) or plasma displays that can be placed in the most suitable location. It is important that the display have a position indicator for each axis. In this way, the actual position of each axis can be recognized and determined if the target position has already been reached.

Electronic data can be set to zero or a defined value, saving the programmer complicated computation work to convert drawing dimensions into absolute machine positions. At any given time, the machine operator needs to have access to the following information:

- Program number, name, and memory requirements
- Program contents
- Required or still-available storage capacity of the CNC system
- All correction values, zero offsets, and other corrective actions
- Active feed rates and spindle revolution values

- Active G- and M-functions
- Subprograms and cycles
- Workpiece and tool management
- Alarms and status and error messages
- Machine parameters
- Input and simulation graphics
- Diagnostic programs
- Service and maintenance instructions
- And others

Depending on the expandability of the CNC system, smaller or larger displays can be used. For some values, the display size is switchable, and graphic output can be “zoomed.” Sometimes the CNC unit has interfaces for a second or third display, a feature that can be advantageous for large machines.

TOUCH OPERATION OF THE CNC SYSTEM

Most CNC manufacturers have been offering touch-enabled displays since 2015. These are usually 15-inch displays or larger so that error-free usage, even under the challenging conditions of a production environment, can be ensured. Through the use of capacitive sensor systems, touch panels can be used in a contaminated industrial environment and are usable with work gloves. With the touch operation, a completely new operating philosophy can be realized. Thus setup or data-management functions can be summarized as an app and can be quickly called up by the machine operator. Furthermore, with the design of their own apps, CNC operations can be customized by both machine manufacturers and machine operators. A current topic is multitouch operation of CNC machines. Input with intuitive gesture, known from smartphone and tablets, is increasingly used in the production environment 6.2 and Figure

TABLE 6.2 Finger Gestures Are Used on CNC Touchscreens to Make the Operation Easier

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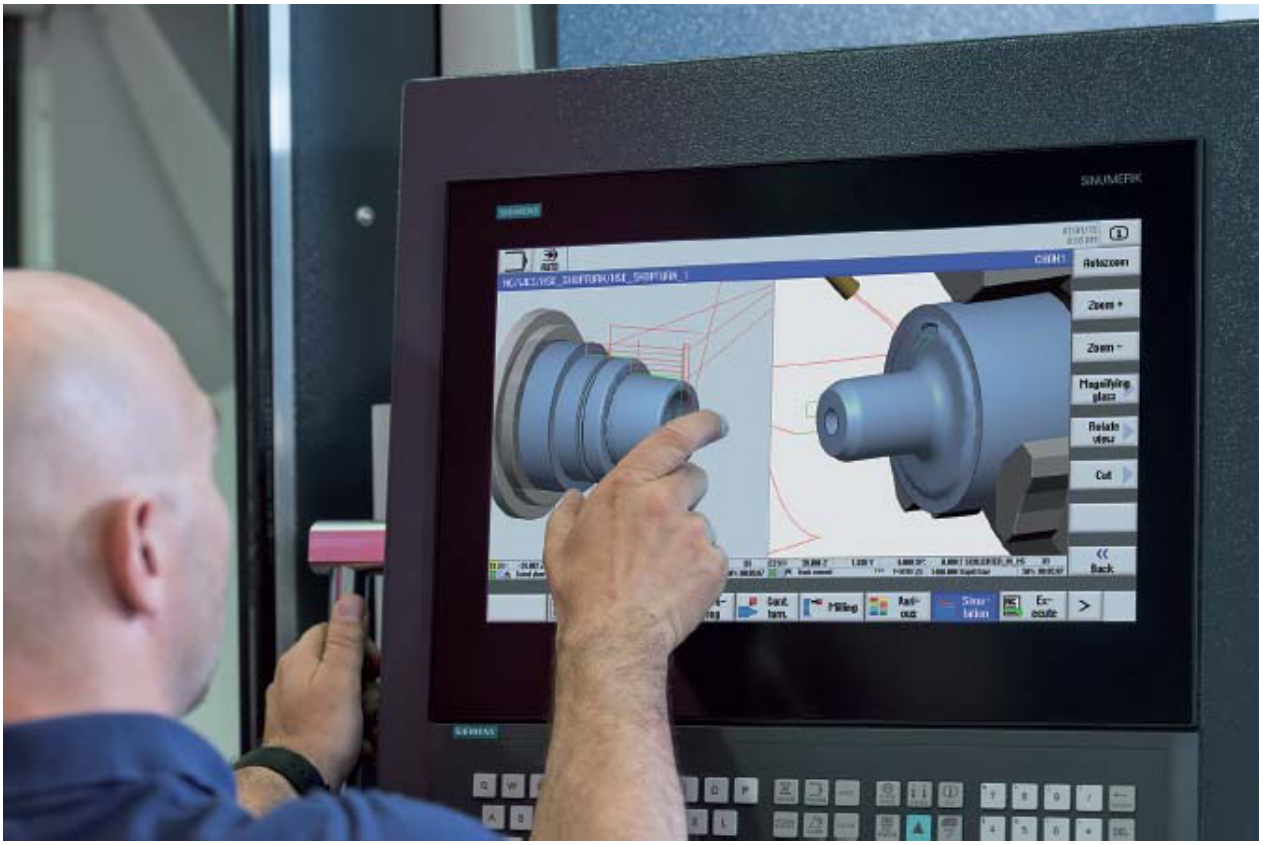

FIGURE 6.39 Touch panel of a CNC system. One can enlarge graphics on the screen for better recognition of workpiece details via intuitive finger gestures, CNC Sinumerik 840D sl. Siemens.)

Complement CNC User Interfaces

The demands on the user interface of a CNC are ever increasing. The user expects the interface to allow best possible access and interaction with the machine's technology and specific properties. The machine manufacturer, additionally, can create an advantage for the brand with a smart user interface, thus creating selling points in terms of functionality and design.

The term *human-machine interface openness* for CNC machines describes the design freedom of the user interface by machine manufacturer or end user. The design of a specific user interface relies on the operating system supplied by the CNC manufacturer and is always based on the same principle: the communication with the entity that is connected to the bus system takes place via interfaces. Visualization of the data from the electrical equipment is generated through the development environment and displayed at the HMI in real time

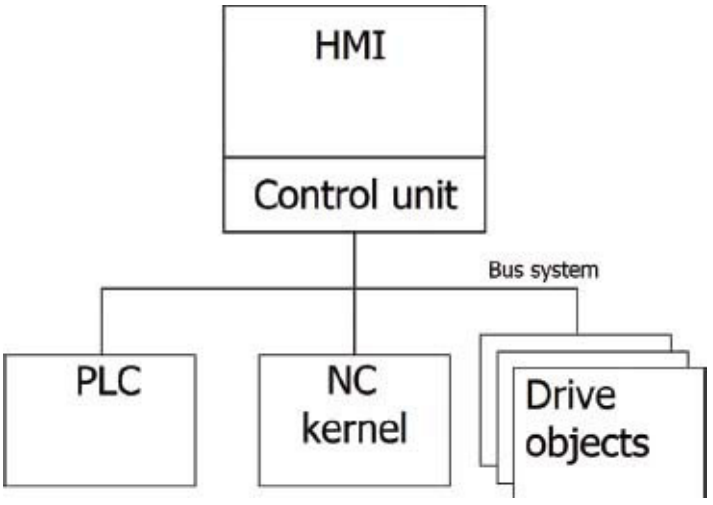

FIGURE 6.40 Schematic depiction of a data access structure.

Various CNC manufacturers offer complete programming packages for the design of the user interface that cover the following functions:

- Description of the interfaces to the subscribers, e.g., CNC, PLC, and drive
- Provision of services, such as alarm, event, or data services
- Direct storage of the HMI application on the CNC system
- Complementing operating areas for the actually closed system
- Development tools with preintegrated program-building routines
- Software for interface verification

There are different reasons why machine manufacturers want to make use of variable design of the user interface:

- Special cycles generation
- Custom user guidance for special technologies that are not supported by the CNC supplier, e.g., grinding or wire cutting
- Additions to the diagnostics and commissioning functionality
- Generation of unique selling points

- HMI as part of a corporate identity
- Customer retention and loyalty through positive user experiences
- Creating a predefined way of customization by the end user
- Control and administration of highly automated systems
- Connection to higher-level data systems

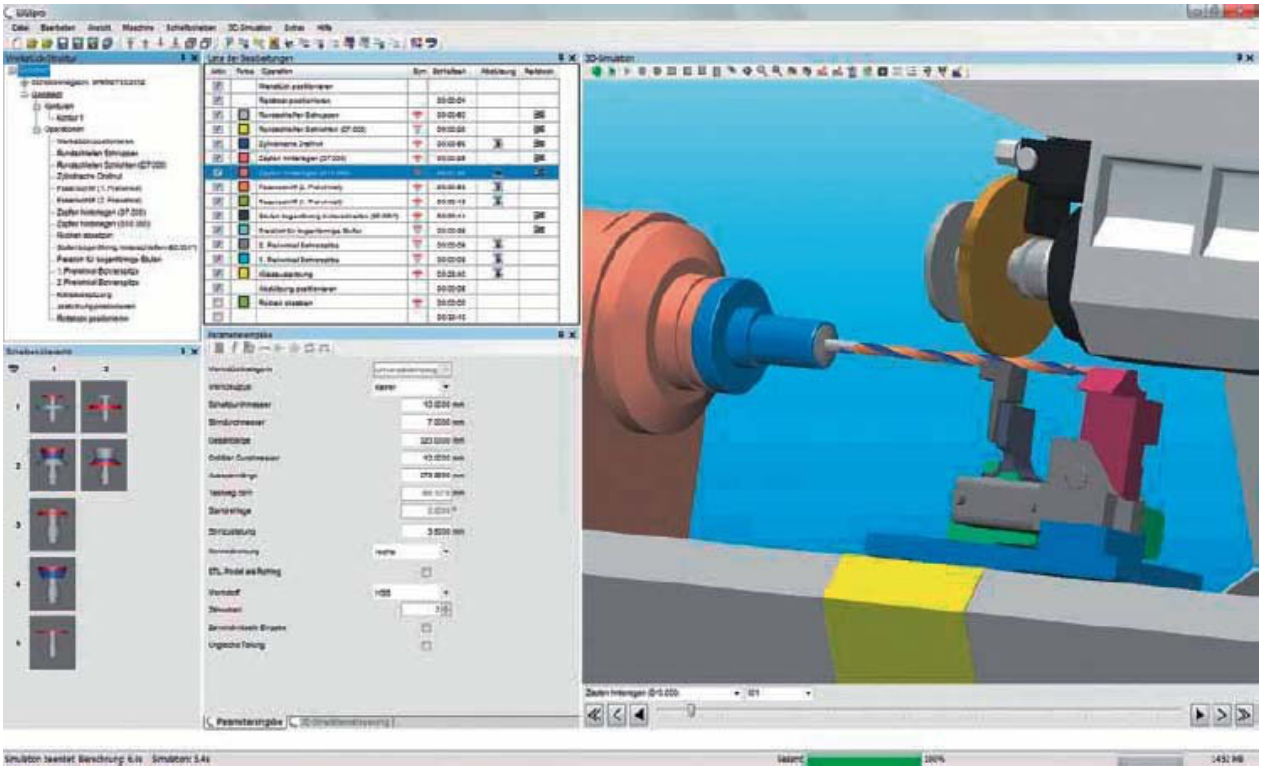

FIGURE 6.41 Technology-specific solution of an HMI. SIGSpro, Schüttle.)

The CNC operating interface Celos should be mentioned here as exemplary. The 21.5- inch touchscreen displays, apart from the actual CNC operation, a host of interesting functions such as a job manager for scheduling and managing jobs, a job assistant for defining and processing jobs, and a CAD/CAM viewer. Similar to consumer touch devices, these functions are offered as intuitively working apps.

Another example of a grinding machine shows the increasing use of touch panels for CNC machine operation. A Swiss company develops and manufactures high-precision grinding centers for the machining of indexable inserts out of carbide, cermet, ceramic, cubic boron nitride (CBN), and polycrystalline diamond (PCD). The current software generation expands the use of touch control so that an operation without additional mouse or keyboard is comfortably possible. The user interface is context sensitive. Depending on user level and context, only relevant input elements are available to the operator. It is possible to trigger safety-relevant functions on the touch panel with a proprietary user concept 6.42 and

FIGURE 6.42 The 21.5-inch touchscreen by Celos with many practical apps simplifies the integration of the machine tool and the internal processes. DMG-Mori.)

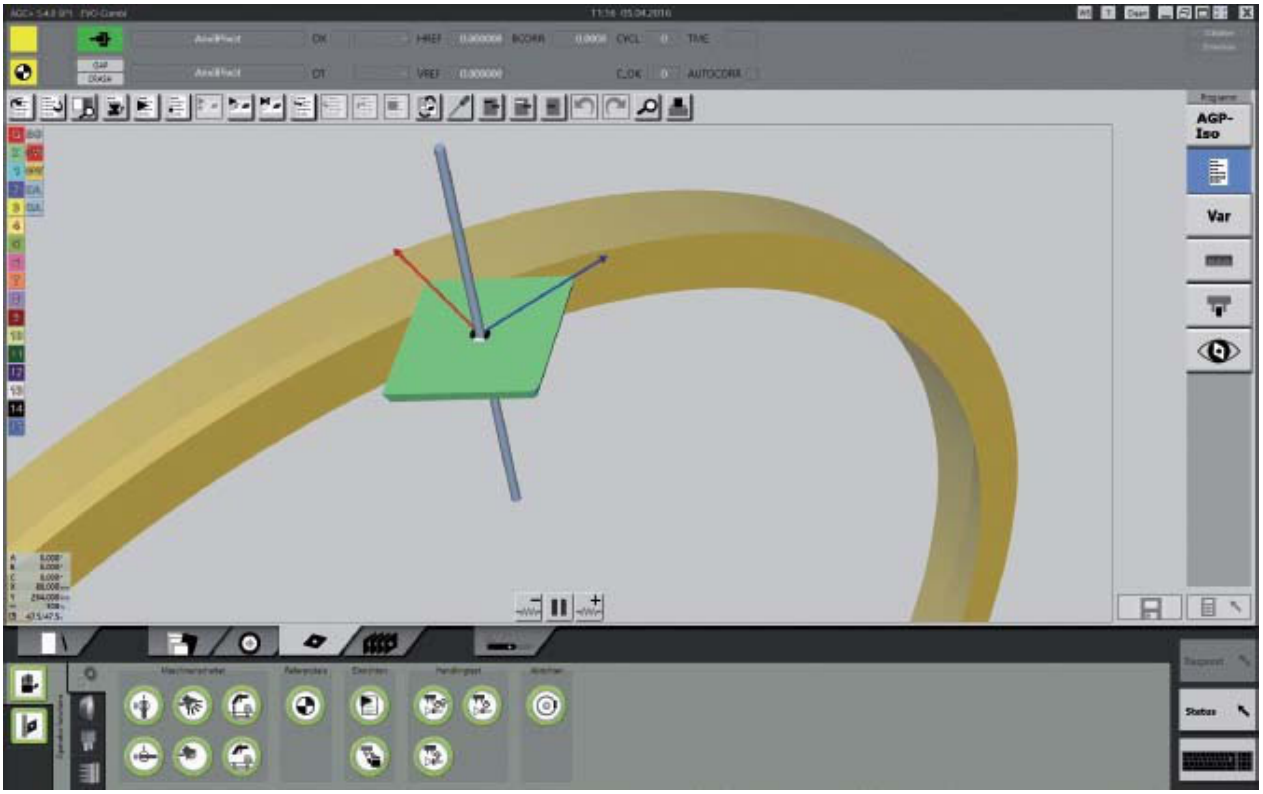

FIGURE 6.43 Dynamic grinding simulation. To investigate the geometric situation of the clamping, the 3D representation can be rotated and zoomed by means of finger gestures. The lower part contains the context-sensitive soft machine panel. Agathon.)

Touch panels can also be combined with conventional technologies, for instance, as an additional solution for operator control and monitoring of machine tools, next to the actual CNC operating panel These touch devices provide intuitive and easy-to-learn operating options that users, based on their experiences in daily life, are already familiar with. Information exchange between the CNC system and mobile devices is easy because of WiFi connectivity and various other wireless standards. This saves extra foot traffic; up-to-date information can be accessed quickly. In this context, safety aspects must be observed. If a CNC machine is operated via a touch panel, in addition to the secure data exchange between the CNC

system and the touch device, the safety of personnel and machine must be guaranteed. Signals such as “EMERGENCY STOP” or enabling buttons must be transmitted securely. Input gestures for touch-based operation, established in consumer devices, must not lead to uncontrolled moving of machine axes.

The end user augments the existing system with own written applications and defines macros, cycles, or operating masks for visualizing, controlling, and simplifying complex conditions on the pertinent machine The control manufacturers offer a variety of tools for support. The market today offers comfortable cycle editors or proprietary programming languages for interaction with an ASCII editor.

FIGURE 6.44 NC Touch offers a touch-enabled web-based application for presentation and preparation of the data from the Sinumerik 840D sl for mobile terminals. Mill IT.)

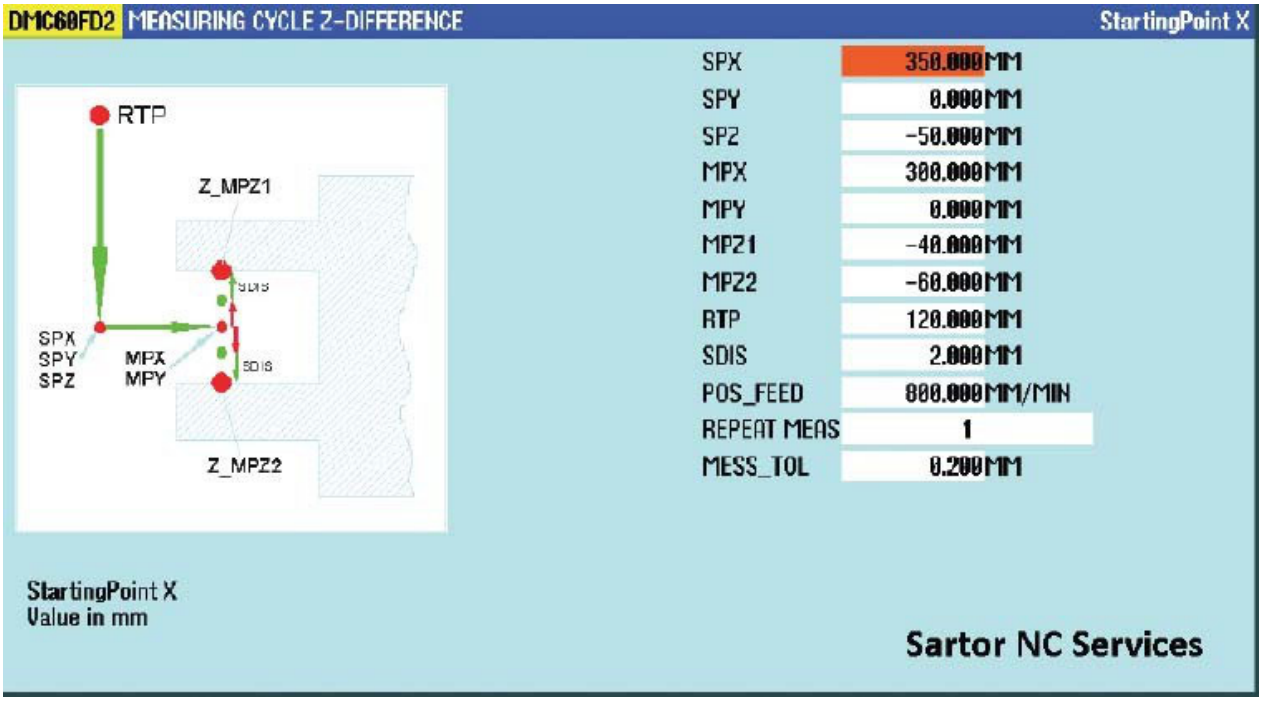

FIGURE 6.45 Customer-specific measuring cycle to measure a recess with a T-shaped probe. Sartor NC-DL.)

OPEN CONTROLS

The definition of *open CNC* has been discussed in professional circles for a long time. Finally, it has been agreed that there are several criteria for "openness" of a CNC system, all of which are of equal importance. Basically, one has to distinguish between at least six different characteristics of openness of a CNC system:

■ *Open to the operator:* providing graphic support, in order to enhance programming and machine operation

■ *Open to the machine manufacturer:* providing the option to offer custom user interfaces and displays

■ *Open in the hardware selection:* to be able to use components from different manufacturers

■ *Open in the choice of the CNC operating system:* to be able to use existing standard software

■ *Open regarding input-output interfaces:* for instance data or drive interfaces

■ *Open regarding the CNC kernel:* providing machine manufacturers with the opportunity to integrate their process know-how directly in the CNC system

Thus the idea is generally to make CNC systems more adaptable and more cost-effective, at least when it comes to input interfaces, through the use of series-produced computers and their associated standards

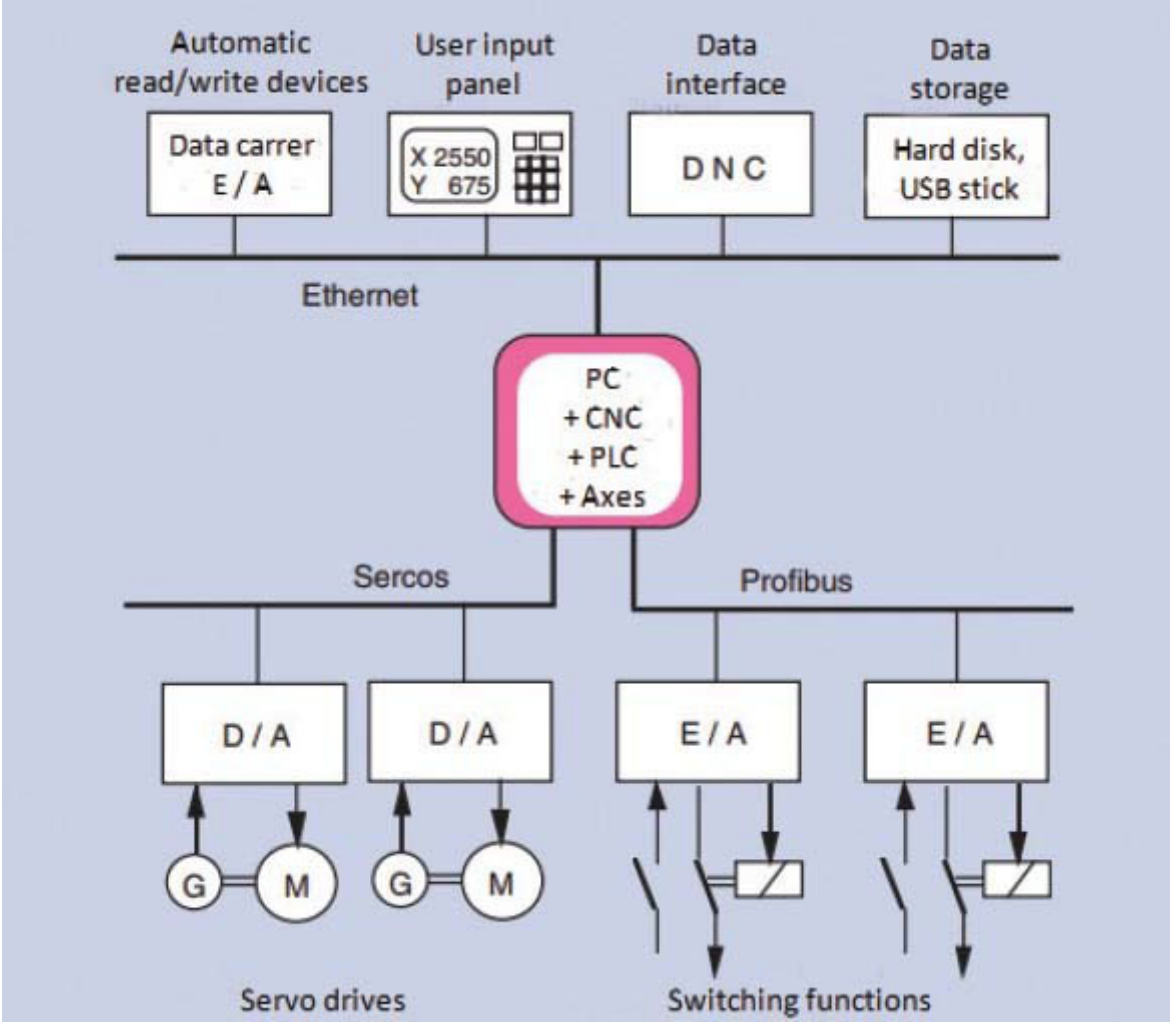

FIGURE 6.46 Principle of an open compact CNC system with serial interfaces (e.g., Ethernet, SERCOS, ProfiBus).

Today's CNC systems are almost invariably closed systems. Special hardware is controlled by specially developed software with special applications. There are no, or only a few, standards. Each function must be newly developed, even if such functions are

available in other areas or have existed in previous CNC generations. The consequences of this are high development costs, long development times, a rigid environment, and no room for individual solutions. Such solutions are too expensive!

Borrowing the term *open* from computer technology, an open CNC would be a numerical controller in which all software interfaces would be disclosed and described. This is comparable with computers that have an *open system* However, this definition is not sufficient for CNC systems.

After many discussions, the participants seem to come to an agreement to put a PC upstream from the CNC core controller This can bring significant benefits, such as:

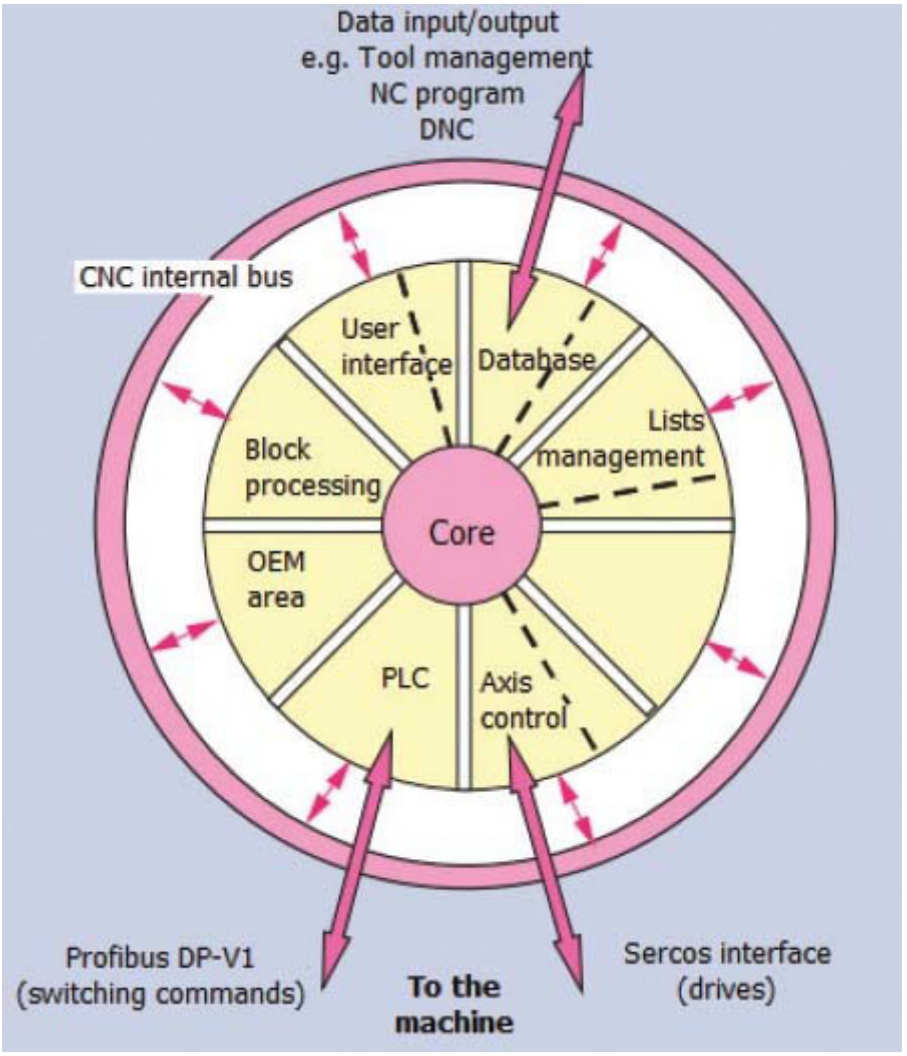

FIGURE 6.47 Principle of compact, open CNC.

- A simpler, cheaper standard CNC system
- To a large extent free design of the user interface
- Freedom to establish shop floor programming (SFP)
- Easier computer connection

■ Easy transfer of CAD data

■ Use of standard interfaces for peripherals, such as:

- Hard disk drives
- Memory cards
- Standard displays
- RS 232C or 242
- SCSI ports
- Ethernet

But even open systems have their own limits!

It must be understood that open CNC only comprises a share of no more than 20% specifically required functions. This leaves 80% functionality protected from customization—to the benefit of users. Because the availability of customization could have very detrimental effects, instead of the desired uniform standard control on all machines, there would be no limit to the variety of possible input and display options.

PRICE CONSIDERATION

The prices for numerical controls with comparable specifications have fallen by more than 90% within 20 years The price drop went along with an immense increase in functionality of today's CNC systems. Both machine manufacturers and users benefit from the emerging completely new machine concepts, which, in turn, increase productivity in the metal-cutting industry. Color displays with up to 21-inch screen sizes, simultaneously interpolating axes, a variety of transformations, integrated user interfaces and programming systems, tool management programs, flexibility of automation through open bus systems, data interfaces for networking, and almost unlimited expandable data storage are standard today.

FIGURE 6.48 Price development of numerical controls with constantly increased power compared with the development of wages in the metal industry. When setting the wages and the prices for NC machines at 100% in 1970, wages have risen until 2010 about 465%, yet the prices for NC/CNC machines dropped by 80 to 90%. At the same time the the weekly labor hours have been reduced. For many companies this was a great incentive to automate by investing in CNC machines.

Elaborate custom cabinets were replaced by small, freely programmable PLCs, and the entire control logic has been implemented in software. The software can be reproduced with speed, low cost, and no errors, saving time, effort, and money. With the use of *surface-mounted device* CNC technology experiences another innovation boost

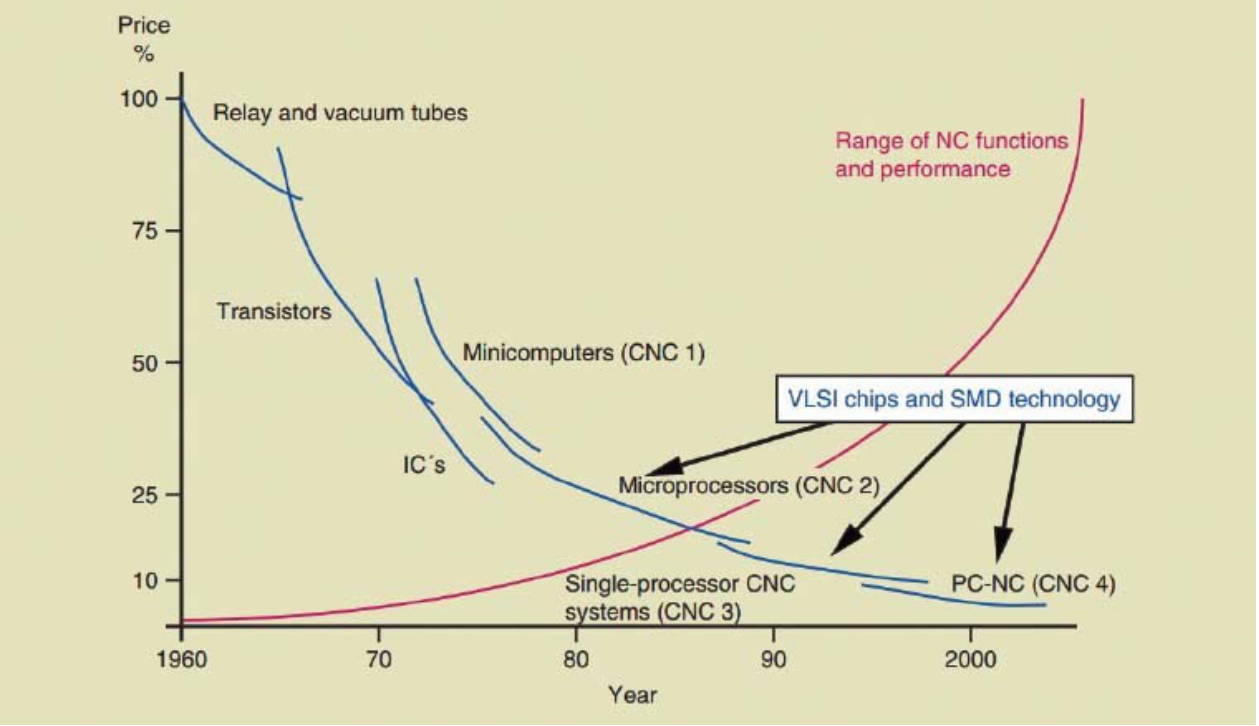

FIGURE 6.49 Price development of numerical controls by using ever more highly integrated electronic components.

Although many users frequently bemoan the limited lifespan of the individual control generations, on the other hand, they quietly accept the improved price-performance ratio as self-evident. The modern user also has ever-increasing demands. For instance, *high-speed milling* (HSM) is supposed to yield ever-increasing surface quality with equal or even shorter processing times. The call for higher productivity puts the topic of complete processing into focus. Consequently, machine concepts have been developed that combine various technologies in one machine, aka A CNC system, it is expected, should naturally meet the requirements of both the workshop and mass production.

The servo drives must be digitally controlled because analog technology is too slow and too inaccurate. These drives must have a contouring error near zero in order to have dynamic accuracy even at high speeds. These and many more requirements can only be met with powerful hardware. Even as the hardware costs are falling, the core knowhow of CNC machining lies in the system software. This means that for the time being, it continues to be impossible to use a cheap standard consumer PCs to satisfy all the demands of the CNC industry.

In general, manual operation of modern CNC machines is only used for setting up and touching off tools. This alone is evidence of the high technical performance of numerical control.

Development of Processing Power through Higher Integration

Moore's Law

Gordon Moore, one of the founders of Intel, predicted at the beginning of chip development that the number of transistors on a chip would double every 18 months. Naturally, this trend will come to an end, by reasons of either economy or physics, and this could be by 2020 or so. Then the chip structures should only have a dimension of a few atoms per transistor

ADVANTAGES OF NEWEST CNC DEVELOPMENTS

All required hardware and software functions are integrated in one central module in the control cabinet:

■ High-performance processors ensure the shortest CNC and PLC cycle times.

■ Despite its compact design, the expansion capability is always guaranteed with the help of the drive bus system.

■ New technologies ensure the highest reliability and manufacturing accuracy—with qualities in the nanometer range.

■ HMI software provides, without an additional operating PC, intuitively operable display output for all operating situations.

■ Convenient editor functions ease CNC programming and testing. The HMI software is multilingual, and switching the language takes place without restarting the CNC system.

■ Integrated user management prevents expensive downtimes caused by incorrect operation.

■ Alarms and messages are put out in plain text and recorded in an integrated log.

■ Programs and parameters can be stored with the push of a button on a USB stick or network drive.

■ Compressing the hardware while increasing functionality will continue

■ The networking of production facilities opens up new possibilities for the use of CNC systems. Data interfaces and software packages support the integration of CNC machines into global production networks.

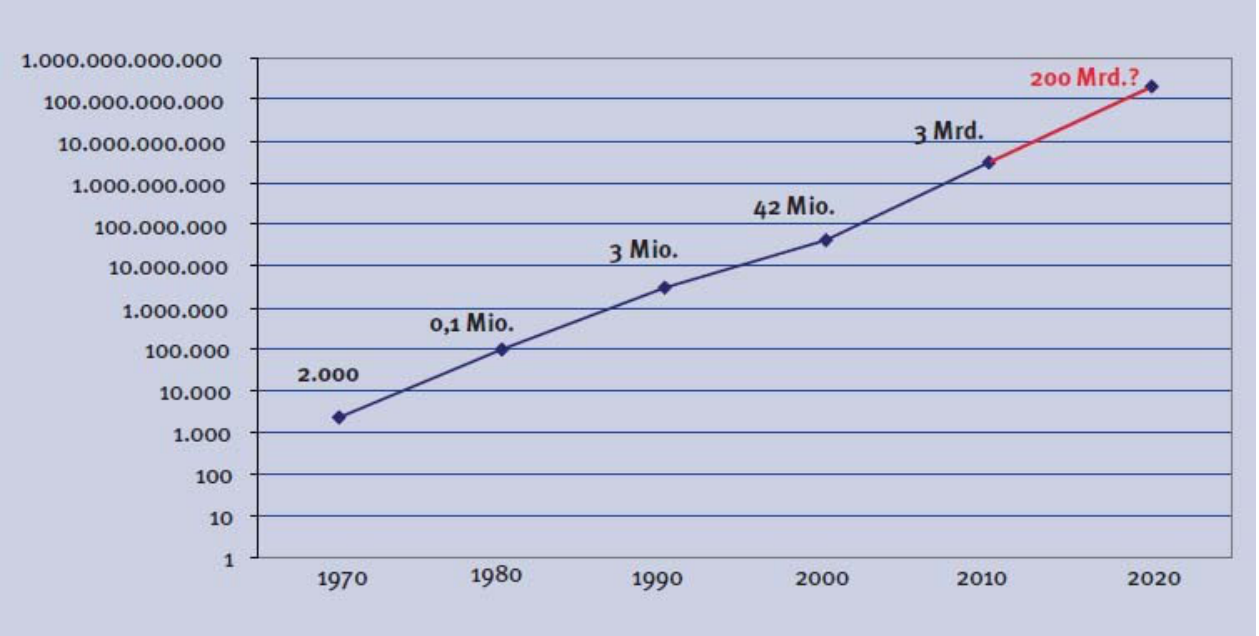

FIGURE 6.50 Development of number of transistors per chip. Wikipedia.)

SUMMARY

CNC systems are special, powerful electronic controllers with integrated process computer functions. CNC systems make it possible to fulfill almost all the requirements of modern users regarding functionality, reliability, accuracy, speed, and safety of machine and CNC system. In the span of only a few years, simple, numbers-comprehending machines have morphed into data-processing manufacturing systems with an arbitrarily adjustable degree of automation. The open CNC is destined to provide additional options to the operation for acceptable costs. But beware, the user is increasingly seeking the universal standard CNC system!

The tendency for more machine-based intelligence was only made possible through CNC systems and will continue. Today's generation of CNC systems is comparable to PCs or exceeds them particularly in terms of data entry, management, and storage. In addition, given their constantly improving electronic components, CNC systems are becoming faster in processing, more flexible in customization, and more universal in application possibilities. On top of this, machine manufacturers also can develop proprietary software applications.

Another task with constantly developing new requirements is the IT connection of the CNC systems with the transmission of CNC programs, drawings in CAD, test plans, quality assurance data, MDE/PDA data with evaluation, service, maintenance and

diagnostic data via Teleservice/internet, and so on. In the broadest sense, all information that is available in databases and useful for production preparation, process, and improvement can be made available through network connection to the CNC system. PCs connected to the internet, new CNC functions, and software updates can be installed via the data network in the CNC system. Because of the increasing use of standard PC boards or special PC/CNC cards, all necessary procedures can be easily performed by PC-literate personnel. On this basis, the useful lifespan of a CNC machine generation can be extended compared with earlier CNC systems

FIGURE 6.51 Modern CNC machines provide great ease of use for shop floor programming and quick, dynamic processing of part programs. Siemens.)

A software architecture that is consistently user oriented offers wide-ranging openness in all functional areas. Function libraries and software components based on the Windows operating system

enable users to create their own customized operating and programming interface for their “own” CNC machines. In this way, process-specific optimization can be generated by adding or adjusting existing functions.

IMPORTANT POINTS TO REMEMBER

1. A CNC system is a numerical controller in which all switching functions can be realized through one or more integrated microcomputers and appropriate software.

2. Modern CNC systems have the following characteristics:

a. A program memory with almost unlimited expandability

b. Storable tool data with automatic administration (tool life, wear)

c. Specially adaptable and expandable functionality

d. Measurement cycles with probes and evaluation programs and documentation of safety-relevant measurement data of workpieces

e. Typically an integrated machine-specific programming system for programming the machine

f. Data interfaces with connection to a network, e.g., Ethernet

g. Dedicated space for customer-specific functions and expansion.

3. CNC systems with a modular design offer many functions and options. The end user must decide which configuration is the

right one for the jobs at hand.

4. SFP-capable CNC systems offer very powerful, graphically supported programming aids.

5. CNC systems have several different and expandable data storage options for:

a. The operating software

b. Parts programs with automatic reloading

c. Fixed and fee cycles

d. Integrated user guidance

e. Diagnostics software and trouble-shooting wizards

f. PDA/MDA data

g. Alerts and error messages in text form

h. Tool management and pallet management

i. Zero-point offset, tool wear compensation, tool offset data

j. Machine parameters and more.

6. Available interfaces to connect appropriate peripheral devices are of great importance.

7. Important criteria for the speed of a CNC system are data transfer rate, computation speed, block cycle time, servo sampling rate, and cycle time of the PLC. Modern CNC systems often combine CNC, PLC, and drive functions (control circuit connections) in one unit.

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DEFINITION

PLCs are controllers with a computer-like structure for use in industrial environments to implement certain tasks and functions, including sequence control, logical operations, time and counting functions, arithmetical operations, spreadsheet management, and data manipulation. They vary according to their level of performance but are always structured with "neutral" wiring. Like computers, they consist of a central processing unit (microprocessor), program memory (RAM, EPROM, or FEPROM), input-output (I/O) modules, and interfaces for exchanging signals and data with other systems.

The logic controller is programmed using PCs and a system-specific programming software. Input can be in the form of a ladder diagram, instruction list, or function block diagram or by means of graphically supported languages or higher-level programming languages (e.g., Structured Text). All these use the graphical support for programming and simulation of the generated switching functions.

For economical CNC systems, the motion control for the NC axes and the PLC functions are combined, creating an integrated software PLC that is controlled by a common processor. The previously preferred method of distributing higher tasks such as processing speed and scope of functions to a processor and a coprocessor is no longer practical in today's control systems. Efforts to create uniform and international standards for PLC

programming languages are documented in International Electro-Technical Commission Standards IEC 1131 (in Europe IEC 61131).

ORIGINS OF PLC

In 1970, a new type of electronic control system was presented for the first time at the machine tool trade show in Chicago and immediately attracted great interest. While up to that point machines had been controlled using relays with complicated wiring, contactors, or electronic function modules, this new control system had been developed from computer technology and had completely new characteristics. The essential feature was that the control logic was no longer "hardwired" but was rather "freely programmable" like a computer. This was done using a computer-like programming device and a programming language developed especially for that purpose. During commissioning, the control program remained in *random-access memory* that could be changed quickly. Once the test phase was complete, the program was transferred permanently to *erasable-programmable read-only memory* Any subsequent changes that became necessary could be made in the same manner without any complex changes to the wiring. The resulting advantages, such as the smaller size of the controller, commissioning time, and ease of modification, were so attractive that the only obstacle to immediate success was the high price tag.

The similarity to numerical controls— which were also quite new at that time— was unmistakable. The continually increasing requirements regarding automation were so complicated and difficult to implement in terms of control functions that these PLCs were put into use very quickly, especially in conjunction with complex CNC machines.

Thus, in just a few years, a large number of new PLC products appeared on the market, many of which were designed for special applications. Unfortunately, the positive experiences that had been gained with the timely standardization of CNC technology were not put to use here. As a result, there is no uniformity in the programming of PLCs from different manufacturers. This means that the programs that are created are PLC specific and will not run on PLCs from other manufacturers. The now-proven principle of object-related "neutral" NC programming and subsequent controller-specific adaptation via postprocessors was never realized with PLCs. The manufacturers put most of their efforts into designing new types of programming to suit the skills and wants of employees in electronics departments; no priority was given to universal PLC programming. In retrospect, the fact that comparable systems were "speaking different languages," as well as the high prices for the programming devices, resulted in a delay in market introduction. The IEC 1131 standard is a first step in the direction of universal PLC programming.

STRUCTURE AND FUNCTIONS OF PLCs

Figure 7.1 shows the basic structure of a PLC. PLCs consist of the following functional modules: the power supply unit, central processing unit, program memory, generally several modules for inputs and outputs, various additional functions (e.g., markers, timers, counters, or axis modules), and a rack on which the modules are mounted. An interface or coupling module serves to connect the programming device and to interface with the periphery, typically an Ethernet interface. Either direct I/O modules or a suitable field-bus interface are provided for control of the actuators and sensors.

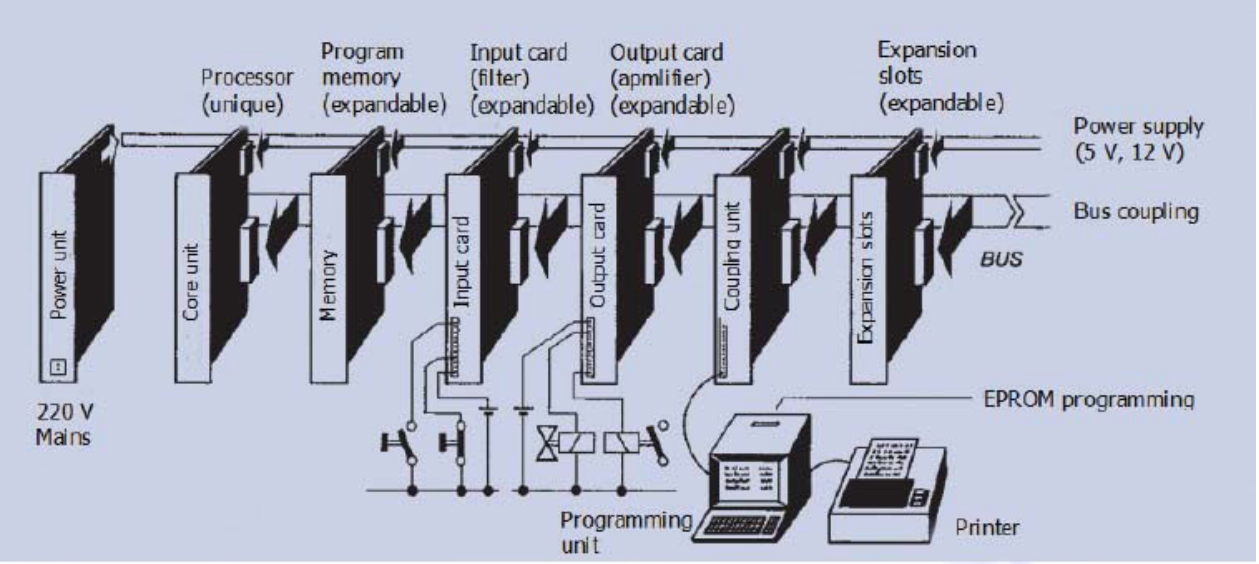

FIGURE 7.1 Principle of the individual modules of a PLC. Today, the entire electronics components fit on one circuit board.

All PLC hardware modules are connected to the power supply and the internal system bus when they are plugged into the module rack. The system bus consists of a number of parallel connecting cables

and is subdivided into the address bus, the data bus, and the control bus. Data transmission between the individual modules is organized and monitored by the control unit of the CPU.

In CNC-coupled PLCs, the hardware structure has changed greatly as a result of advancement in electronic components. The functions of individual plug-in modules for data I/O, data processing, and time and counter functions have all been taken over by the CPU. This created highly integrated one-board controllers in which the CNC system, the PLC, and the output of axis command values all were combined on the same circuit board Such circuit boards generally can function in any PC with a Windows operating system. A field-bus interface is available for connection to the decentralized peripherals; the servo drives are connected via a special interface (e.g., SERCOS interface). The axis control circuits, that is, position controllers, speed controllers, and current controllers, are located in the decentralized drive amplifier.

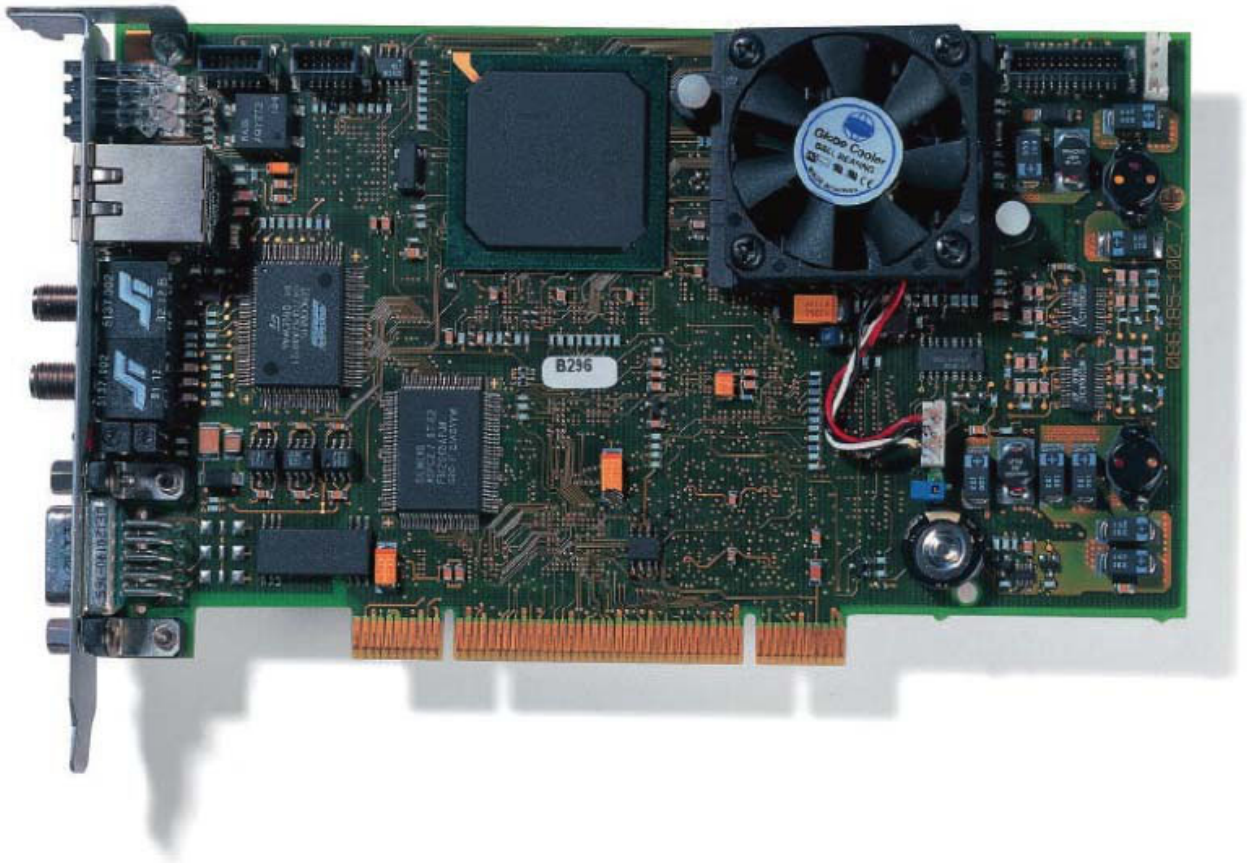

FIGURE 7.2 Single-board solution: PCI bus plug-in card with MC, CNC, and PLC functions, plus TCP/IP, PROFIBUS DP, and SERCOS interfaces.

The connections for monitor and keyboard are provided as standard on *industrial PCs* These are PCs that have been constructed for installation on shop floors, with a rugged metal housing and easily accessible interfaces.

In principle, PLCs fulfill the same tasks as controllers that are constructed based on relays or electronic functional modules:

- Receiving command input and feedback

- Linking, branching, and blocking these according to a predetermined programmed matrix

- Using this matrix to generate the corresponding control commands and outputting them to the actuators

Process Monitoring

In modern machine tools, PLCs are also used to monitor the process itself. In higher-priority program sections, various CNC data are monitored, for example, in order to detect tool breakage within a fraction of a second and to quickly move the machine head away from the workpiece in the right direction before further damage can occur.

Additional sensors monitor temperature, oil pressure for lubrication and hydraulics, and other functions. Depending on the kind and size of the deviation, error messages are activated or the machine will be shut down.

Generally, it is possible to define two different areas of application for PLCs in machine tools:

1. *Program* These control, without support of the CNC system and based on a fixed, defined special program, repetitive sequences in machines, such as the changing of workpieces, speeds, and feed rates on automatic rotary index machines. The signal for proceeding is only given after all processing stations have returned to the home position.

2. *Machine control* These are connected between the CNC system and the machine and have the task of transmitting all the switching functions output by the CNC system to the actuators. This happens with regard to certain conditions because all motions must not endanger personnel, the machine, or the workpiece. This *monitored function control* can include, for example, the automatic processes for tool changing, pallet changing, or handling other process-related equipment. Thereby the entire sequence of functions is predefined and merely triggered by the CNC system by means of an output signal. After all functions have been carried out and the process is completed, a signal from the PLC is put out to the CNC system for continuation of the machining program.

Similar tasks also apply for setup and manual operating modes, where the commands are issued manually by the operator.

In the case of large production plants, the control functions can be distributed among several PLCs. This is called *multiprocessor PLC* and has the advantage that the individual system components can be tested independently of each other. Depending on the specific configuration, subsequent data communication takes place either directly, within the rack, or via a network, with field bus or Ethernet.

DATA BUSES AND FIELD BUSES

In the course of the advancement of PLC systems, it was very important to take the constantly increasing volume of data traffic into account. Today's control systems make use of the technical and cost advantages of bus connections. These consist of one or more parallel connecting cables and provide bidirectional data transfer between multiple "devices" in a system. It was soon realized that it was not possible for one single bus system to cover all the diverse tasks and requirements in the field of manufacturing, and thus various tasks were distributed among a number of different bus systems

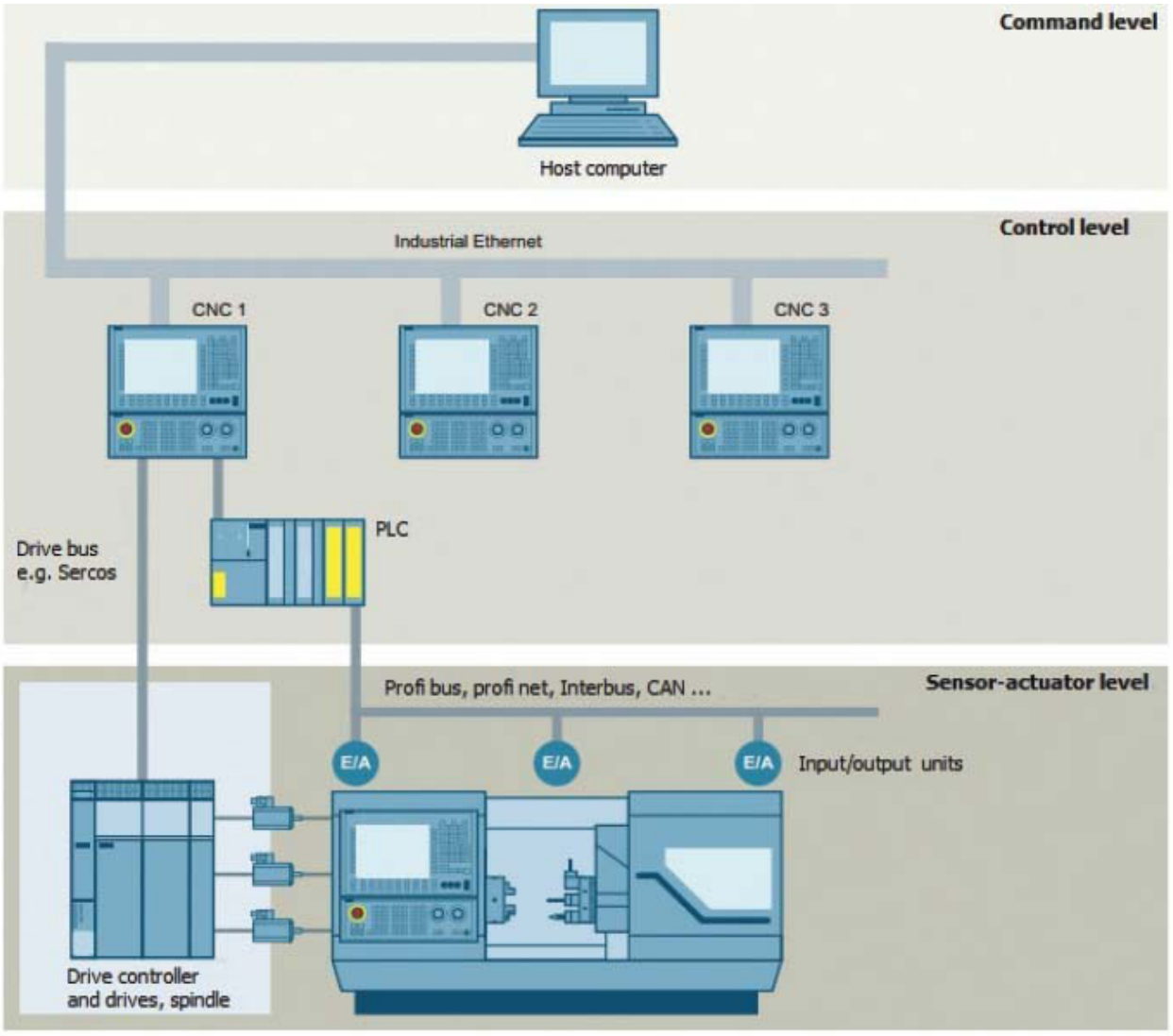

FIGURE 7.3 Use of various bus systems from the host controller to the machine.

Ethernet has become the preferred data bus and is now regarded as the industry standard. At present, it uses a data transfer speed of 10 or 100 Mb and can reach 256 or more connected devices directly, depending on the address configuration.

The physical transmission medium involves special four twisted-pair cables with eight-pole standard connectors. In today's industrial installations, the singlecable principle is no longer used but rather proven network technology, where each device is connected to a switch. Up to 24 devices can be connected to each switch. The advantages of this are that it is possible to transmit large data packets between devices in each switch while using the full bandwidth. Second, the functioning of the overall system is not endangered if there is a malfunction in one of the devices, and troubleshooting is made easier.

Special backup procedures make data transmission within a network absolutely reliable. Special field bus systems, such as PROFIBUS, InterBus, and CANbus, have been developed for signal transmission, that is, for the control of actuators and the feedback of sensor signals.

Fiber-optic cables are preferred for the SERCOS bus, which is available especially for controlling servo drives. Fiber-optic, in contrast to copper, cables avoid all electrostatic and electromagnetic

interference in the signal cables between the CNC system and the drive control.

The use of bus connections instead of complicated individual wires minimizes not just the number of cables and contacts but also the number of potential sources of malfunction. Which bus is best suited for the individual tasks depends first of all on which "level" of the automation pyramid corresponds best to the requirements. The top level involves a small number of non-time-critical data, whereas the requirements are reversed on the lower level: constant transmission of time-critical data packets for open- and closed-loop control of the process.

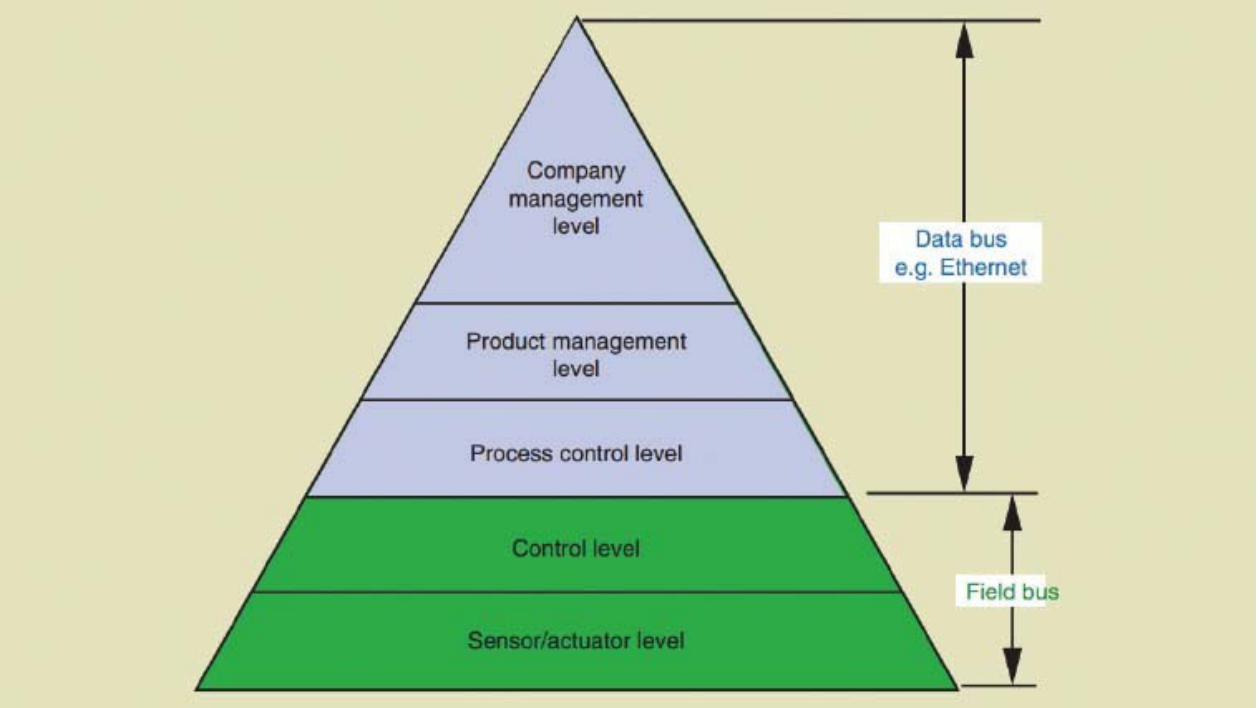

FIGURE 7.4 The automation pyramid represents the various levels of automation. Field bus systems are used for the control and sensor/actuator levels in combination with PLCs.

The typical requirements for a bus are as follows:

- The maximum number of devices (actuators and sensors)
- The required longest response times (short reaction times)
- The scope of the data being transmitted
- The maximum transmission distance

The control level uses Ethernet, which is the worldwide standard with the widest distribution. The required interface modules are small, inexpensive, and widely available.

The strengths of the field bus systems CAN, PROFIBUS DP (decentralized peripherals), and InterBus-S lie primarily in the sensor/actuator area. In contrast, Profibus FMS is suitable for higher levels, that is, larger data packets, but is increasingly being supplanted by Ethernet. When establishing networks for large plants, the use of fiber-optic cables is preferred because of the long distances that have to be covered and in order to avoid interference.

Real-Time Ethernet and SERCOS III

Many companies use a number of networks that either cannot communicate with each other at all or only with great difficulty. It would be useful if a machine could report errors not only to the personnel at the machine but also to production planning systems, material management, and the manufacturers of the machine and/or controller. A direct link between the developer PC and the CNC

system of a production line also could be used to transmit software updates faster and more cost-effectively.

For this reason, companies are relying more and more on a uniform protocol for communicating information between various divisions. Ethernet and TCP/IP have become standard for data transmission while also forming the basis for internet and office communications.

Because factory automation sets high requirements in terms of ruggedness, reliability, and security in information networks, Ethernet on the production floor differs somewhat from Ethernet in office environments. Industrial Ethernet has to fulfill three important requirements:

1. The most important requirement is real-time communication in order to ensure that important information is transmitted immediately or at the required time intervals. This is the only way to coordinate complex sequences.

2. The second important characteristic is reliability. Heat, dust, vibrations, and strong magnetic fields can induce currents in unshielded cables, thus causing transmission errors. Wherever parts are in motion, there is always the possibility of broken cables. None of these effects must endanger the reliable, error-free transmission of data.

3. The same applies for security against external access. On the one hand, simple communication is desirable, but on the other hand, unauthorized access to production systems must be prevented. To

ensure safety for the machine and personnel, secure data transmission using a certified safety concept is essential (e.g., SIL3 according to IEC 61 508).

Real-Time Ethernet Solutions

The term *industrial Ethernet* in practice can stand for various solutions that differ greatly from each other. Some systems may offer real-time functions but with limited synchronicity; that is, there is no guarantee that a number of connected modules will work at the same system cycle rate. Others are based on a close connection between the control and network functionalities, which limits the user's choices when selecting automation systems. Yet others are in fact open but require rigid network planning with a large number of control units that make it difficult to make changes later and sometimes make even simple, standard communications very slow.

Today, field buses and industrial Ethernet systems offer basic functions that can be used to perform typical control tasks. Real-time applications that require, for example, precise interaction between a number of servo motors or that have to process sensor data very quickly have to have a network with a very high data throughput and guaranteed synchronicity. Fast Ethernet with a data throughput of 100 Mb/s guarantees the fast transmission of information. The full-duplex property of fast Ethernet means that it is also possible to communicate directly between the connected devices in order to make response times as short as possible.

Seamlessly Integrated Information

At the field level, that is, the communication between individual drives, sensors, or CNC systems, SERCOS III, because it was designed for demanding CNC applications, guarantees the necessary

precision. At the same time, it is extremely simple to link the network to the higher control level.

The user can use real-time data and the full functionality of TCP/IP data transfer via a non-real-time channel. In this way, for example, a webcam can be used for production monitoring via the SERCOS protocol without compromising the real-time function. This allows comprehensive system planning without additional wiring and related costs. Various modules can even use the same wiring without any compromises regarding security or reliability.

SERCOS III relies, as did previous SERCOS generations, on proven hardware synchronization that is implemented using *application-specific integrated circuits* The design of these makes additional hubs and switches as expensive switching points superfluous. Synchronicity is thus a basic characteristic of every SERCOS solution and requires no additional modules or protocols.

The cycle time of 31.25 µs in real-time operation does not mean that any individual module would demand the entire bandwidth for itself alone. Up to eight drives can receive and transmit 8-byte cyclical data in motion-control applications. This is sufficient for even the most demanding tasks that can be imagined today in the field of mechanical engineering. Even fast, high-precision modern CNC machines are operating with minimum cycle times of not more than 500 µs. Thanks to the high efficiency of the SERCOS technology, there should be no applications in the foreseeable future that would require a higher network speed.

Flexibility is a basic requirement in production environments, and industrial Ethernet is a suitable component that helps to coordinate

planning and manufacturing while avoiding long lead times. In practice, however, modern networks have to meet even more demanding requirements. Intelligent CNC systems make it possible to recombine machines to suit specific requirements, thus grouping individual units to form new cost-effective solutions. This requirement places high demands on the flexibility of the network. Generally, individual components, also called are controlled by a unit, or The typical linear structure of a production section is derived from this. The individual CNC machines, in turn, can communicate with each other over a common network segment.

Direct data exchange is also possible between a sensor and a drive controlled by different control units. This reduces the load on the central controller and decreases the data traffic in the network. So-called control-to-control (C2C) cross-communication between masters, such as two PLCs, for example, is the basic principle for the decentralized control of complex manufacturing systems. This flexibility in communication, which leads to shorter response times between master and slave devices and thus also shorter response times in the overall processes, ensures constant synchronous axis control even over multiple SERCOS networks.

The technology that enables cross-communication between individual nodes not only contributes to the efficiency and flexibility of SERCOS but also increases security because SERCOS III networks can be created with a ring structure. This provides a redundant signal path in the event of a broken cable. The SERCOS network coordinates itself and offers a flexible choice of strategies: a classic linear structure to save materials or a redundant ring structure to increase safety. Engineers and planners can choose the appropriate

cabling for their specific requirements without having to consider additional elements for the network infrastructure.

Standardization

Since October 2007, the SERCOS III real-time Ethernet solution has been a component of both the binding International Electrotechnical Commission (IEC) standards. This confirms the worldwide importance of the SERCOS interface, for SERCOS II had already been standardized worldwide. In a parallel step with the standardization of the third-generation SERCOS, the IEC also decided to transfer the existing IEC 61491 standards from SERCOS II to the new IEC 61158/61784-1 series of standards. The SERCOS drive profile also was included in the IEC 61800-7 standard.

The same applies to the safety of data transmission. SERCOS inherently provides a certified safety protocol to ensure that information is transmitted securely. SERCOS safety meets the requirements of safety standard IEC 61508 up to safety integrity level 3 (SIL 3). This covers risks due to system failures that could lead to personal injuries and material damage. Previously, this required separate wiring. With SERCOS III, all safety-related information can be transmitted over the existing data cables, thus guaranteeing that the power supply will be cut off immediately when the "EMERGENCY STOP" button is pressed, for example. This elimination of additional hardware reduces costs with no loss of safety.

SERCOS safety is protected against possible errors such as repetition, loss, insertion, incorrect sequences, corruption, delay, and interchanging of safe data with standard data. The safety protocol has been certified according to IEC 61508, and it has been tested by the technical inspection authority (TÜV) for satisfying safety

requirements. For safe data transfer, SERCOS safety uses the *Common Industrial Safety Protocol* of the Open DeviceNet Vendors Association (ODVA). This is used by various communications standards such as DeviceNet, ControlNet, and Ethernet/IP and allows users to employ the same safety mechanisms on various platforms. This allows the seamless connection of multiple CIP-based networks.

Advantages of SERCOS

The combination of high performance, flexible use, and verified safety allows SERCOS III to satisfy all the requirements for a modern integrated automation network. Suitability for everyday use is provided by the proven capabilities of the SERCOS protocol, and the real-time Ethernet solution offers future compatibility. Because of fast Ethernet and synchronous cycle times of 31.25 µs, SERCOS III features very high-performance data and can handle even very complex automation tasks. For example, up to 330 drives with 4 bytes of I/O data and eight digital I/Os, respectively, can communicate with each other in a cycle of a millisecond. SERCOS III's performance thus already exceeds the requirements of today's advanced production machines. What is more, SERCOS III allows quick processing of process data via decentralized I/O modules in central control systems.

ADVANTAGES OF PLCs

At first, PLCs were relatively expensive and complicated to program and had limited performance. Therefore, they were initially used mainly on prototypes, custom-built machines, and special-purpose machines, which, based on experience, would involve large-scale changes in the wiring during the commissioning and test phases. The first experiences with PLCs were not particularly spectacular, but their potential to save time and costs was recognized. Continuous increases in performance combined with reductions in price and space requirements have resulted in PLCs being used in more and more areas. For simpler applications, compact devices with a limited number of inputs and outputs will suffice. Where demanding performance requirements have to be met, PLCs are available in a graduated range of different sizes, with a large number of I/Os and a comprehensive set of instructions.

Today's PLCs have major advantages over relay-based control systems or earlier electronic digital control systems. These include the following:

- Compact installation space, smaller control cabinets

- Elimination of extensive wiring through the use of data and field buses

- Significantly lower power consumption and heat generation

■ Greater reliability, for example, no switching contacts, fewer cable connections/contact points, longer service life of electronic modules, wear-free software

■ Online correction of the PLC program without interrupting operations

■ In series-produced machines, the PLC program can be copied with no changes

■ Shorter switching and response times

■ Remote diagnosis and troubleshooting via internet/Ethernet connection

■ High-performance laptops can be used for programming

■ Automatic documentation instead of individually created circuit diagrams

■ Integrated automatic function test software with error message displays

■ Overall significantly lower time and cost requirements

Today, PLCs are an indispensable component in almost all industrial machines and plant components. The basics and use of PLCs are already being taught in vocational and technical schools, with advanced training being offered by the manufacturers. Trained personnel are absolutely essential for programming, deployment, and connection of PLCs, as well as subsequent troubleshooting.

SERCOS III interface offers numerous advantages:

■ SERCOS is a worldwide standardized interface for digital communication between CNC systems and field bus participants (IEC 61491 and EN 61491). It synchronizes, with high precision and in real time and controls servo drives, inputs and outputs, frequency converters, encoders, and so on.

■ SERCOS I and II use a fiberoptic ring as a transmission medium. SERCOS III uses Ethernet for communication.

■ SERCOS III operates at the fast Ethernet speed of 100 Mbps.

■ Random Ethernet-based protocols can be transmitted in parallel with the real-time data without affecting the real-time characteristics.

■ Direct cross-traffic. Any number of participants can directly communicate with each other within a communication cycle with minimum communicative delay time.

■ Freely selectable cycle time. The communication cycle can be varied between 31.25 µs and 65 ms.

■ Synchronicity in the submicrosecond range

■ For highly available automation solutions, SERCOS III automatically ensures, when using the ring topology, that cable breakage or node failure can be reliably detected and the communication capability maintained

■ The necessary time for detection and response to a cable break is a maximum of 25 µs, so at most the data of one cycle are lost. Then the communication is continued undisturbed.

■ The synchronization is maintained in case of redundancy with the same quality.

■ Safe and nonsafe users can be mixed in a network without affecting the security technology.

■ Centralized and decentralized control architectures are supported.

■ Devices can be arranged freely within the network.

■ Line or ring topology can be used. In addition, hierarchical, synchronized, and real-time coupled network structures can be realized.

■ The protocol automatically detects where in the topology the device is connected. This allows a simple localization of the affected device in case of the need for service.

■ Wiring is easy as well because the physical order of the devices must not be maintained. Also, the wiring order of the two SERCOS III ports on the device does not matter.

■ In CNC technology, mainly the digitally controlled servo drives are connected via SERCOS interfaces in order to achieve high dynamic and static precision.

■ There are more than 80 suppliers of SERCOS interface products worldwide.

PLC PROGRAMMING AND DOCUMENTATION

With PLCs, as it is with CNC machines, cost-effective use depends heavily on the capabilities of the programming system and the programming language. This requires user-friendly programming, all the functions have to be programmable, the programs that are generated have to be error free, and it should be easy to make modifications.

Although initially attempts were made to standardize programming, first with DIN 19 239 and later with IEC 1131, even today, programs are specific to the individual PLC and not interchangeable. Programming with the use of symbol keys and function keys is adequate for simple, low-cost applications. Experience has shown that this does not present major difficulties to the user as long as he or she has experience in working with relay-based control systems. The display of the ladder diagram during programming is very similar to traditional circuit diagrams. Given its limited range of functions, however, this method is not suitable for complex machine control systems.

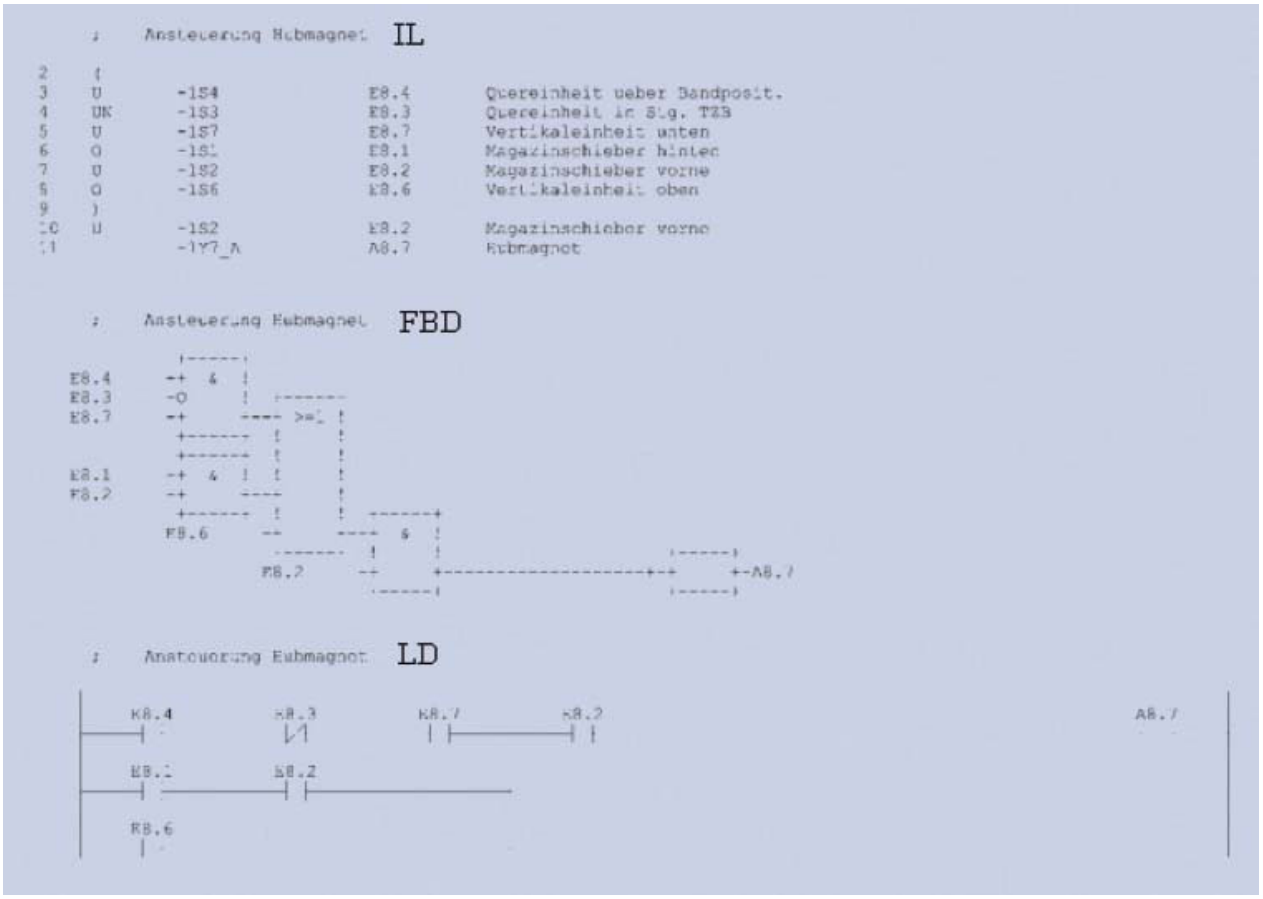

FIGURE 7.5 Programming and documentation of PLCs as an instruction list (IL), function block diagram (FBD), and ladder diagram (LD).

PLC programming for machine tools is much more complex and requires Windows-based computers. The PLC programming software is supplied by the PLC manufacturer. In the early days, there was a need, now overcome, to use a manufacturer-specific programming device for each PLC. This also removed a long-standing obstacle that prevented the quick dissemination of PLC systems

Using a laptop for PLC programming provides a number of other advantages, such as:

- Universal, portable, and complete mobility

■ Paperless documentation, always up to date and related to the specific system

■ Built-in software help, available on the spot

■ Automatic documentation of all changes

■ Trouble-free data management, for example, documentation on a central computer via a standard Ethernet interface

■ Replacement of manuals, drawings, instructions, and hand-written notes about changes

The Windows operating system provides a number of options for PLC programming:

■ According to IEC 1131 (IEC 61131 in Europe)

■ In the high-level language C or using *Structured Text* primarily for mathematical tasks

■ As with older devices, according to DIN 19 239, as:

- IL = instruction list

- SFC = sequential function chart

- LD = ladder diagram

- FBD = function block diagram

Of these, ST, IL, and SFC are classified as *textual* whereas LD and FBD are *graphical* All these languages are included as standard in today's PLC programming systems. It is important for the user to select a PLC that includes the required scope of functions and that also offers personnel the benefit of being able to convert existing circuit documentation into PLC programs without any major difficulties. All systems provide the advantage that when input is made in one form, the other form appears simultaneously. This means, for example, that during programming of an instruction list, a ladder diagram is generated, and it is possible to switch from one input mode to the other.

Once the program has been created, the user expects further support from the programming system, such as:

■ Depiction of the IL with all comments and device designations

■ Depiction of assignment lists, which show how the connections are assigned

■ Depiction of cross-reference lists, in order to determine which input or output is being "talked to" at which address

■ Depiction of the ladder diagram, which contains the configuration and designations of the contacts, as well as additional written information

■ Support when troubleshooting by showing individual steps, interrupt points, display of memory contents, and so on

■ Archiving of PLC programs

A significant advantage of so-called mnemonic languages is that they do not limit the performance of the PLC in any way. Programming languages based on Boolean operations are no longer offered today.

PROGRAM

The logical connections between the variable input signals and the output signals that are generated in an electric circuit are conventionally depicted in an electrical circuit diagram. Using Boolean algebra and the appropriate mathematical laws, it is possible to convert such ladder diagrams or circuit diagrams into logic diagrams. This is the actual task of the programming system.

PLC programs are essentially based on the fundamental functions AND, OR, and NOT. By combining these three logic operations, it is possible to construct further logical functions such as NAND and NOR. On top of these, there are time and counter functions, shift registers, mono-and bistable clock generators, and so on.

The program generated in this manner is entered into the memory of the PLC's CPU, where it is tasked to generate the desired control sequences. Proper execution of the program depends on the sequence of the programmed commands. A *command* is defined as one individual program line of the PLC program.

It is a characteristic of PLC systems that the program is executed sequentially, that is, step by step, one command after the other. Although this serial processing takes place at high speed, on average at about 0.1 ms per 1,024 program steps, the execution of the overall program depends on how long it is, that

is, on the number of commands. Therefore, for longer programs, the entire program cycle may take several milliseconds. This time is called *cycle time* and indicates the response time of the PLC.

Given, for example, a cycle time of 20 ms, the program is run through 50 times per second. If the input status of a signal changes immediately after it is scanned, then it will take a maximum of 20 ms until the next time it is scanned. This time can only be reduced by using a faster PLC or one with special jump commands. In addition to the logic operations, the PLC often has other tasks, for instance, those related to *data* such as the administration and updating of tables, detection and decoding of barcodes and assigning them to the correct table, correspondence via the information network, and so on.

In modern PLC systems, it is possible to define program sections with various cycle times or to make them event controlled. In this way, it is possible to execute a very time-critical task, for instance, tool-breakage monitoring, with a significantly quicker cycle rate than that for functions that are less time critical, such as compensation values due to heating.

PROGRAM MEMORY

Today's PLCs use exclusively semiconductor memory with various characteristics For initial testing of new programs, *random-access memory* with a backup battery is preferred in order to be able to quickly insert and test changes. These memory modules are *volatile* in the event of a power failure and therefore have to have a battery as a backup power supply. Because of this kind of memory's high level of reliability, subsequent operations can also run via RAM.

TABLE 7.1 Memory Types and Their Characteristics

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Once test operation is complete, the preferred procedure is to transfer the programs to FEPROMs for storage and prevention against loss. These data-storage devices, also available as *memory* can be erased by means of an electrical pulse and then written on again immediately. For this, it is not necessary to remove them from the device or out of their slot because erasure and writing take place onboard. There is no need to manually exchange the storage device.

Earlier EPROMs that could be erased using ultraviolet (UV) light are no longer used today because of their disadvantages. This module could be written on again after a waiting period of about 1 hour. In industrial PC-based PLCs, data also can be saved on the computer's hard drive. When the computer is switched on, the PLC program is transferred to RAM, resulting in a short waiting period.

With today's memory modules, the storage density, that is, the number of bits or bytes that can be stored on a particular volume, is so large that the program length no longer plays any role. When structuring and optimizing a program, less effort is devoted to minimizing the program length but rather to making it clearer and easier to diagnose and to give it a subprogram structure. This is mostly relevant for the user to allow for quick troubleshooting and to minimize downtime of the production system. It is also possible to provide diagnostic programs that record not only the control sequence and cycle times but also the

point where the interruption occurred, putting out an exact error message in plain text. Special self-learning diagnostic functions are also available. These first learn the correct operating sequence for correct functioning and then compare each sequence with the stored one. In the event of a malfunction, they indicate the program step where the error occurred.

PLCs, CNC SYSTEMS, AND PCs IN INTEGRATED OPERATION

The most important building block for PLC technology had already been put down at the end of the 1970s through the use of microprocessors. These could be used to process much larger amounts of information in a very small space, and their improved price/performance ratio made PLC technology attractive even for smaller systems. The most important arguments here were the ability to copy existing executive programs quickly and without errors and to insert modifications without difficulty even at a later time.

PLCs of a specific design are even suitable for use in safety-related areas and for systems that have to satisfy high requirements regarding availability. This all contributed to the fact that PLCs became the premiere automation system, especially in manufacturing technology. The ability to save current-switching states in the event of a power failure contributes greatly to fast, error-free, and safe restarting of the system once power has returned.

Future advancements will be directed less toward further miniaturization and increased performance of the PLC and more toward optimization of interactions with other automation components and toward the *principle of distributed* This refers to the relocation of function blocks to a number of decentralized points, for example, intelligent drives.

Today, many tasks can only be automated efficiently and economically if the strengths of PLCs, CNC systems, and computers are combined and used interactively. The most important arguments in favor of PLCs have always been the ease of modifying programs and automatic documentation. The development of application-oriented graphical tools has revolutionized PLC programming in much the same way as graphically supported programming and simulation had already revolutionized the creation of CNC programs. When used in combination with CNC systems, graphically supported PLC programming and function testing can be performed using a separate PC, for example. Later, once the CNC system has been connected, the last changes and corrections can be made using the CNC system's screen and keyboard. In the end, CNC systems and PLCs even have access to a common database. Only in this manner is it possible for each of the systems integrated into a *computer-integrated manufacturing* network to use all the data present in the system, to update the data automatically, and to pass the data on without delays. In this way, it is also easy to send machine and manufacturing data quickly to the technical office, where they can be analyzed for weaknesses and to provide information for management purposes. Today, CNC systems are available with a complete range of functions, integrated SoftPLC, and axis control all combined on one single PC plug-in card.

SELECTION CRITERIA FOR PLCs

PLCs are offered by a large number of manufactures in various countries. However, comparing the individual products with the list of customer-specific requirements will cut down the number of choices significantly. It is often possible to avoid this effort by taking a look at large-scale users of PLCs; these players test the products that seem most attractive every three to five years and make new selections accordingly. On the other hand, large companies in particular rely on the strengths of market leaders and continue to buy their products. This also helps to reduce costs for personnel training and spare parts management.

The selection of a PLC combined with a CNC machine often involves very different selection criteria The most resource-intensive solution is when the CNC system and PLC are linked via individual connections This does not conform to current standards anymore and cannot be considered a viable option.

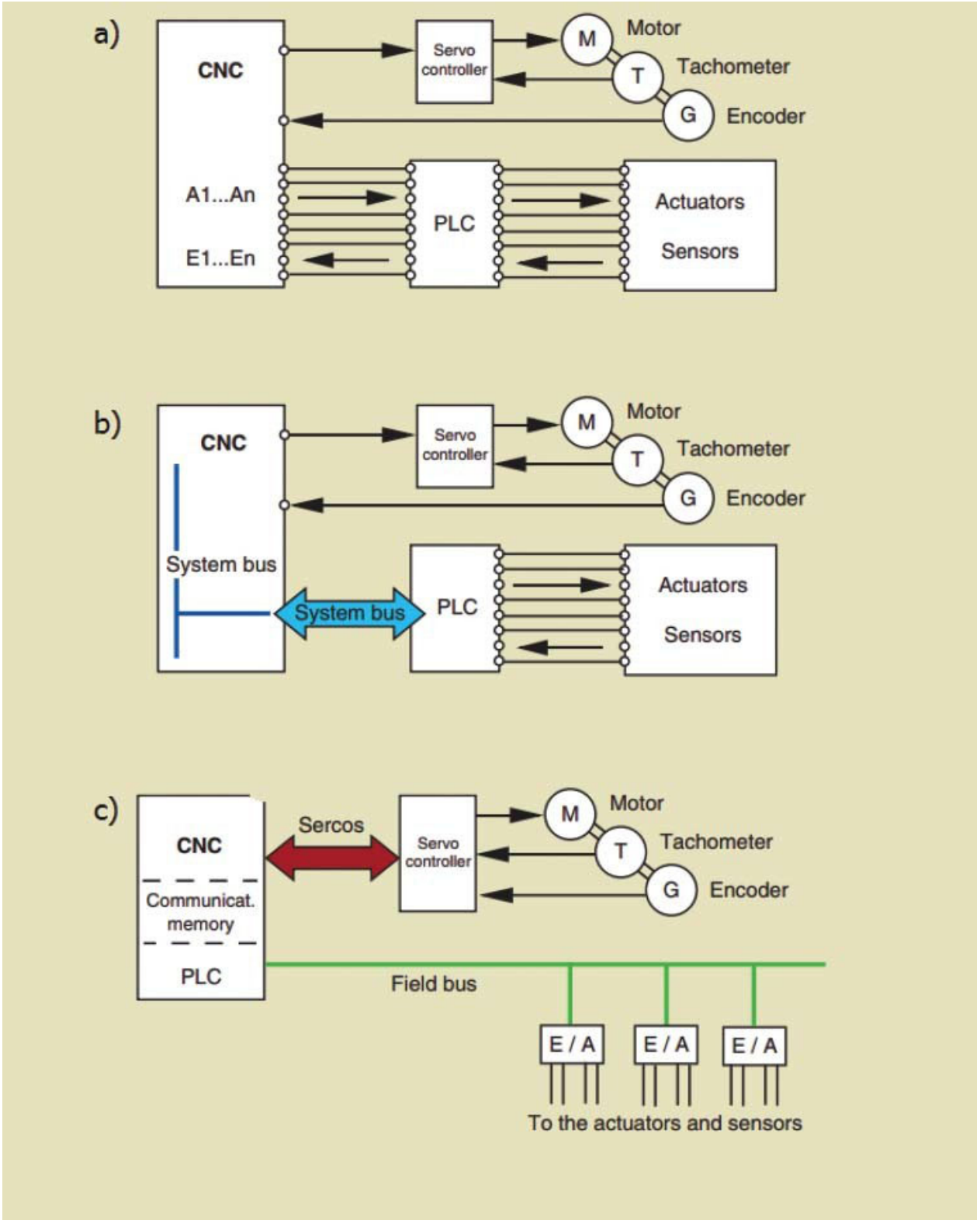

FIGURE 7.6 Options of CNC/PLC coupling. (a) CNC system with separate PLC; information exchange takes place via I/O modules. (b) CNC system with PLC linked via bus; information exchange takes place directly via the bus, without I/O modules, (c) CNC system with

PLC integrated via software; information exchange takes place in the CNC/PLC operation software.

Today, CNC systems and PLCs from different manufacturers can be easily combined via standardized data interfaces, for example, Ethernet. In these instances, the customer tolerates the somewhat higher costs for the benefit of the advantages of PLC uniformity

In some CNC systems, the PLC functions are already integrated into the CNC system as a software PLC, and a field bus connects all the actuators and sensors of the machine with the CNC/PLC This ideal solution had been under development for a long time but only became possible when standard interface modules became available.

SUMMARY

The use of PLCs in connection with CNC systems is the general standard today. The increasing performance of PLCs has led to the shift of more and more of the tasks and functions from the CNC system to the PLC. This gives machine manufacturers and users the ability to program and modify machine- or application-specific functions themselves according to their own ideas. These functions include tool management, tool-changing processes, and pallet changing, as well as their graphical representation and data management. In this way, the manufacturers' know-how remains protected and thus can be adapted to new developments in the machines and new conditions. PLCs can also be considered optimal solutions for the requirements arising in connection with the automation of complex manufacturing equipment.

In series-produced machines, the fact that proven error-free PLC programs can be copied means that commissioning time can be much shorter. For these machines with integrated CNC systems, PLC and axis target value output are also an ideal solution because few machine-specific program modifications are to be expected. In contrast, for special-purpose machines and complex systems, a separate PLC has the advantage that the machine manufacturer can program and test all the process functions of the individual subcomponents even before commissioning of the CNC system.

For further information about bus systems, see:

- www.SERCOS.de
- www.profibus.de
- www.interbusclub.com
- www.ubf.de/ethernet.htm
- www.tecchanel.de

COMPARISON TABLES CNC/PLC

The option to combine a CNC system with a PLC and, in reverse, to upgrade a PLC with additional CNC modules can possibly lead to a confusion of terms and raises the question: which controller really "controls" the CNC machine? Basically, the CNC system performs the most important part of the control functions of a machine, namely, the control of the axes and the entire machining process. The PLC as an interface controller takes over switching commands from the CNC system and controls predetermined function sequences, such as workpiece and speed changes, as ordered by the CNC system. Table 7.2 lists the main differences between a CNC system and a PLC system.

TABLE 7.2 Comparison of CNC and PLC: The Essential Differences between CNC Systems and PLC Systems in the Use of Machine Tools

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IMPORTANT POINTS TO REMEMBER

1. What were formerly NC systems with a separate machine control interface now have become CNC systems with a PLC that is either integrated or linked via a bus.

2. PLCs replace not only relay controls but also perform additional control, monitoring, and display functions.

3. Basic functions include AND, OR, NOT, SAVE, and DELAY. Additional functions include COUNT, COMPUTE, COMPARE, and jump commands and Subprogram Technology. Higher functions are table management, analog (A)/digital (D) and D/A conversion, closed-loop control, NC axis modules, and communication via data networks.

4. Important characteristics of PLCs include:

(a) Range of functions

(b) Maximum number of inputs and outputs

(c) Cycle time, measured in ms/k commands (ms per 1,024 commands)

(d) Number of flags

(e) Size of the program memory (for commands)

5. Instead of wiring, PLCs use a program, also called The program is created by the user with the aid of a PC and system-specific software and specifies how the individual signal inputs are linked and blocked relative to each other so as to generate the required output signals.

6. The program is stored in electronic components; for testing, it resides in RAM, for later operation in EPROM or FEPROM.

7. There are five ways to program the PLC:

(a) Ladder program

(b) Instruction list

(c) Functional plan

(d) Structured text

(e) By means of graphically supported languages

8. The advantages of PLCs are:

(a) Installation and wiring of hardware does not depend on software.

(b) Much shorter assembly and commissioning times

(c) Quick and easy corrections, also during commissioning

(d) Automatic documentation and copying of software programs

(e) Automatic generation of cross-references, notes, and information

(f) No wear; therefore, high reliability

(g) Simple installation, small space, low energy consumption

■ Much shorter commissioning times due to identical, meaning tested, and error-free programs.

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MACHINE CONFIGURATION

The principal reason for numerical control's influence on machine configurations is that there is no need for manual operations and continuous observation and monitoring of the operation. At the same time, the continued development of cutting technology has led to significantly higher cutting speeds, feed rates, and cutting depths, greatly increasing the cutting properties of the machine, often approaching the limit of these tools. These advancements require increased stiffness and drive power.

With large machines for processing large parts, weight and size of the workpiece place limitations on automatic workpiece and tool changes. Therefore, for these large machines, application-specific solutions must be developed.

Yet machines used to process smaller workpieces offer many options for far-reaching improvements of the entire machine. Thus, for small and medium-sized lathes, it has become standard to place the machine bed at the rear, whether inclined or vertical, as it had already been introduced for duplicating lathes. In this way, chips do not fall on the machine bed, and where they fall there is sufficient space in which to install a chip-removal conveyor. Also, the machine operator has easier access to tools and the workpiece.

Furthermore, the use of compact three-phase motors with variable speeds allowed the design of hanging vertical spindles. Here longitudinal and transverse motions are being performed not by the tool but by the spindle This configuration allows easy part changes based on the pickup principle, two-surface machining from the top and bottom on machines with two spindles, and favorable chip removal during boring operations. Also, access to tools and the workpiece is uncomplicated, and below the work area, there is room for chip-removal devices.

FIGURE 8.1 Vertical lathe using the pickup principle for automatic loading and unloading of workpieces.

Concerning large lathes, the configuration of conventional lathes has been kept, that is, a horizontal bed in machines for long workpieces and a carousel design for short workpieces. For longitudinal and shaft lathes, it may be possible to install a chip conveyor inside the bed. In carousel lathes, the horizontal clamping surface interferes with chip removal. Automatic chip removal is almost impossible, especially during boring operations.

Free program design and the practically unlimited amount of data input have led to lathes with two or even three tool slides that work independently but in coordination with each other. This shortens the production time per piece and increases the number of tools available.

Even lathes developed especially for conventional automated production, in which the tool motions are cam controlled (e.g., multiple-spindle automatic lathes), have by now been converted to numerical control. However, the fundamental machine configuration did not change.

As for drilling machines, the radial drilling machine, with its non-Cartesian motion orientation, has been discarded entirely. The standard type is now a design with a vertical spindle and a horizontal workpiece table. The division of the axes between the table and the pedestal follows the workspace of its conventional predecessors. As a result of automation, however, automatic tool changing becomes almost obligatory, with a corresponding influence on the machine configuration.

In milling machines as well, it is possible to find machine configurations that already existed among conventional machines. However, the freedom of programming in numerical automation led to a trend toward complete machining and thus a new type of machine: the machining center, a machine that uses an array of spinning tools. Naturally, this makes it necessary to have an appropriately dimensioned tool changer and one or even two rotational axes in addition to the three translational axes. Also, the configuration of these machines mainly corresponds to that of conventional machines, especially those of boring machines. To expand the automatic sequence, these machines generally are also equipped with an automatic workpiece-changing system. These additional components, of course, also influence the structure of the basic machine.

In all these machines with a horizontal clamping surface, there is a problem with chip removal and placement of a chip conveyor. For this reason, in a few cases in machines for processing smaller workpieces, the workpiece is machined with a vertical clamping surface after it has been clamped in the horizontal position in the clamping station.

Concerning the various kinds of grinding machines, the typical original machine configuration is unchanged because the characteristics of the grinding process had to be given priority. Only with smaller outside grinding machines, in which the longitudinal motion traditionally is assigned to the workpiece, is a different configuration occasionally adopted. That is, just as with the lathe with an inclined bed at the rear, the longitudinal motion is performed by the grinding head.

Gear-cutting machines are by nature single-purpose machines with a fully automatic sequence. Therefore, their configuration was kept completely the same during the transition to numerical control (NC).

A completely new configuration for machine tools with an entirely different structure only became possible with the advent of CNC systems with high-performance computers. These are machines with a positioning of the tool via a parallel kinematic system. Here the command position values specified in the Cartesian coordinate system have to be converted quickly into the command values for the lengths of the individual jointed arms. Because of the low masses being moved, this kinematic system allows very rapid responses but has serious disadvantages when it comes to the range of motion that is possible, especially for swivel motions.

MACHINE FRAMES

The requirements placed on machine frames are essentially identical to those for conventional machine tools. However, the higher precision requirements call for an optimization of the static and dynamic stiffness. To provide for uninterrupted automatic production, maximum thermal stability and low thermal drift are also important. Temperature changes from the environment or owing to heat sources in the machine should not lead to gradually increasing positional deviations in the machine. Because of the higher machine performance, the heat sources inside the machine can cause particularly noticeable negative effects. These are temperature elevation of the frame due to hot chips and high loads on the main drive motor and bearings to the high speed of the main spindle. Here machine frames made of cast mineral composites are useful because of their large mass and the poor thermal conductivity of concrete

FIGURE 8.2 Machine frame made of cast material composites and machine slide on a 45-degree oblique guideway, welded lightweight design.

A certain degree of freedom in the design of function-related machine frames, especially for small and medium-sized frames, makes considerations of aesthetics moot because modern machines tend to be completely enclosed.

Machine parts that are moved in closed-loop position control are subject to particular requirements with regard to their weight, especially those positioned by linear drives. For machine slides, optimization of stiffness using *finite element method* analysis and weight reduction by means of topology optimization can produce considerable benefits not only in cast constructions but also most notably in welded designs Because of their cost, fiber composite

materials have not achieved much success in series production so far.

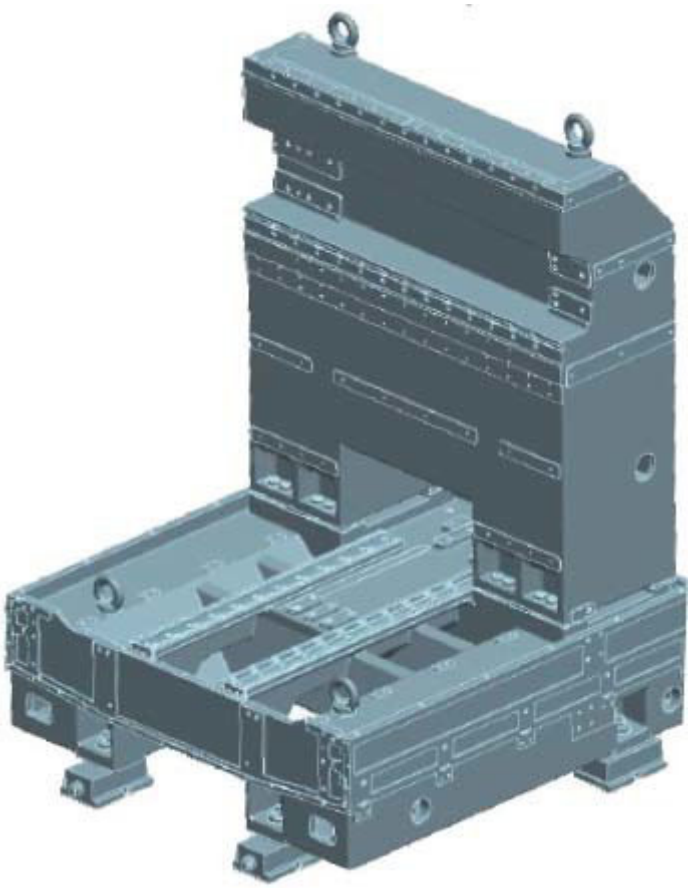


FIGURE 8.3 Machine frame made out of cast iron.

GUIDES

As a general rule, guides, especially those that are moved during machine operation, are subject to the following requirements:

- Low friction and no stick-slip effect so as to allow precise positioning
- High stiffness in order to absorb operating loads without undue displacement
- High damping to suppress vibrations
- Low wear to ensure precision over a long time period
- Low cost

In conventional machine tools, these requirements were met adequately by sliding guides with a wide variety of designs. They could handle heavy loads, were reliable under operational conditions, and provided good damping. Low friction and the no stick-slip effect could be achieved by lining them with plastic low-friction liners.

In contrast, closed-loop position control requires particularly low friction and freedom from the stick-slip effect in order to achieve high positioning accuracy. Therefore, diverse types of roller-bearing

guides are used in CNC machines. These guides are supplied by specialized manufacturers and have become quite inexpensive. This trend is supported by the high rapid traverse speeds that are being employed to save time. Here the lower friction allows lighter feed drives. Additional improvements have been achieved using hydrostatic guides, especially with regard to damping characteristics Some manufacturers of roller bearings offer these as mass-produced products

FIGURE 8.4 Hydrostatic guide with identical dimensions to a linear roller guide in order to ensure interchangeability. INA.)

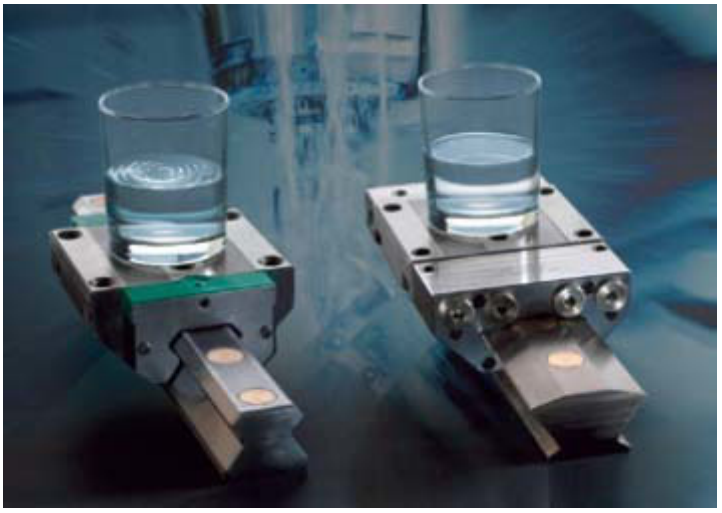


FIGURE 8.5 Damping test. A roller guide. A hydrostatic guide. INA.)

MACHINE ENCLOSURES

In terms of main drives, it has been noted that automatic work sequences are necessary for full use of the high-performance characteristics of modern cutting tools. One result of this is that chips are thrown outward at high speeds, presenting a risk of injury to personnel in the vicinity. This fact must be addressed through the use of appropriate enclosures and by securing the workspace.

In small and medium-sized machines, such enclosures generally are a sheet-metal construction attached to the body of the machine, often combined with the electrical cabinet and sometimes encompassing the top of the machine. Thus they form a single transport unit together with the machine, a so-called hook machine, meaning that it is suitable for single-point suspension. The machine enclosure not only serves as protection against chips but also retains the vaporized coolant and provides good protection against process noise. These enclosures are a key component of occupational safety and thus are subject to a large number of regulations. On the other hand, they must ensure easy operation, service, and maintenance of the machine. Consequently, the enclosure must satisfy a number of comprehensive requirements that are often conflicting.

For example, machine enclosures must make the workspace easily accessible for setup and tool changing. For this purpose, they generally employ large access doors. These doors, however,

must be locked when the machine is in operation, or at least the work sequence has to be interrupted immediately when they are opened. The doors and often other parts of the fixed enclosure have windows to allow safe observation of the work sequence. These windows have to withstand the impact of airborne chips without becoming opaque. This is only possible with silicate glass. Then again, in the event of a collision, because they cannot entirely be avoided, the windows have to be able to survive impact by large parts, such as airborne workpieces, clamping equipment, or tools. In this regard, plastic windows would be a better choice. Therefore, composite windows are often used. It is also important for the windows to be firmly anchored in their frames to prevent them from being pressed out with little force.

Covers that enclose the entire machine often obstruct access to areas that have to be accessible for cleaning and maintenance work. Thus they must be easy to remove or open.

Frequently, the operator panel with the keyboard and control equipment, as well as control elements for manual operation of the machine for setup and maintenance work, is also integrated into the machine enclosure. After all, the machine enclosure is a decisive attribute in the appearance of the machine and therefore represents a salient feature of the design.

COOLANT SUPPLY

Because in CNC machines the tool can move freely in the workspace, the coolant has to be coupled with the tool. With lathes, this is done by feeding the coolant over the turret to the tool holder located in the working position, which, in turn, feeds it to the cutting edge via a preadjusted tube. For recirculating tools, the coolant is fed to the tool via the main spindle. Because of the generation of coolant mist, however, there are efforts under way to facilitate dry machining.

CHIP REMOVAL

Large volumes of chips are produced in any given time interval as a consequence of the high productivity of CNC machine tools. These chips have to be removed from the machine without adversely affecting the work sequence. The issues associated with chip handling and the installation of chip-removal hardware in the machine were discussed earlier in this chapter.

Various types of conveyors are used depending on the shape of the chips. The most common and widely distributed conveyors are hinged-belt conveyors. Scraping conveyors are more suitable for very small and friable chips. Magnetic conveyors can only be used for magnetic steel chips.

SUMMARY

The automatic work sequences made possible by numerical control have extensive effects on the design of machines because there is no need for continuous handling and observation by workers. This makes it possible to focus the design of the machine on optimal execution of machining, making full use of the increased performance of modern tools. This requires a main drive with correspondingly high output and a completely enclosed workspace. The high productivity of such machines results in a high volume of chips, and these have to be removed automatically.

Automatic work sequences require a higher level of precision, which has to be taken into account, especially in the design of the machine body and guides. CNC closed-loop position-control systems also place requirements on machine designs. Moving parts have to be as light as possible, especially when driven by linear motors. The guides should have low friction and be free from stick-slip effects. Machine designs also must take into account automatic tool changing and workpiece changing, which are often associated with considerable space requirements.

IMPORTANT POINTS TO REMEMBER

1. CNC machines are machines that operate automatically. They do not have to be tended by a worker. For this reason, they often have a different configuration than conventional machines. In particular, because of their very high cutting speeds, their workspace should be completely enclosed.

2. Machine frames should have high static, dynamic, and thermal stability to achieve trouble-free automatic production.

3. The demanding requirements on guides have resulted in increased use of roller bearings.

4. Machine enclosures have a very wide range of functions:

a. They protect against flying chips.

b. They contain coolant vapor.

c. They allow observation of the work sequence.

d. They allow machine setup and clamping of the workpiece.

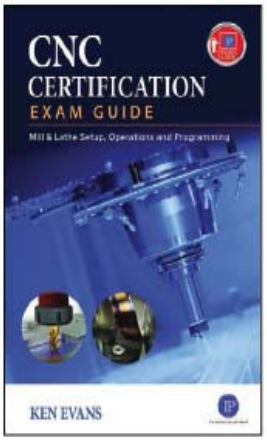
e. They contain airborne parts resulting from collisions.

5. The coolant must be coupled with the tool; with recirculating tools, it must be fed through the spindle.

6. The chips must be removed in such a way that they do not interfere with the work sequence and so that they do not cause local heating in the machine frame.

7. With the use of compact, speed-controlled, three-phase motors with stable suspension, a new generation of lathes with a hanging vertical spindle was created. Here longitudinal and axial motions are performed by the spindle, not the tool. This allows simple workpiece change according to the pickup principle, two surfaces from top to bottom on machines with two spindles.

LEARN FROM ONE OF THE BEST CNC GURUS



CNC CERTIFICATION EXAM GUIDE

SETUP, OPERATION, AND PROGRAMMING

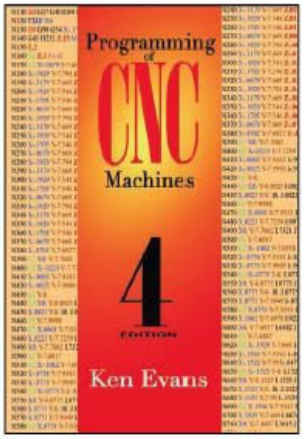
Ken Evans, 384 pages, ISBN 978-0-8311-3637-6, $64.95

This guide is focused on providing the knowledge base required for obtaining certification, credentialing and/or job preparation in CNC Machining with CNC Mills and Lathes. It covers foundational skills that all those seeking employment as a CNC Operator/Machinist must possess. Managers responsible for workforce development in manufacturing facilities will use the book as a guide for on-the-job employee training and apprenticeships.

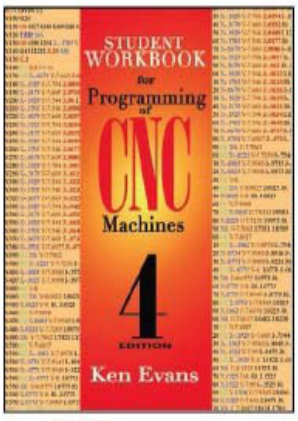
Additionally, it can be used as a curriculum component for technical schools and colleges for students preparing for certification and credentialing exams based on the National Institute for Metalworking Skills (NIMS) Machining Level I standards for: CNC Mill Programming and Setup and Operations, and CNC Lathe Programming and Setup and Operations. At a time when the CNC market is experiencing a shortfall of skilled, qualified workers, this guide is the perfect resource.

PROGRAMMING OF CNC MACHINES, FOURTH EDITION

Ken Evans, 500 pages, ISBN 978-0-8311-3524-9, $59.95



Written in a simple, easy-to-understand language by a skilled programmer with many years of experience teaching CNC machining to industry and in the classroom, the latest edition offers a new chapter on feature-based Machining using Siemens, plus a new chapter featuring Fanuc NC guide I programming. It provides full descriptions of many operation and programming functions and illustrates their practical applications through examples. It provides in-depth information on how to program turning and milling machines, which is applicable to almost all control systems. It keeps all theoretical explanations to a minimum throughout so that they do not distort an understanding of the programming. And because of the wide range of information available about the selection of tools, cutting speeds, and the technology of machining, it is sure to benefit engineers, programmers, supervisors, and machine operators who need ready access to information that will solve CNC operation and programming problems.



STUDENT WORKBOOK FOR PROGRAMMING OF CNC MACHINES

FOURTH EDITION

Ken Evans, 176 pages, ISBN 978-0-8311-3600-0, $34.95

This new edition is the perfect complement to *Programming of CNC Machines*, 4th edition. It is filled with many practical exercises and is one of the few workbooks available that tests users through the application of programming functions commonly used in CNC programming. Together with its companion text, this workbook can be used as a complete CNC training program; or, it can be used on its own by students or professionals to verify that they have the basic skills needed to write a CNC program.

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9 Drive Control for CNC Machine Tools

10 Feed Drives for CNC Machine Tools

11 Main Spindle Drives

12 Dimensioning of Drives for Machine Tools

13 Mechanical Layout of the Main Spindle Based on the Process Parameters

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DEFINITION

There is a big difference between open-and closed-loop control systems. Open loop is a control system without feedback of the actual value or position. Closed-loop control is a system in which the output is measured by a transducer and fed back for comparison with the input. By comparing the actual value with the commanded value, the comparator gives an error signal to the amplifier to minimize this deviation.

In CNC technology, the control of tool position, feed rate, and spindle speed is indispensable. The entered values must be kept most exactly. The control difference and the control gain result in a value that is used to attain and maintain the target value, such as spindle speed or axis position.

Control technology is an engineering science that is needed for many technical processes. The term implies that it has to do with math and formulas. In this chapter, however, only the functional relationships of control technology are explained. In CNC technology, these are primarily the control of spindle speed and the movement of the NC axes. The basic structure of a standard control loop is shown in Figure

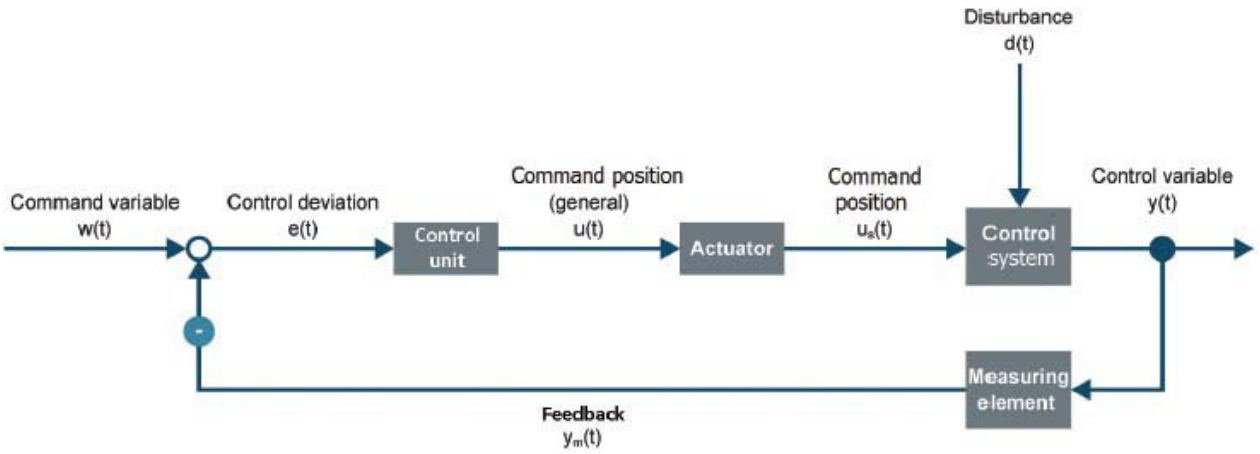


FIGURE 9.1 Standard control loop block diagram (command variable = speed control set point; control deviation = difference between actual and command positions; target value = set point for actuator [amplifier]; control system = servo motor + mechanic; disturbance = load changes, for example; control variable = speed [rpm]; measuring element = rotary encoder; feedback = speed actual value).

Figure 9.2 shows the step response, that is, the reaction to the command to set the number of spindle revolutions to a certain target value. The left graph shows a nonoptimized CNC setting; the right graph shows an optimized CNC setting. It is evident that the graph of the optimized setting more faithfully conforms to the command value (blue) than the nonoptimized setting.

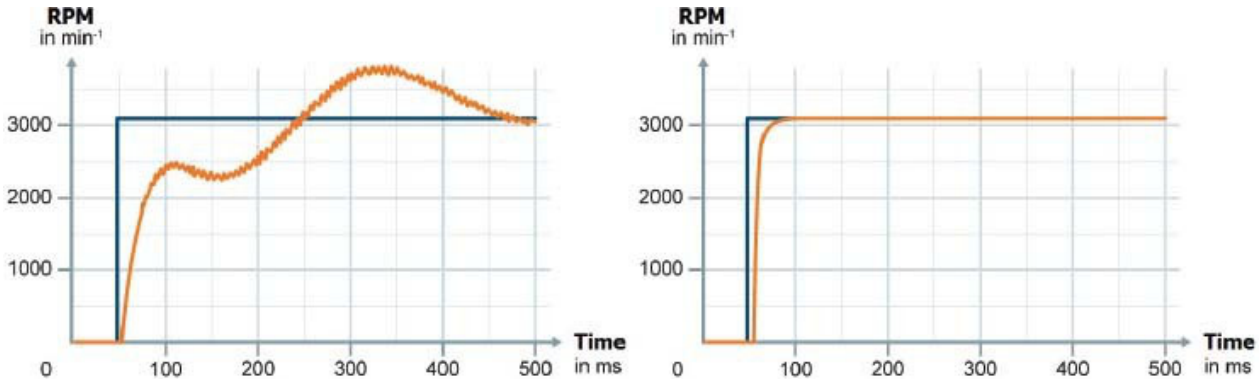


FIGURE 9.2 Step responses (dynamic behavior) of a speed-controlled main spindle: with control default values; with optimized control settings (blue, command value; red, actual value).

When adjusting the CNC setting, two requirements tend to contradict each other. That is, the target spindle speed must be reached in the shortest time possible yet without overshooting. Given a particular cutting operation, overshooting could result in unintended material removal and errors on the workpiece.

MECHANICAL AXIS

In order to explain the drive control of an NC axis, a consideration of the axis mechanics is in order. A simplified schematic of the mechanical design of an axis is shown in Figure

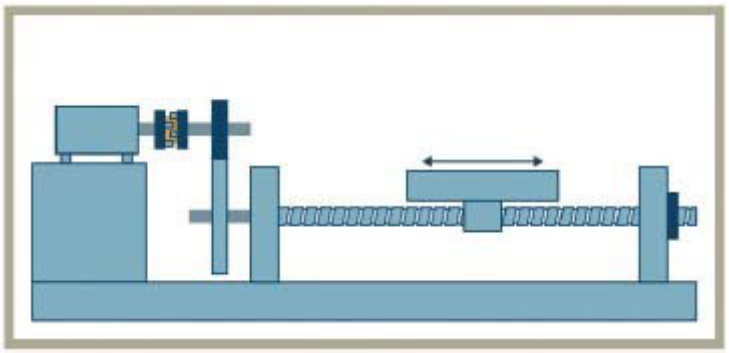


FIGURE 9.3 Simplified mechanical construction of a machine axis.

Each NC axis is assembled with different components such as motor, clutch, transmission, and ball screw. These have different mechanical properties on different machines, and the interplay of these determines the dynamic behavior of the axis, such as moment of inertia, response, friction, and so on.

To achieve the best possible movement, meaning to lead the axis in a highly precise dynamic manner along a programmed workpiece contour, it is necessary to adapt the CNC system to the actual mechanics and to optimize the CNC settings specific to the system.

Next, the generation of target values— position values issued by the CNC system— needs to be considered. These values are calculated by the NC program because the contour of the workpiece and the feed rates to generate these contours are defined. Based on these data, the CNC system continuously calculates position, velocity, and acceleration values for each of the axes involved. In addition, compliance with certain limit values is ensured: actuator and motor are designed for a limited current, and the mechanics can only be loaded with the maximum permissible force or torque. These limits determine the permissible acceleration. It must be ensured that fewer vibrations are generated by the moving parts and that jolts, generated by extreme accelerations, are limited. The position and speed values are calculated by the CNC system and are given out as a continuous array of target values to the drive controllers.

ANALOG CONTROL

A relatively complex controller structure is required to realize a highly dynamic, precise motion control in a CNC machine. This is explained next in a simplified way

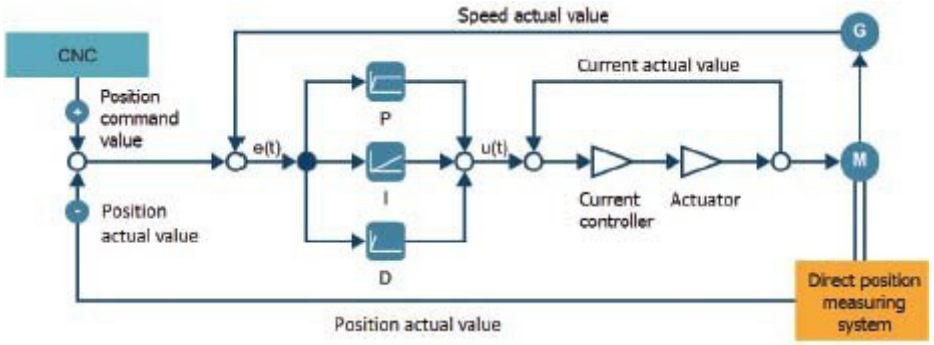


FIGURE 9.4 Analog position control of a servo drive with superimposed (cascaded) control circuits for motor current, speed, and position. Another control circuit for *electronic commutation* would be added for a synchronous servo motor.

The most important task of position control is to follow a calculated path precisely or to reach a programmed position quickly by means of an appropriate motor speed and to retain this position in a stable fashion. The actual position values are constantly controlled via a measuring system. The CNC system constantly compares the actual position, or *actual* with the calculated position, or *command* The difference is converted to a target speed. Speed control continuously "regulates" the deviation in order to strictly adhere to the command speed values.

The concept of *nested control* also referred to as *cascaded control* is applied to control position and speed concurrently for all servo motors With these, it is easier to set the target values and the individual control loops separately from each other in the best possible way.

Closed-loop position control is the most important outermost structure of a CNC machine. It is followed by the speed control loop, which is fed by the output of the position controller (= control deviation) of the CNC system. This means that the current controller receives its target value from the speed controller. Thus the speed value can be set without explicitly having to calculate the current beforehand. The required current then results from the cascaded control circuits. The return of the actual current value also assumes the important task of limiting the current to the motor in order not to exceed the specified limits of torque and heat. The structures of a cascading control circuit are evident: position controller, speed controller, and current controller.

ANALOG VERSUS DIGITAL POSITION CONTROL

Figure 9.5 shows a simplified structure of a digital control loop. The start of the effecting chain is again made by the CNC system. The interpolator of the CNC breaks down the geometry of the workpiece into individual mathematically defined sections or linear polygons; limits that need to be taken into account are considered in the target value calculation. The interpolator in the CNC machine calculates cyclically and in short time intervals the position target values for each machine axis.

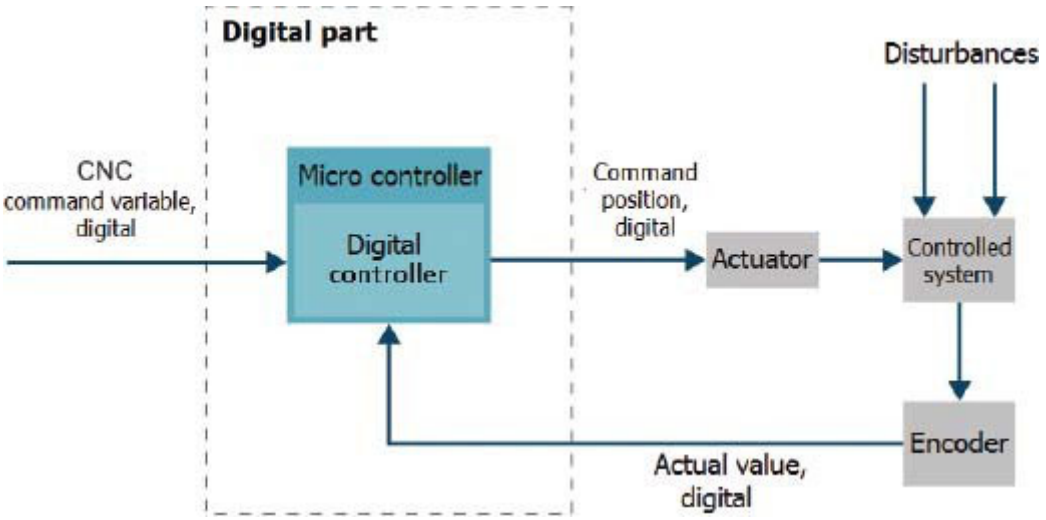


FIGURE 9.5 Simplified controller structure of a digital axis drive. The digital part of the controller is located within the dashed area. All other parts continue to work analog or digital in newer control loops.

Also involved are filters for compliance of tolerances, maximum speed, acceleration, and jolt, as well as some position target value

filters that, among other things, serve the minimization of the following error of the affected axes (see Figure The resulting continuous position target value is constantly fed into the control loop.

Numerical controls and drive technology in recent years have achieved a high standard of performance. For a long time, there was only one internationally standardized analog ±10-V drive interface available for controlling the drives. For this reason, drive control was performed mainly by means of the analog interfaces until a few years ago. Today, it is the preference to do this digitally. Here a microcontroller takes over the tasks of the digital controller. This has the advantage that the control units are much easier to configure and less prone to interference.

In addition, the individual control loops can be harmonized automatically. Also, the actual values are returned and processed directly, so a digital-to-analog converter is not necessary. The theoretical disadvantage of digital control loops is that there is no continuous signal flow any more, but all measured values must be "sampled" simultaneously. The sampling frequency determines the controller dynamics. The higher the sampling frequency, the more precise is the control quality. Because of the high performance of modern processors, a much better control loop behavior can be achieved than with analog drives.

The functional diagram of a typical digital control loop (see Figure reveals that the power actuator and the controlled system (the alternating-current [AC] servo motor) can continue to work with analog signals. It is merely that the microcontroller takes

over the task of a CNC system by executing a programmed control algorithm. This also includes instructions that control the reading of the measured values and output of the calculated target values. All this can only be done periodically with the sampling frequency and repeated simultaneously for all measured values.

DIGITAL INTELLIGENT DRIVE TECHNOLOGY

The entire signal processing of a modern digital intelligent drive can be done with a microcontroller The CNC system can take over the conventional torque and speed control; without additional hardware, it can perform fine interpolation and position control with extremely short cycle times and with the highest precision. Significantly higher accuracies are achieved, particularly at high speeds, compared with conventional analog position control in the CNC system. The fine interpolation, furthermore, provides continuous and jolt-free motion at low feed rates. Making use of these possibilities also saves costs by simplifying the CNC hardware and saving on wiring.

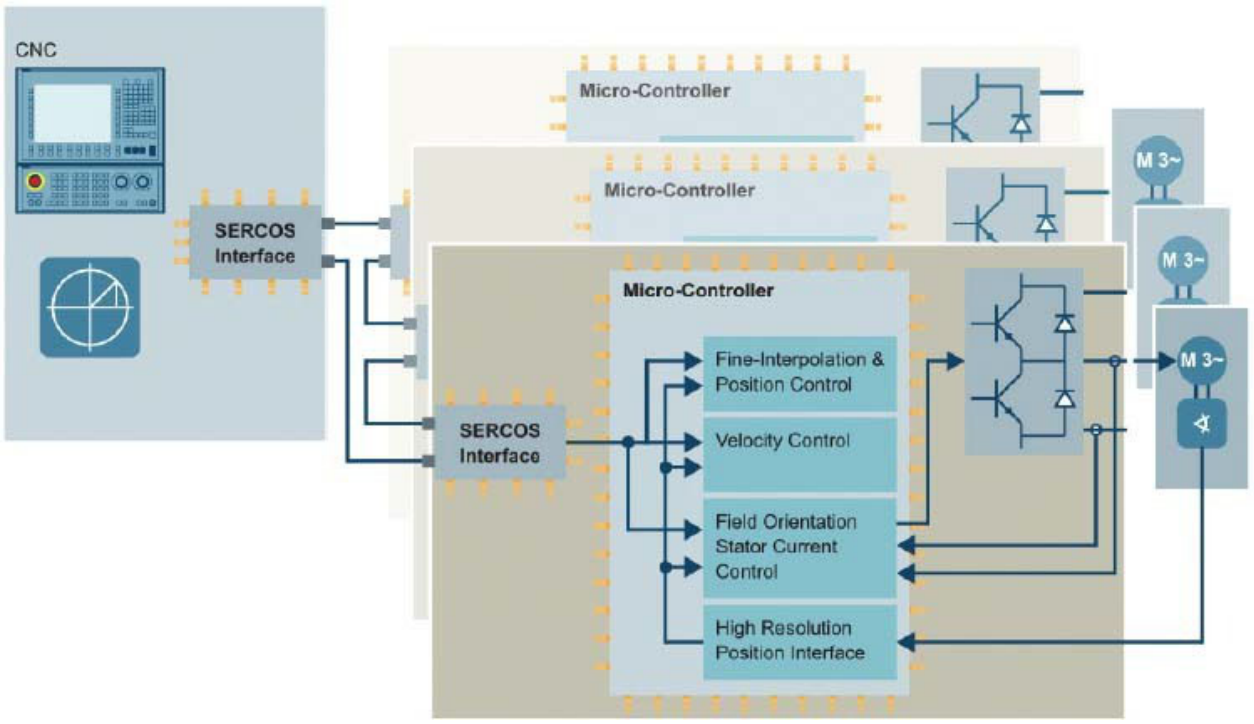


FIGURE 9.6 Connection of several digital control loops via the SERCOS interface to the CNC machine. The drive microcontrollers assume the functions of speed control with fine interpolation at low

speeds, field weakening range of the stator (for asynchronous motors), and high-resolution position measurement for fine interpolation. SERCOS.)

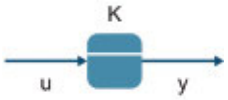
These advantages, however, can only be realized via a suitable digital interface in the controller. Because a CNC machine usually has multiple control loops for the NC axes and the main spindle, a connection of all control units via a powerful bus system is indispensable (see Figure Examples for this are the SERCOS interface and ProfiNet. SERCOS III (third generation) and ProfiNet can connect almost any number of drives to the CNC system.

Digital drives work cyclically for transmission of the target and actual values. These data must be updated simultaneously in each interpolation cycle of the CNC system with all drives in order to make a precisely coordinated speed control of several NC axes possible. This is required, for instance, to maintain the tolerances when milling complex paths or surfaces. The times when the actual position values are captured and the target values become effective in the drive are just as important for the precise coordination of the axes as are the accuracy of the interpolated position values and the measurement accuracy.

CONTROLLER TYPES AND CONTROLLING BEHAVIOR

Basically three different controller types with different controlling behavior are used for servo drives:

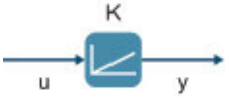
■ *P-controller, or proportional* The input of this controller is multiplied by the constant control gain *K* and passed on to the output, meaning that the output value *y* is proportional to the input value



Advantage: Very fast response to control difference of the actual and target values that is present at the input.

Disadvantage: Almost no response to very small control differences. By the rules of physics, there must always be a residual control error because at a control difference of 0, there cannot be an output signal.

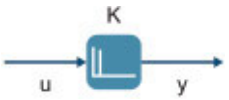
■ *I-controller, or integrating* The input will be interpolated over time and put out weighted with the reset time The longer a control difference is present, the higher will be the output value rise. With this, the controller also records the past course of the control difference.



Advantage: No permanent control error, meaning that the I-controller secures a stationary accuracy.

Disadvantages: Can trigger over-shooting of the control variable. Because of its comparatively slow response time, an I-controller is never used alone.

■ *D-controller, or differential* This controller is used only together with P- and I-controllers. It does not react to the size of the deviation but only to the speed change and therefore cannot work alone. D-controllers put out a short pulse when there is a jump in the target value in order to shorten the response and settling time.



Advantage: Shortens the settling time.

Disadvantage: Can cause vibrations if the parameterization is incorrect.

■ This consists of a parallel connection of P-, I-, and D-controllers and combines as a *universal controller* the functions of P-, I-, and D-controllers. The P-share of the controller settles large deviations; the I-share settles small residual deviations and guarantees that no permanent control deviation remains. The D-share ensures a shorter response time

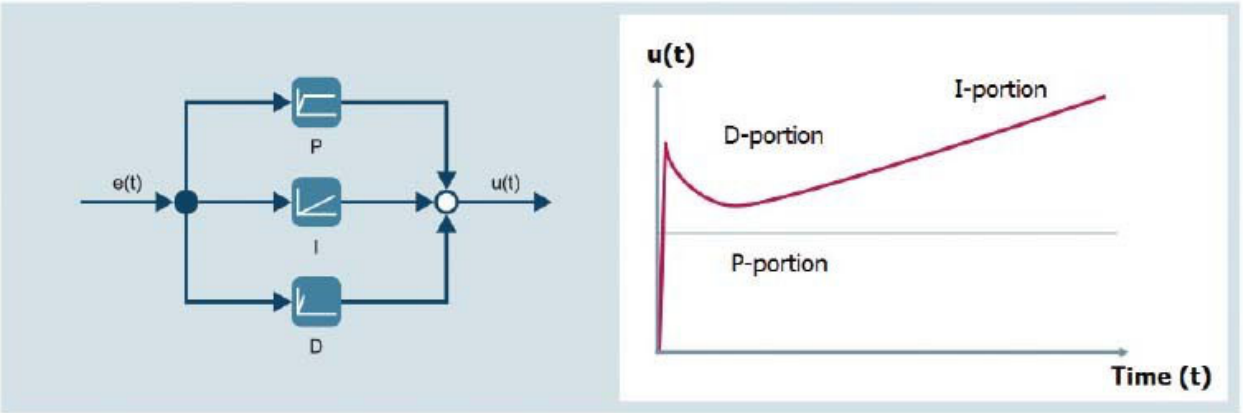


FIGURE 9.7 Parallel connection of P-, I-, and D-controllers; the step response of a PID-controller.

The sketches above do not reflect that the response curves of each controller must function equally well at positive target value jumps, breaking, or at rotation reversal, meaning at negative target value jumps.

For a comparison of the three controller types in terms of a controlled path, the following parameters are optimized

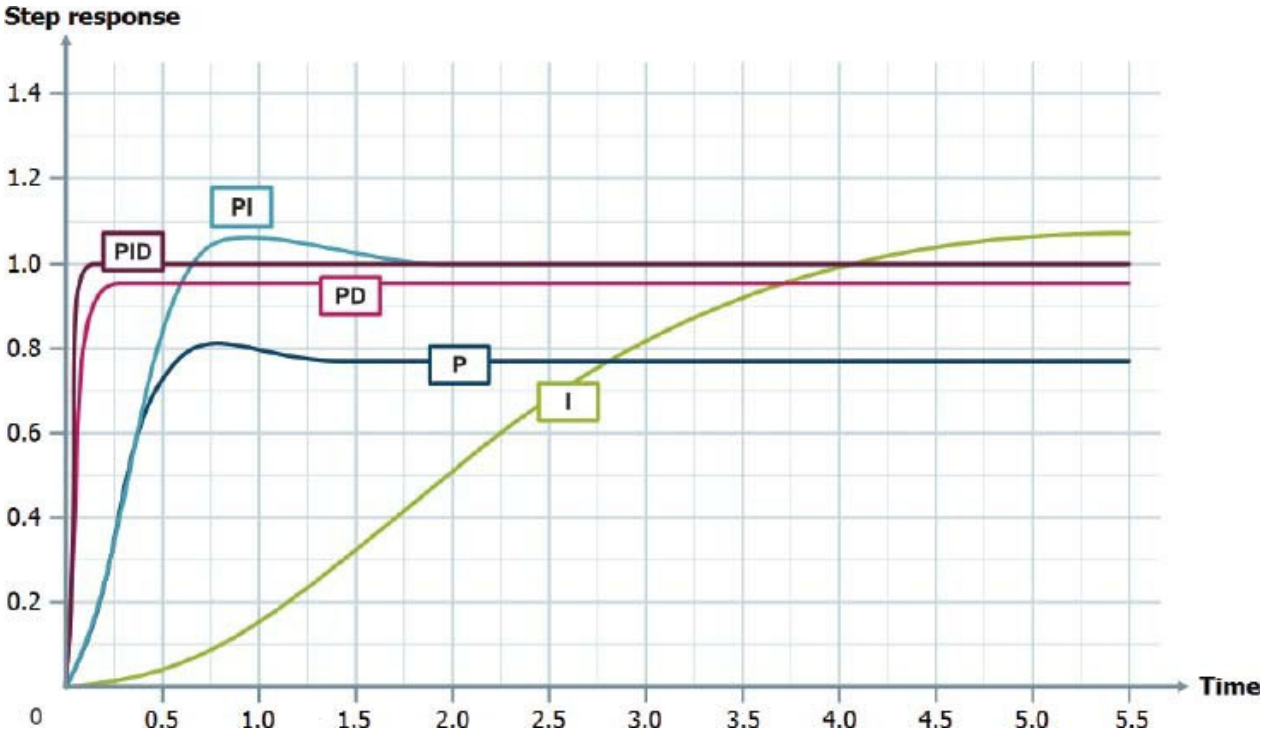


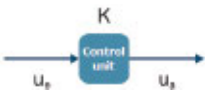
FIGURE 9.8 Speed control. Comparison of temporal behavior with different controller types. In the event of a sudden change in the input voltage (set point jump), the different controllers generate the respective behavior of the speed (= step response of the control route). The correctly parameterized PID-controller shows the ideal result: shortest response time without overshooting. Controllers without an I-component exhibit a permanent control deviation. Regelungstechnik-rn-wissen.de.)

■ The amplification factor meaning to the limit value of (±10 V). The parameterization of this controller significantly determines the factor of the control loop and thus its stability.

■ The size or duration of the pulse (= derivative time)

■ The reset or integration time. The longer this time is set, the more slowly the output value changes toward the limit value.

■ Th e size or duration of the pulse (= derivative time) depending on the speed change of the control deviation. This means that slow jumps from generate a lower short output pulse and fast input jumps generate a high, possibly longer-lasting D-pulse.



LOOP GAIN AND FACTOR

The loop gain in a standard loop defines the gain factor, for instance, in speed control. The gain factor has no dimensions and is defined by the ratio with an open control loop at the target value–actual value comparison point.

The factor, in contrast, of CNC machines defines the feed rate in meters per minute, where the tool has a lag of 1 mm. In principle, this is a parameter of the dynamic accuracy of an NC axis and is determined in particular by the proportional loop gain.

The factor is therefore a measure of the gain in a position control loop. This is why it is also a measure of rigidity of the drive and the dynamic accuracy of the machine. The more precise a contour must be followed, the slower the motion must be executed with the same factor. If the contour must be machined faster, the factor must be increased for the same accuracy to be obtained. For this, the mechanical load-bearing capacity of the machine must be known because too large a factor will cause vibrations in the control loop and instability of the drive system. This, of course, will have a negative effect on the machine and the processing result.

The factor of an NC axis says more than the loop gain about the influence of the gain factor on the behavior of the NC axis. The unit for this is

$$K_V = \frac{\text{feed rate (in m/min)}}{\text{lag distance (in mm)}}$$

The size of the positional deviation at a certain speed can be calculated using the determined factor. If a certain axis lag cannot be exceeded to satisfy the specified tolerances, the maximum permissible feed rate can be calculated using the known factor.

The larger the factor, the faster a CNC machine can process a part and do so with the required precision. The best way to achieve this is the use of direct linear drives. Average values for CNC machines are 1 to 5 m/min × mm. When direct linear drives are used, the maximum value can be increased up to 10 m/min × mm depending on the machine.

The *circularity test* can be used to test the path accuracy of a machine tool, to measure the factor, and to check the factor of individual axes and make corrections if indicated.

PRECONTROL

Because the speed and torque values needed to reach a certain position are known through the calculations of the path interpolator of the CNC system, it is possible to bypass the respective superimposed controller for this size. The calculated value will be added directly to the output of the previous controller and thus set as target values for the next controller. This is called By bypassing the superimposed controller, the time that it needs for the calculation is saved. Thus the target value is forwarded to the axis earlier, and the lag error is reduced more quickly

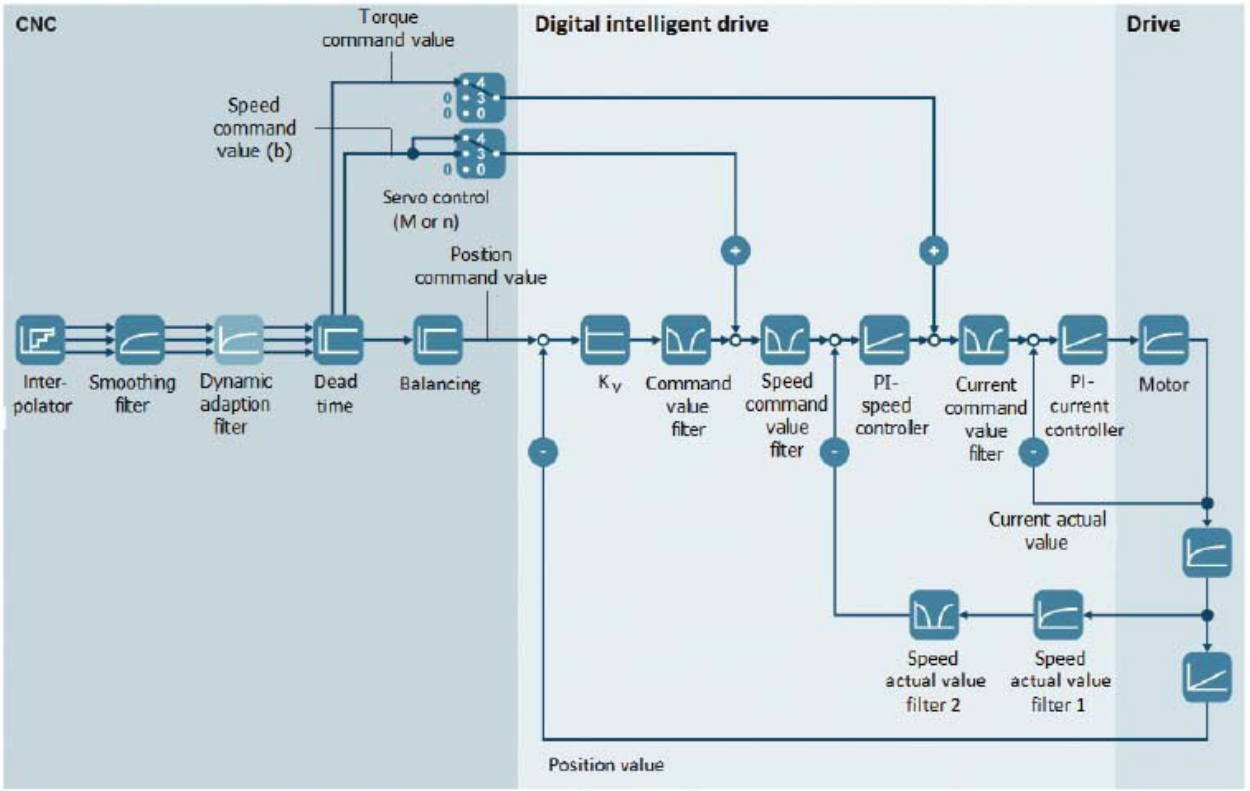


FIGURE 9.9 The digital intelligent ac-drive controller with ProfiNet using the example of a Sinumerik and Sinamics drive system with precontrol for torque and speed Siemens.)

In addition, the controllers are relieved by precontrol because now they only need to control errors instead of unavoidable influences such as friction, differences in the workpiece volumes, different clamping elements, and so on. In this way, an optimization of the controller for the elimination of errors is possible so that the errors can be corrected faster and the positioning behavior becomes more accurate. In modern machine tools, both spindle revolutions and torque are precontrolled.

FREQUENCY CONVERTER

Today's CNC machines are preferably equipped with controllable three-phase servo motors; compared with other servo motors, these offer several advantages (see below). Synchronous and asynchronous motors in a regular direct-current (DC) network are running only with their rated speed, given a nominal frequency of 60 Hz and depending on the stator winding with 3,600, 1,800, or 1,200 rpm. For asynchronous machines, slip must be deducted. Speed control is not possible. This can only be achieved by changing the voltage frequency, which is the task of a frequency converter.

Frequency converters are purely electronic devices that operate in very complex circuits and use modern high-voltage electronics. They change a 120/240 voltage with 60-Hz frequency into an alternate voltage with adjustable frequency and amplitude. CNC machines use the output voltage of the frequency converter for speed control of a three-phase servo drive of an NC axis or the main spindle. This requires that frequency and amplitude of the voltage are precisely controlled depending on the speed and load.

For the operation of synchronous servo motors, an additional feedback input is required for detecting the instantaneous angular position of the rotor by means of a rotary encoder. This feedback controls the electronic meaning the forwarding of the rotary field. At the same time, acceleration is also prevented from becoming too high or an overload is prevented from flipping the speed and turning off the motor.

Construction

Frequency converters in principle consist of four components

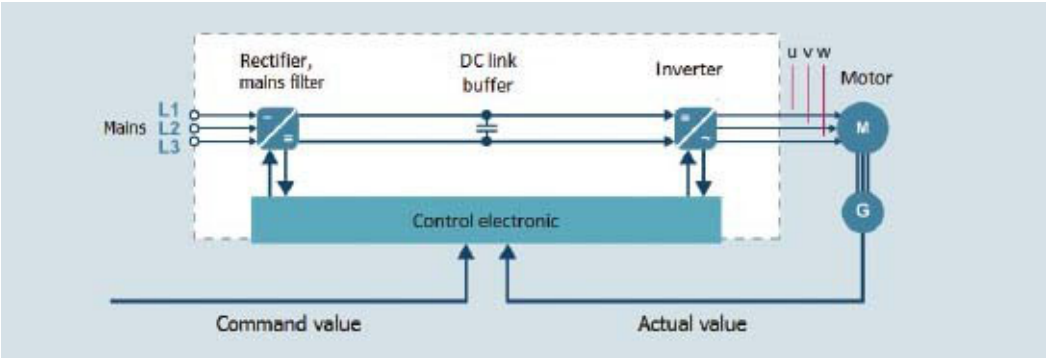


FIGURE 9.10 Schematic basic structure of a frequency converter for speed control of three-phase synchronous or asynchronous motors.

■ This supplies a DC link by means of a rectifier bridge with direct current. It uses diodes, thyristors, or transistors because these best meet the requirements of feedback given their high-frequency switching capability.

■ *DC* This consists of a high-voltage capacitor whose capacity is adapted to the output power of the inverter. Its task is the smoothing of the rectifier generated direct current. A variable DC link voltage can also be created with transistors.

■ This provides, from the DC voltage, the three-phase output voltage in the required size and frequency for speed control of the connected motor. This is the technologically most demanding electrical component because it must provide the controlled motor with the best possible sinusoidal direct current. When controlling a synchronous motor, the inverter additionally must recognize the precise instantaneous angular position of the rotor and take it into account in the clocking.

■ *Computerized control* These are used for precise control of the entire inverter electronics. They generate the voltage and frequency required for speed control of the servo motor so that the speed or position values specified by the CNC system can be executed exactly.

Frequency converters generate strong frequency interferences on the motor supply, which require appropriate countermeasures such as the installation of additional smoothing chokes. These and other technical measures contribute to the positive result but are not subject of this account.

Interfaces

Frequency inverters have digital and/or analog interfaces for data exchange; they have a display and keyboard for user input. Often the display of the CNC system can be used. Today, because of the high requirements for speed and position control, mainly interfaces for a field bus or industrial Ethernet are required, for instance, a ProfiNet or one of three SERCOS versions (see IEC 61800-7). For this, another *intelligent interface* is available that can be a separate device with an integrated microprocessor.

Parameterization

The adaptation of the frequency converter to the connected motors is made by parameterization. This can be done either via a keyboard and a display or through automatic parameterization during the commissioning. The determined parameters are either stored in the electronics of the device or on a designated removable storage medium. CNC machines with several NC axes require identical parameter settings of all NC axes in order to maintain best possible path accuracy at any speed.

Four-Quadrant Operation

Four-quadrant operation signifies that the inverter controls the motor in both directions of rotation and also returns energy back into the DC link during braking. A controlled rectifier and more electronics components are required to synchronize the feedback with the network frequency. This effort is only economical for larger quantities of energy.

Because the capacitor in the DC link can store only a limited amount of electrical energy, additional braking resistors should be provided. These also allow, in combination with a special emergency stop circuit, braking in the case of a power failure. This is done by short-circuiting the voltage generated by the synchronous motor over the resistor and dissipating it as heat.

Speed Control

The inverter controls voltage and frequency for speed and position control of the connected three-phase servo motor, proportionally up to the rated speed The torque is largely constant. At speeds toward o rpm, the voltage in the lower frequency range is automatically raised to prevent a torque drop.

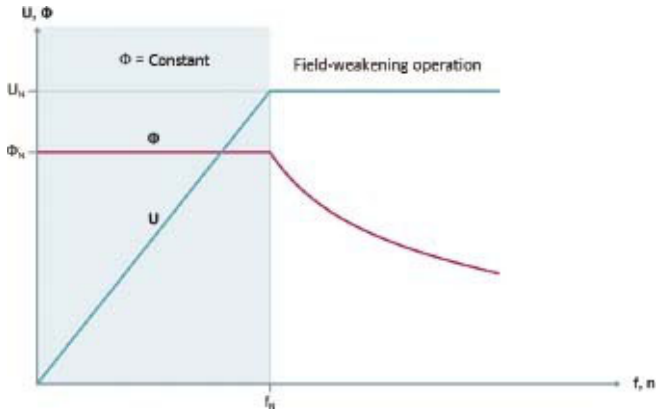


FIGURE 9.11 diagram of an inverter. The voltage increases from o to the nominal voltage the rated speed of the motor. Given a constant voltage, starting with nominal frequency only the frequency further increased. As a result, the motor automatically goes into field-weakening operation with reduced torque.

For speed control of an asynchronous motor beyond the rated frequency, only the frequency is increased, and the voltage remains constant. As a result, the motor automatically goes into the field-weakening range, and the torque decreases with increasing speed (see Figure

Control Range

Asynchronous motors, because of their stable cage rotor, are better suited for higher speeds than synchronous motors. Synchronous motors carry the risk of delamination of the permanent magnets from the rotor at high speeds; this requires a safety-related speed limitation.

Even at o rpm, synchronous motors have a holding torque near the nominal value. Given the correct parameter setting, no position deviation can be detected in case of a shock-like external torque load on the motor shaft. At continuous operation, the energy supplied for cases such as weight compensation requires an additional fan, water cooling, or a mechanical holding brake to protect the motor from overheating.

The inductive resistance of the motor windings and additional inductors smooth out short pulses of variable duration in the current so that a sinusoidal ac voltage is generated. The higher the frequency

of the pulses, the better and smoother is the sinusoid of the ac output current.

Mode of Operation

The last link in the frequency converter is the inverter. This component creates the variable frequency and voltage amplitude for the servo motor. It is very complicated in terms of electrical engineering to generate a sinusoidal three-phase current for smooth operation of a synchronous servo motor from the DC voltage of the DC link over the entire control range Power transistors proved to work best for this task. Their high switching frequency of several 10,000 Hz makes it possible to vary the voltage as well as to produce an almost sinusoidal current curve. The arrangement consists of six transistors arranged in pairs per phase A special control circuit clocks the transistors in pairs according to a given control principle and thus determines the voltage and frequency of the direct current.

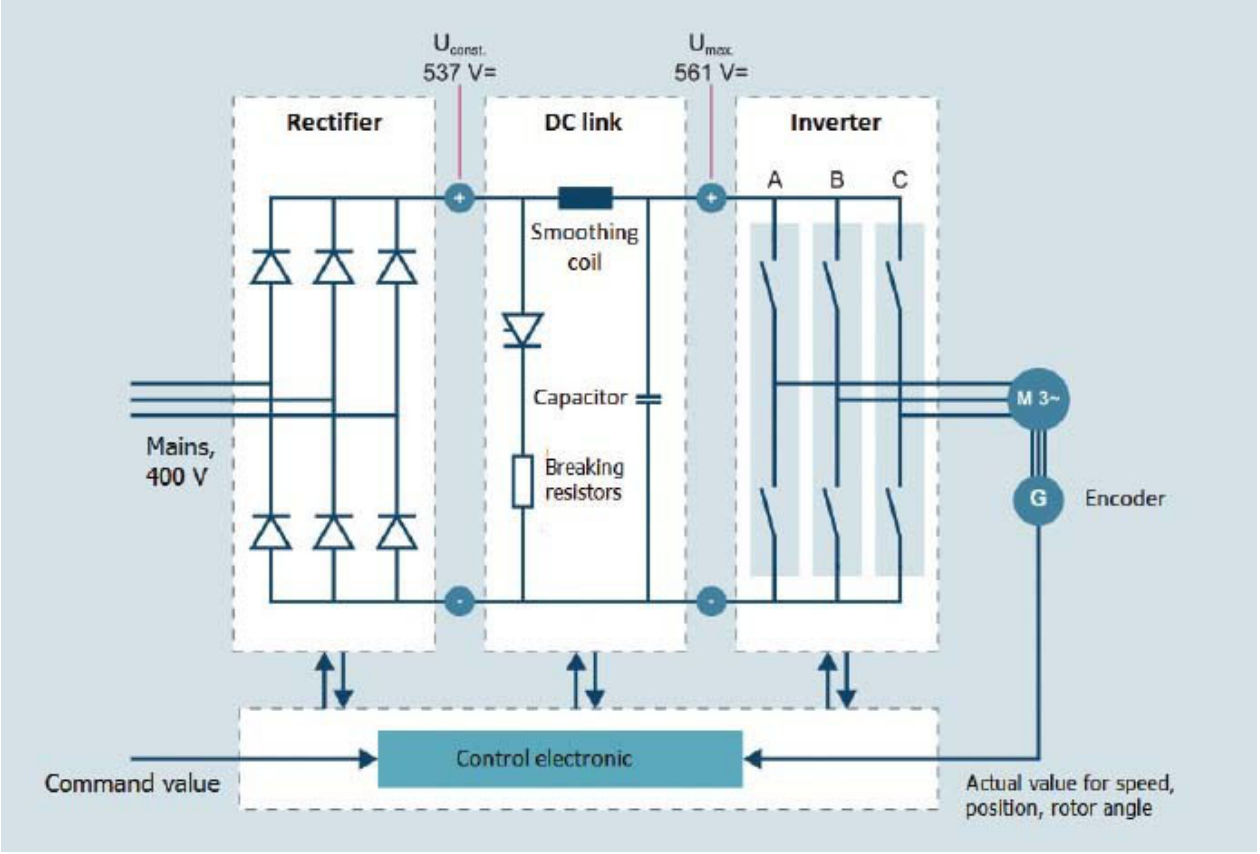


FIGURE 9.12 Functional diagram of a frequency converter. The DC voltage generated by means of an uncontrolled rectifier bridge is smoothed in the intermediate circuit and stored in the capacitor. It supplies the energy to the inverter, which consists of six electronic switching elements, preferably switching transistors, which are divided into three groups (A, B, C). Of these, only one switch out of two changing groups is always switched. This results in a three-phase current of variable frequency and is proportionally adjusted at the output amplitude.

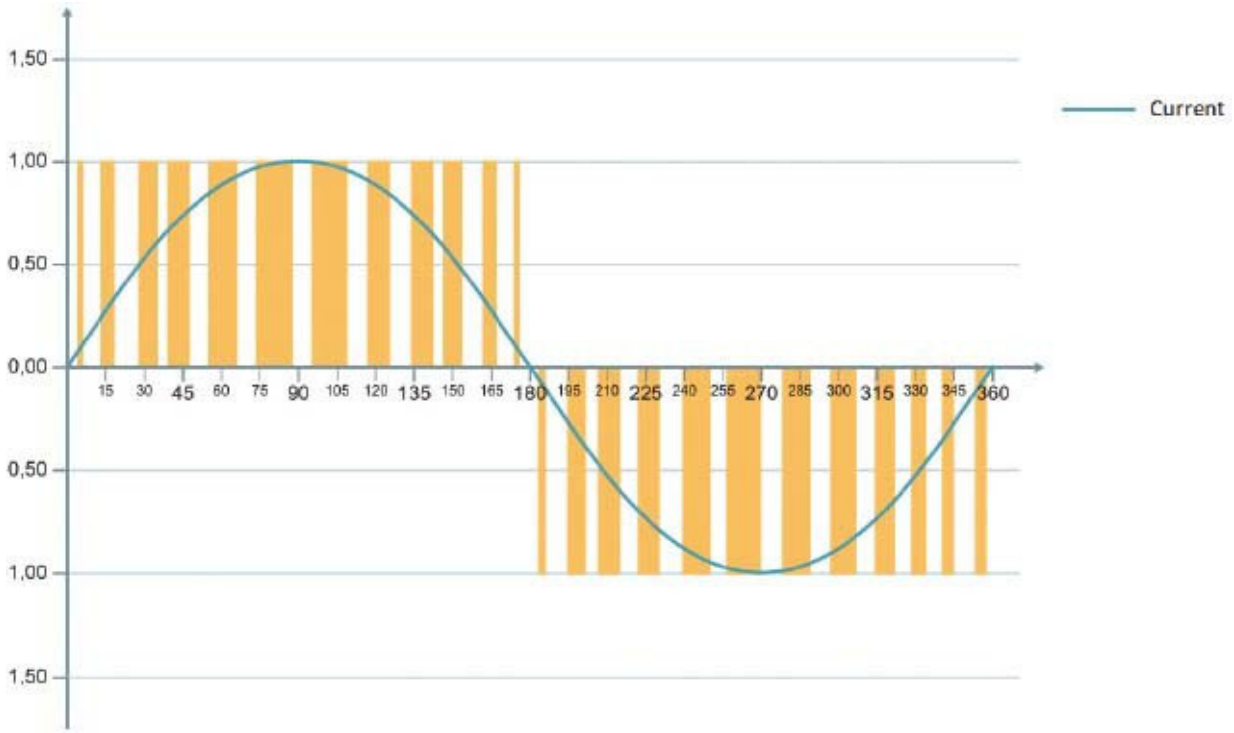


FIGURE 9.13 Through high-frequency voltage pulses of varying durations (pulse-width modulation), a sinusoidal three-phase current is created by the inductance of the motor windings, whose rotational frequency determines the motor speed.

A decisive function of the inverter is the pulse-width modulation, which controls the duration of the successive pulses through the control electronics. For high requirements in terms of speed-control range and concentricity of the drive, the control of the switching time is no longer performed by the microprocessor but rather by an additional digital circuit. This module is customized by the manufacturer.

The voltage can be controlled with the pulse width. A narrow pulse generates a low voltage that increases with the increase in the pulse width. Starting with a switching frequency of 1,000 Hz, the generated current is almost sinusoidal. With a combination of microprocessor technology and switching transistors, the clock frequency of the inverter can be refined in such a way that at every frequency an almost perfect sinusoidal voltage is generated. *Example:* Given a switching frequency of 1,000 Hz for the generation a 60-Hz voltage, meaning for 3,600 rpm of a two-pole motor, 20 pulses per sinusoidal wave are possible. Today, depending on the transistor and motor power, pulse frequencies of 10 to 40 kHz are used.

Rotor Position Encoder

To control a synchronous servo motor, the actual position value of the rotor is needed to synchronize the inverter switching frequency. In comparison with DC motors, this is also referred to as *electronic* The value of the rotor position is provided by a digital absolute encoder, a resolver with two analog output voltages offset by 90 degrees, or an encoder with a meter.

Protection Functions

This short account of the complexity of the entire electronics does not reveal that certain operations or an emergency shutdown could

potentially trigger very high voltages or very high temperatures in the device or in the motor, causing damage and failure of the frequency converter. For this reason, and based on experiences, several electronic protective functions and technical protective devices are provided.

SUMMARY

Precise control of the calculated tool path and spindle speed is decisive for the accuracy of the machined workpiece. Until a few years ago, analog position control was standard, and controllable three-phase servo drives were not yet available. For many decades, therefore, a standardized ±10-V interface had to suffice as an international standard.

However, manufacturers and users of CNC machines were increasingly dissatisfied with the results achievable. The deviations from the target path were too large for precision machines; in addition, the direction of travel and other disruptive factors played a role. Development of the entire drive technology therefore focused on four areas:

1. Three-phase DC servo motors (synchronous, asynchronous) and powerful frequency converters

2. Intelligent digital ac drive controllers, also called with additional functions for speed control, position control, fine interpolation, stator current control, and a high-resolution position interface for controlling the frequency converter

3. An intelligent data interface for transmission of measuring and control signals between the CNC system and all drives

4. High-resolution, absolutely reliable digital encoders with a precision of up to 0.1 µm and higher

In general, this would have been a very demanding task for any manufacturer that could only have been satisfied with great effort.

Introduction of fast processors made it possible for an intelligent digital controller via a control loop to take over the entire signal-processing work of a drive. This controller performs speed control, position control, and fine interpolation at low speeds with the highest precision. The result is higher precision and a significant relief of the CNC system.

The prerequisite, however, for benefiting from these advantages is a suitable digital interface, also called a *motion control* between the CNC system and the drive controller, such as the well-proven internationally standardized SERCOS and the ProfiNet interfaces. These allow an angle-synchronous speed control of several servo motors from acceleration to deceleration and standstill. With this, it is also feasible to maintain the position target values issued by the CNC system over the entire feed-rate range with the highest precision.

The entire drive control today is configured in such a way that the parameter adjustment of all servo drives on the CNC machine can happen quickly and mostly automatically. A highly dynamic and precise control can only be achieved with three-phase synchronous servo motors or linear motors. The features and benefits of these drives are explained in Chapters 10 to

IMPORTANT POINTS TO REMEMBER

1. The job of control technology is generally the management and monitoring of processes with the objective of precisely meeting the command state of a system.

2. Control means measurement of the pertinent variable and feeding back the actual value to the CNC input, thus establishing the actual deviation.

3. To understand the control technology, it is essential to familiarize oneself with its technical terms, functions, and circuit diagrams. These are specified in DIN EN 60027-6.

4. The current state of the controlled variable is constantly measured with transducers with analog or digital output.

5. The three most important types of controllers are P-, I-, and D-controllers.

6. The individual blocks of a control loop are response free, meaning that the signal or information flow takes place only from the input of a block to its output.

7. The advantages of CNC systems are their compact design, the parameterization, and the direct use of digital process signals.

8. The difference between digital and analog control circuits lies in the way the signals are processed internally. Analog controllers use operational amplifiers. CNC systems use a microcontroller that processes signals digitally.

9. CNC systems work cyclically. All target values and actual values must be updated synchronously in each interpolation cycle of the controller for all drives.

10. A digital drive interface must provide synchronization between the cyclic controller and the likewise cyclic digital drives. This synchronization must be accurate within microseconds because the precise coordination of the drives is only guaranteed if the actual values in all digital drives are measured simultaneously and all target values become effective simultaneously.

11. The control of the CNC system can be shifted to a separate digital system in connection with a digital motion control bus, for example, SERCOS or ProfiNet. This not only relieves the load on the CNC system but also guarantees much more sophisticated and precise control.

12. Adaptation of digital drives to the controlled system is accomplished through parameterization. For this purpose, digital drives have display and input options. These are absolutely necessary because checks and adjustments are practically impossible by simple means, as is the case with analog drives.

13. Digitally controlled synchronous and asynchronous motors are predominantly used as servo drives for modern CNC machines.

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Feed drives provide the mechanical energy required to move the CNC axes. Thus they are an important element of the control loop that controls axis position. Furthermore, they are used for a variety of transport and auxiliary applications, such as tool and pallet changers.

The three essential components of a feed drive are:

- The servo motor
- The drive controller, consisting of controller and power unit
- The axis mechanism with the position-measuring system

The motor acts as an energy converter to move to and hold a position. A rotary motor works with revolutions per time and torque; a linear motor works with speed and force. Parts of the motor, besides the electrically active parts, are additional modules such as the brake and the encoder for angular position and revolutions per minute (rpm). The encoder's signal is often also used for position control. Rotational drives often have a pinion or clutch on the drive shaft, possibly with integrated overload protection.

The motor is controlled by a drive controller that combines the control and power units The control for voltage, speed, and position in modern drive controllers is digital (i.e., by means of microprocessors). Therefore, higher accuracies and reaction speeds than in analog controllers can be realized. Digital controllers also have a variety of additional application-specific functions, monitoring and diagnostic capabilities, and communication interfaces.

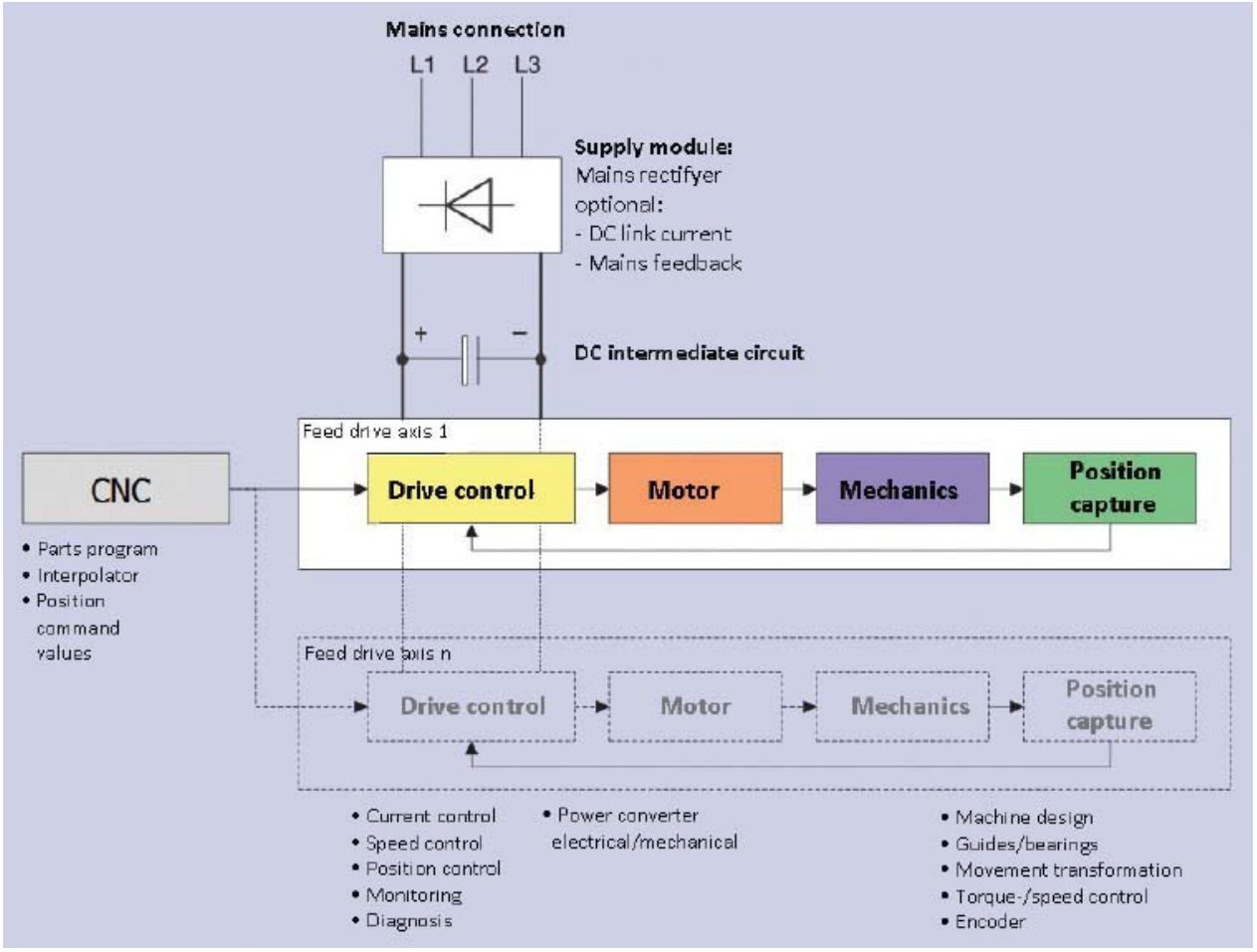

FIGURE 10.1 Main components of a feed drive.

A feed drive in a machine tool is generally powered by a modular drive controller. It consists of a supply module, which rectifies the three-phase main voltage and supplies the drive controller of the individual drives with the downstream DC link. The power actuator of most of today's drive controllers is a rotor position-controlled inverter. It creates a multiphase AC from DC link via electronic commutation. Today these are mostly three-phase systems. The axis mechanism consists essentially of the respective carriage or axis construction with the guidance system and the mechanical transmission elements.

REQUIREMENTS FOR FEED DRIVES

One or more axes are involved in the generation of motion sequences depending on the machine type and machining task. The higher-level CNC system controls the axis movements by specifying the position target values for every single axis. The feed drives must follow these position target values as precisely as possible and without delay. At the same time, the influence of disturbing forces should be as low as possible.

This results in the following main requirements for feed drives:

- High power density, that is, high torque or high transmission power in a compact size
- Great speed adjustment range (≥1:30,000)
- Low moment of inertia or low linearly moved masses
- High overload capacity
- High positioning and repeat accuracy

Machine manufacturers and users today also expect a number of additional features:

- Application-specific functions

- Easy commissioning and error diagnosis
- Monitoring and safety features
- Open, standardized interfaces
- Maintenance-free and a high degree of protection
- Low heating and high efficiency
- Low operating noise
- Small footprint
- Low cost

TYPES OF FEED DRIVES

Feed drives provide all axis movements for the production process. Figure 10.2 shows the different ways of translatory feed motion.

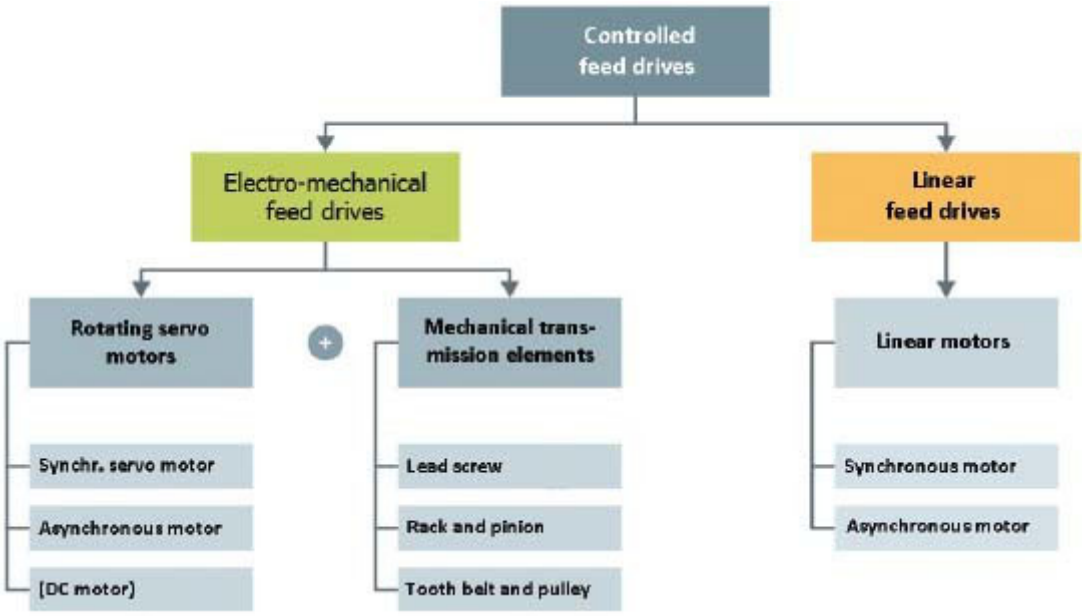

FIGURE 10.2 Kinds of feed drives.

Electromechanical Feed Drives

Many feed drives in machine tools today still consist of a rotary servo motor with a mechanical transmission (e.g., a ball screw). The drive converts the rotational movement of the motor into a carriage movement A transmission between the motor and the ball screw enables optimization of the drive design. Thus the pitch of the thread allows regulation of the feed force, feed rate, rapid traverse speed, and acceleration of the linearly moved mass.

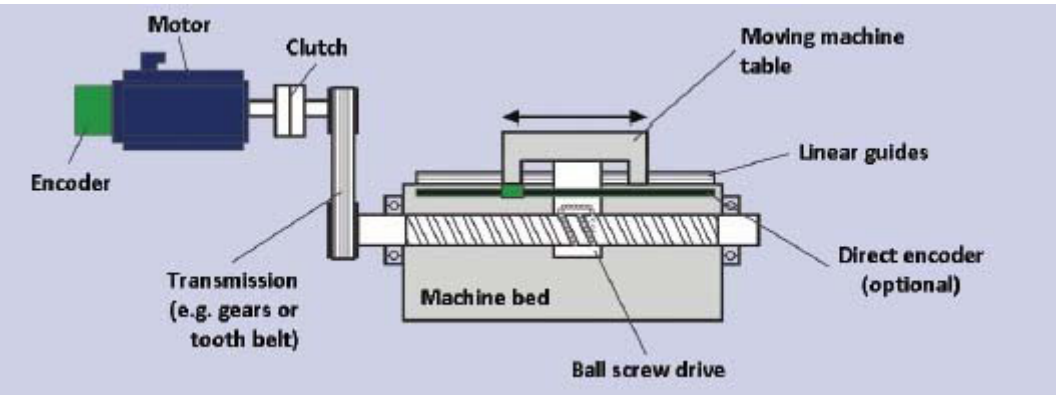

FIGURE 10.3 Layout of an electromechanical feed drive with ball-screw servo drive.

The angular position of the rotor is detected with a rotary encoder for controlling the inverter and for detecting the actual motor revolutions. For reduced demands on positioning accuracy, the slide position can be determined from this motor encoder signal, which is an indirect measuring system. A higher-quality actual position acquisition of the carriage can be accomplished optionally with an additional direct measuring system, a linear encoder.

With the aforementioned choice of gear ratio and lead-screw pitch, ball screws can be well adapted to the requirements of feed drives. Toothed belt drives can be used for more cost-effective designs. The following possible characteristic limits of a ball-screw drive may not be possible all at the same time:

- Feed force of 200 kN
- Acceleration of 10

■ Speed of 90 m/min

For applications approaching these limits, it is advisable to get the approval of the screw-drive manufacturer.

The acceleration capacity of a ball screw is almost independent of the linearly moved mass and is mainly determined by the spindle pitch and moment of inertia of motor and spindle. The technical control range of a ball-screw drive is determined by the natural frequency of the mechanical system. The elasticities in the drive train, in conjunction with the moved masses, will lead in practice to mechanical natural frequencies that allow factors of a maximum 5 (m/min)/mm (see Chapter An increase in the mechanical natural frequencies can be achieved with the use of larger spindle diameters. The moment of inertia of the spindle, however, increases to the fourth power to the spindle diameter and thus limits the achievable dynamic

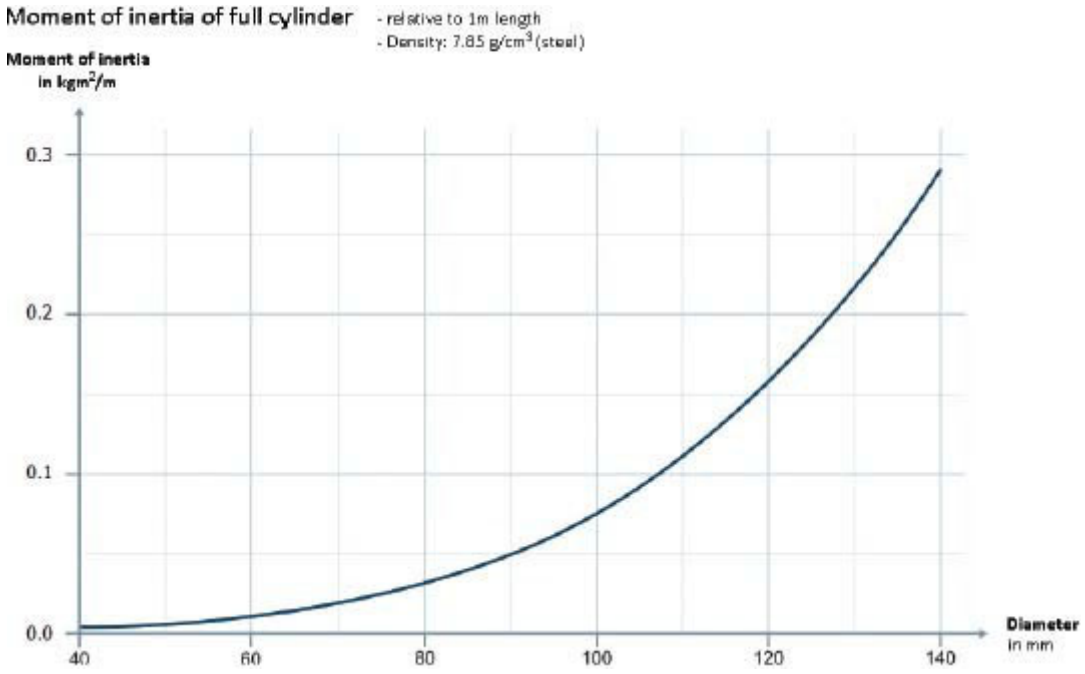

FIGURE 10.4 Moment of inertia of a ball-screw drive depending on the diameter.

When designing a ball-screw servo drive as a feed axis in a highly dynamic machine tool, the optimum in terms of speed, acceleration, accuracy, and lifetime is determined by different parameters. Relevant factors are the threaded spindle pitch, the ratio of the transmission between motor and threaded spindle, and the possibility of using different motors. Other limiting parameters are the critical speed, the moment of inertia, and the position-dependent stiffness of the ball screw. The integration of a ball screw into the machine design will pose no difficulties for the designer, and the system has worked well for many years.

The mechanical transmission elements in the drive train of a ball screw are subject to wear. In collisions, there is usually a risk of damage. In practice, therefore, downtimes for maintenance and repair must be scheduled. Additional cooling measures are required to control thermal expansion in highly dynamic ball screws or very long travels.

Motors

For feed drives of CNC machines or in mechanical engineering in general, the term *servo motor* is in common usage. According to the principle of operation, rotary servo motors are distinguished between:

- DC servo motors

■ Synchronous servo motors and asynchronous motors

■ Stepper motors in conjunction with position control (open loop)

In the past, DC servo motors had a number of advantages over other types of motors available at the time. These advantages included, among other things, the comparatively low cost of the motor and the power electronics. Over the years, however, the cost of comparable controlled synchronous servo drives has come down. At the same time, synchronous servo motors offer decisive advantages, such as higher torque and acceleration, zero maintenance, and better cooling options. Based on these advantages, the synchronous servo motor has prevailed as a standard in machine tool design. Stepper motors are rarely used in machine tools; therefore, they are not included in this account.

Synchronous Servo Motors

For many years, synchronous servo motors with three-phase windings have been used almost exclusively for electromechanical feed drives of CNC machines. This permanent-magnet synchronous servo motor, often called an *electronically commutated* or *brushless DC* best meets the requirements of a servo motor. The operating principle of the asynchronous motor, because of its lower power density and efficiency, was quickly replaced by the synchronous servo motor because it is easier to control and the magnets are cheaper.

The stator of a permanent-magnet synchronous servo motor carries a three-phase winding and permanent magnets in the rotor Modern magnetic materials allow a high power density and thus a high acceleration capacity.

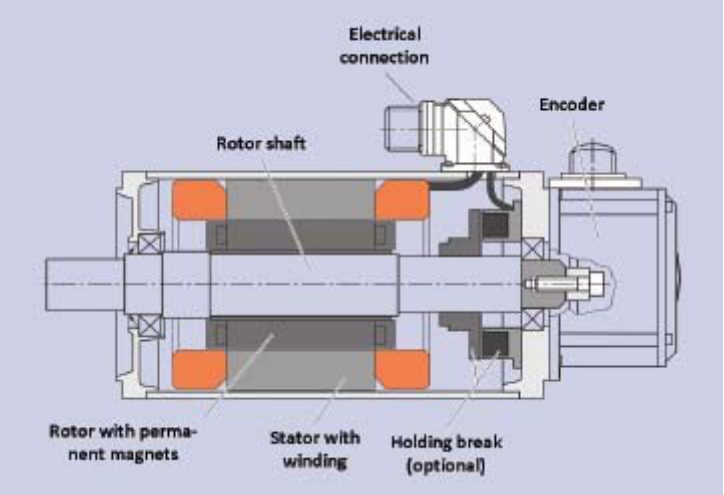

FIGURE 10.5 Design of a permanent-magnet DC servo motor (synchronous motor).

The main feature of a synchronous servo motor is the uniform orbital angular velocity of the rotor and the stator magnetic field. This synchronism is required for forming a constant torque. For this, the rotor position is detected by the motor encoder. Based on the rotor position, the controller calculates and specifies the electrical angles of the stator currents. The amount of electricity is determined by the torque request. The speed change is accomplished via the change of the applied motor voltage and its frequency.

The allowable range of the speed-torque characteristics of a permanent magnet synchronous servo motor is limited via the

current and voltage limits of the drive controller. Their course is determined by the thermal limits of the motor

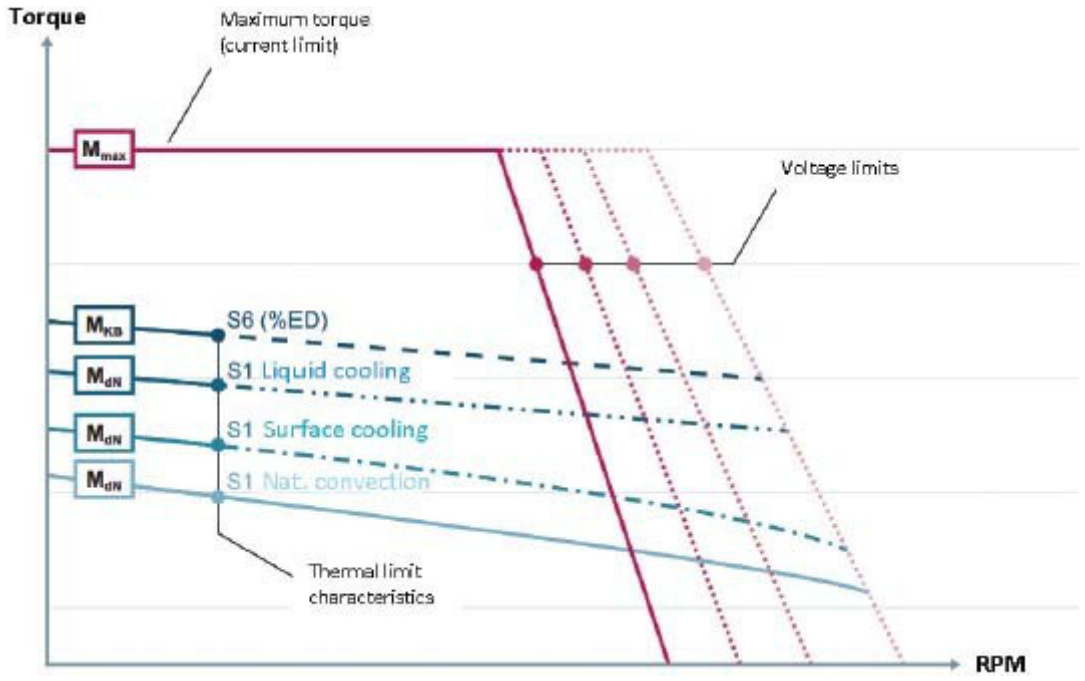

FIGURE 10.6 Speed-torque characteristics of a DC servo motor.

The course of the voltage-dependent limit characteristics is determined by the size of the DC link voltage and the corresponding motor-specific data, such as inductivity, resistance, and motor constant. DC link voltage can be changed through a different structure and the circuit of the supply modules and/or by the amount of the supply voltage. With this, the voltage limit is moved for a certain motor winding, and thus the range of the maximum speed is changed. When operating near the voltage limit, the speed-dependent reverse voltage in the winding approaches the maximum output voltage of the controller. The difference between these two voltages drives the current through the motor windings. Therefore, in the case of added load or a

change of speed, the current is limited to smaller values, and torque is reduced.

The second limit for maximum torque is determined by the short-term allowed current of the power semiconductor in the drive unit. This current limit may only be used for a short time to accelerate and decelerate the motor according to the specs of the device manufacturer.

The course of the thermal-limit characteristics is determined by the speed-dependent losses, for instance, hysteresis losses, and the type of cooling. Different types of cooling yield different characteristics. The thermal-limit characteristic is usually given for the rated torque (operating mode S1, continuous operation) and for the so-called short-time torque (operating mode S6, intermittent operation).

In modern synchronous servo motors, the rated torque is up to 200 Nm, and maximum torque values of more than 400 Nm are available. The maximum revolutions per minute reaches up to 10,000 Because of the availability of motor series with different sizes and lengths, the optimal match for the respective application is possible. The motor parameters of modern servo motors are stored in the motor encoder and are automatically loaded to the CNC system during initial commissioning. This makes commissioning considerably easier.

Additional options extend the range of applications of servo motors:

■ Different motor encoders, for instance, resolvers, high-resolution optical incremental encoders, and absolute encoders

■ Holding brake

■ Different types of cooling, such as convection, surface-ventilated, and liquid cooling

■ Increased degrees of protection (up to IP67/68)

■ Explosion-proof versions

Linear Drives

The use of direct drives with linear actuators offers new dimensions of productivity through increased dynamics and accuracy. The linear motor eliminates most of the mechanical transmission elements; the power is generated translationally and directly. The encoder that is necessary for ball screws is not necessary here

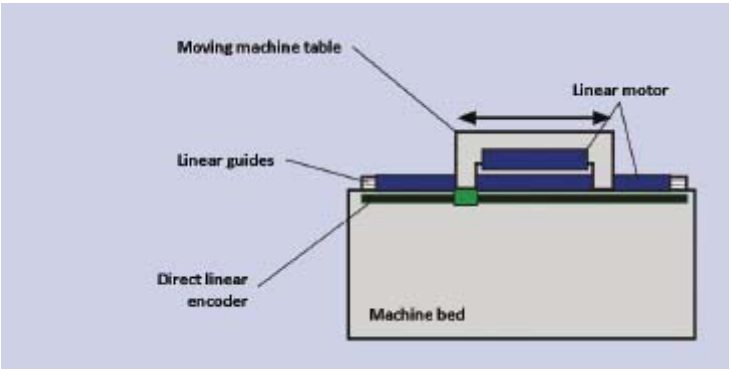

FIGURE 10.7 Sketch of a linear direct drive with linear motor.

The linear motor for machine tools typically comes as a motor kit. The primary and secondary parts are delivered individually and built into the machine by the manufacturer. The motor is completed by linear guides and a linear encoder. The construction of an axis equipped with a linear motor usually consists of:

- A primary section with three-phase winding
- One or more secondary segments
- A linear encoder
- Linear guides
- An energy supply
- Cooling system connections
- Carriage or machine construction

The feed forces for linear motors are limited by the lack of transmission options. The maximum feed forces of modern synchronous linear motors are 22,000 N per motor or primary section. Each axis can have two or more linear motors that are mechanically coupled for the multiplication of force. The

acceleration capability of the linear motor is, as opposed to ball-screw drives, reversely proportional to the linearly moved mass

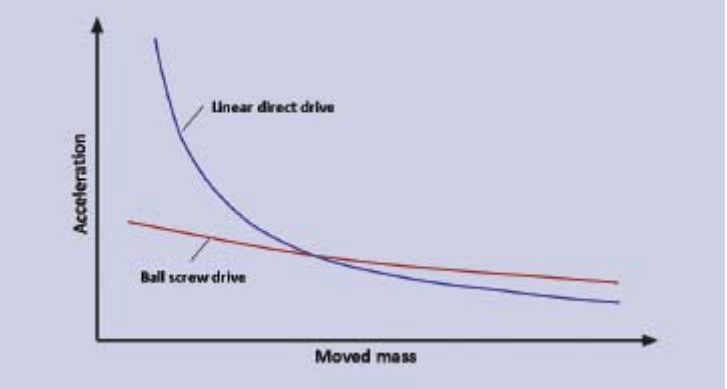

FIGURE 10.8 Acceleration characteristics of a linear motor and a ball-screw motor.

Figure 10.8 provides a comparison of the linear acceleration between a ball-screw drive and a linear direct drive. It is evident that the linear drive loses its dynamic advantages when large masses are moved. If a machine tool must achieve high acceleration values with a linear direct drive, the moved masses must be significantly reduced, and the natural frequencies of the mechanics must be increased.

A guideline for the mass ratio between the machine bed and the carriage is 10 or more; in this way, disturbing feedback from the anchoring of the foundation to the position and the speed-measuring circuit can be limited. Furthermore, a rigid attachment of the moved scanning head of the linear encoder system must be ensured.

The high attraction forces between primary and secondary parts must be considered when designing a carriage guide. The lateral rigidity is important when linear profile rail guides are used because at low values and different positions between the axis of the relative force and the axis of gravity, a tilting of the carriage may take place. This can result in the so-called pointer effect in the measuring system because during acceleration, it reports an incorrect position value to the control loop with the effect of instability in the speed control loop. Attention also must be paid to the possible presence of ferromagnetic chips that could possibly be attracted by the magnets of the secondary part. A tight cover must be installed to prevent this.

These points determine the stability of the position loop and velocity loop. The increased control bandwidth of the digital control loops can only lead to more dynamic and accurate machines if the natural frequencies of the mechanical axis assembly do not limit the achievable gain factors of the control loops. Therefore, it is necessary to realize the highest possible mechanical natural frequencies in order to achieve factors of approximately 20 to 30 (m/min)/mm with linear direct drives on machine tools and to make higher acceleration values possible.

Direct linear drives offer a low-wear and low-maintenance feed axis because of the smaller number of mechanical transmission elements, thus providing a high accuracy over a long service life. The demand for high feed forces in a very small unit with a low mass and adequate thermal decoupling of the motor components typically necessitates a liquid cooling system of the primary section.

TYPES OF LINEAR MOTORS

In principle, linear motors can have all the functional principles that rotary motors have. Yet modern machine tools exclusively use, in the same vein as rotary motors, the principle of three-phase synchronous servo motors.

Synchronous Linear Motors

Force is generated in a synchronous linear motor in the same way as torque is generated in rotary synchronous motors. The primary, or active, part has a three-phase winding. The secondary part (passive part) carries permanent magnets Both parts can be moved. Any given lengths can be traveled by joining several secondary segments.

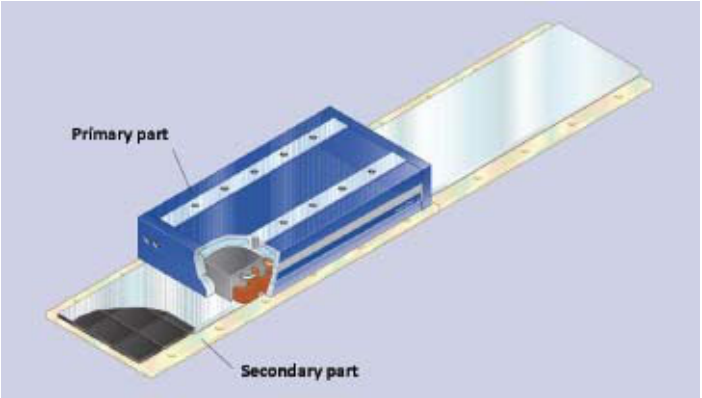

FIGURE 10.9 Sketch of a synchronous linear motor.

The linear motor is significantly more expensive than electromechanical drives for long travels because of high magnet prices. For a travel up to 1 m, which is typical of most machine tools or machining centers, the cost difference between linear drive and ball-screw drive with a rotary servo motor is insignificant. For

very short travels, such as for the traverse axis found on many lathes, it can be useful to permanently mount the primary and secondary parts on the slide. This arrangement can save the supply of power and coolant to the moved element.

Analogous to the speed-torque curve of the rotary motor versus linear motors, because of the translatory sizes, a force-speed curve can be specified. The course and key data of this characteristic curve are determined by the DC link voltage and the corresponding motor-specific data, such as inductivity, resistance, and motor constant. Speed adjustments can be made with different DC link voltages or motor windings

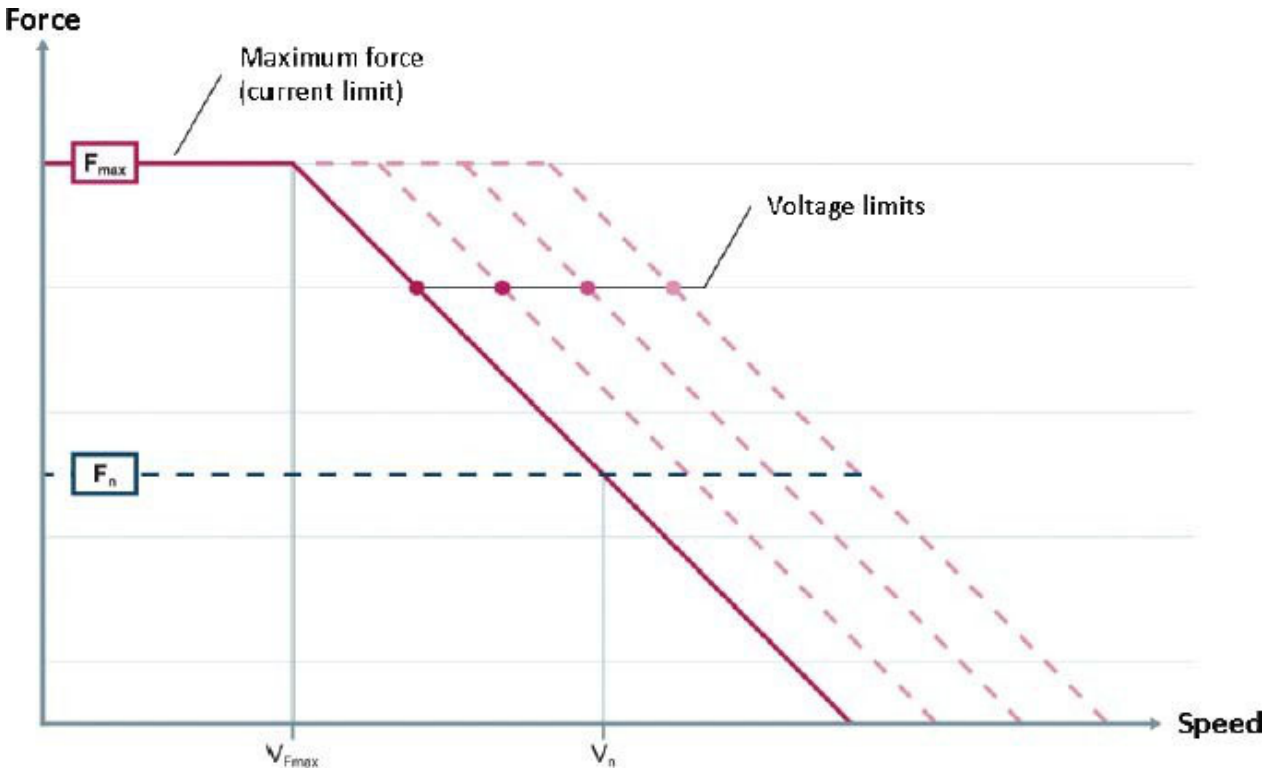

FIGURE 10.10 Characteristic graphs of a linear motor.

The maximum force is available up to the speed With increasing speed, the difference between the output voltage of the drive

regulator and the speed-dependent counter voltage is reduced. This leads to a reduction in the maximum feed force with increasing speed. The rated force is available without a speed-dependent reduction up to the rated speed of the motor.

The modular systems of modern synchronous linear motors allow great freedom of design given the availability of different primary part sizes and lengths and different secondary segment lengths. Today, linear motors on machine tools typically have a feed rate of 120 m/min and accelerations of 10 to 20 The achievable dynamics are limited by the mechanical machine elements. Linear motors can reach speeds of more than 300 m/min and accelerations of more than 100 for handling applications. Appropriate cooling and encapsulation measures guarantee the thermally neutral behavior of the motor and a high degree of protection and reliability even under adverse operation conditions.

ADVANTAGES/DISADVANTAGES OF LINEAR DRIVES

The elimination of additional transmission elements results in a series of advantages:

- Low wear and therefore long service life

- No backlash, no elasticity of the drive train, and great dynamic and static stiffness

- Low total mass and a small number of components

- High acceleration rate

In conjunction with digital regulators, a high performance with a large factor is possible. Thus a low servo lag and good positioning accuracy, even at high speeds, can be reached.

The main disadvantage is the low efficiency and high power loss, respectively. The operation generates much heat in the linear motor and necessitates additional cooling measures.

CONNECTION OF THE DRIVES TO THE CNC SYSTEM

The numerical control of machine axes takes place mainly in position control loops. An interpolator in the CNC system makes cyclical calculations of the position target values for each machine axis. Each CNC axis follows these values. Thus both the precise control of individual axes and the exact 2D or 3D path control of multiple axes take place. The accuracy of the interpolated position target values, the measurement accuracy, and the exact times of the actual value acquisition and processing are equally important for the precise coordination of the axes.

In earlier analog drives, the CNC system transferred analog speed target values. The position control took place in the controller. The achievable accuracy and the number of possible interpolated axes were limited with this target speed interface.

For digital drives, the entire position control with a subordinate speed and current control loop, many basic functions, and the fine interpolation with extremely short cycle times take place directly in the drive. In comparison with position control in the CNC system, this results in significantly higher accuracies at higher speeds. At the same time, the CNC system is relieved because only actual position values are transferred to all drives. To calculate the next interpolation step, the CNC requires the actual position values of the drives from the actual position detectors. This cyclic data exchange in the interpolation cycle of the CNC system allows synchronized operation of almost any number of drives

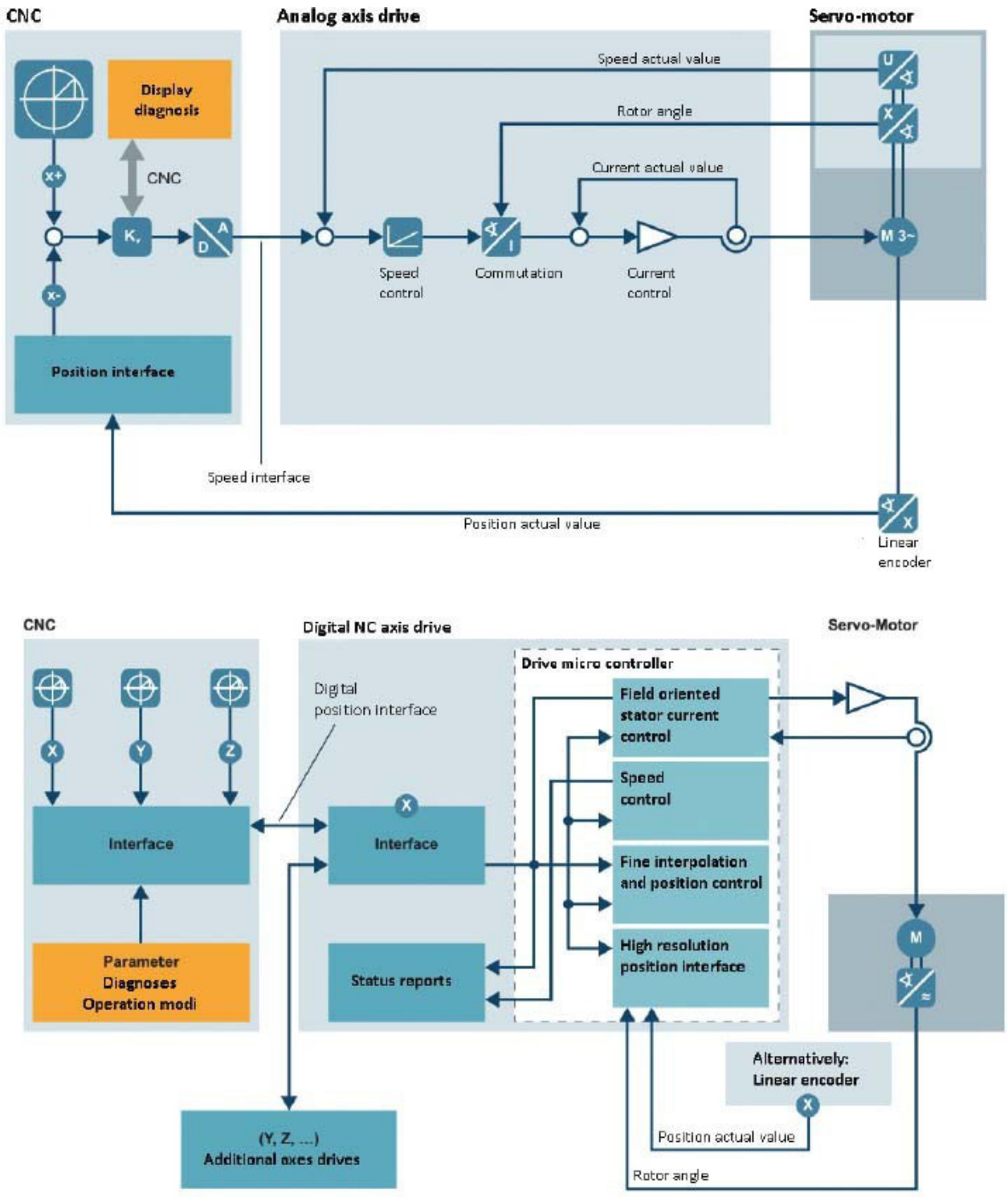

FIGURE 10.11 Principle comparison of an analog versus digital CNC axis drive.

A liberal use of these advantages is only possible with appropriately open digital interfaces between the CNC and drive controller. But company-specific solutions are also used. Real-time behavior in the microsecond range and clock synchronicity of the data transmission are required. Appropriate standardization led to industrial solutions so that CNC and drives from different manufacturers can communicate with each other. The current state of open standards is an Ethernet-based infrastructure. The physical level and the data link layers of the fast Ethernet with speeds presently up to 100 Mb/s can be used for the diverse requirements of data transmission to the drives in CNC machines. In addition, TCP/IP communication is possible, for instance, for status messages to control and monitor installations that are placed outside the CNC system. Standardized solutions are, for instance, PROFINET, SERCOS III, and EtherCAT field buses.

Thus the synchronization of almost any number of drives is possible. The use of these benefits requires appropriate digital interfaces between the CNC system and drive regulator (e.g., a SERCOS interface). Open standardized and proprietary interfaces are available on the market. Data transmission can be serial and/or parallel via optical fibers or wired. In each case, a real-time transfer of signals is required because in addition to the position or speed target value signals sent to the drive controller, for instance, for security functions, actual values are transferred back to the CNC. Given the current state of the open standardized interfaces, data between the CNC system and controller travel via Ethernet. By using the physical layer and the data-link layer of the Fast Ethernet with speeds presently up to 100 Mb/s, the diverse tasks of the data transfer in machines can be accomplished.

Digital drives work cyclically, meaning that all target and actual values must be updated for all drives in every interpolation cycle of the CNC (see Figure Use of the Ethernet allows for a standard open IT communication, for instance, for status messages to control and monitor installations that are placed outside the CNC system.

The commissioning of digital drives and adaptation of the parameters to different machines and CNC systems are done by entering the parameters via the control panel or an external commissioning PC. Modern digital drives offer even more functions to relieve the CNC. Thus standard procedures, such as referencing, are only issued by the CNC as a command to the drive. The drive performs the function automatically and reports its status back to the CNC. In addition, extensive diagnostic functions are standard, such as the so-called oscilloscope function for displaying the course of random actual and target vales in several channels. Costs for external measurement systems thus can be saved.

ENCODER

The axis movements in CNC machine tools and in many other similar machines must be controlled with great precision. This is done with the help of closed-loop position control that is comprised of a position-measuring device, or and a controllable drive. During operation, the encoder constantly captures the position of the moved element. This value is then compared with the predetermined target value for the position; if there is a deviation between the actual and nominal values, the feed drive is given an appropriate correction.

The position encoder and digital control circuits must be very precise. Position and speed control loops must compensate for the disturbances of the machining forces and mechanical transmission elements quickly and as completely as possible. The position encoder must be protected from external influences so that the position control loop can read the actual position in a range from 0.001 mm to a few nanometers. Rotary encoders must read with a resolution of 0.001 degree with an accuracy of a few arc seconds. They must maintain accuracy at speeds up to 200 m/min and a few thousand revolutions per minute, and they must withstand accelerations of a multiple of the Earth's gravitational acceleration.

A direct measuring system is arranged very close to the machined contour in order to minimize tilting error in the moving part of the feed axis. This kind of measurement results in the

best workpiece accuracy. In the case of a linear drive with no backlash, the linear scale is a systemic part of a direct measuring system. There should be no difficulties with the stability of the position control loop and the adjustment a high factor. Period length, resolution sensitivity, and natural frequency must satisfy specific requirements because the actual speed values and the commutation signals are derived from this measuring system for the winding. If a linear scale is used with lead-screw drive, workpiece accuracy is compromised by the reversal error caused by backlash and elasticities in the mechanical transmission elements and the mechanical natural frequencies. Workpiece accuracy is therefore possibly lower than with an indirect measuring system.

In an indirect measuring system, the actual position is derived via the angular position of the lead screw, gear wheel, or servo motor. Reversal errors and lead-screw pitch errors that are located behind the measuring point become evident as permanent position deviations in the workpiece. It is possible to partially control these in the CNC system (e.g., with spindle pitch error compensation). But even if, as is the case with this indirect measuring, the mechanical transmission elements are outside the position and/or speed control loop, the feedback of their oscillatory masses affects the stability of the encoder and diminishes, as a result, the adjustable controller gains. The possible factor, and hence workpiece accuracy, becomes smaller.

SUMMARY

Feed drives work predominantly with CNC systems and permanent-magnet synchronous servo motors. Small machine tools can have linear direct drives or electromechanical ball screw drives. As a rule, the natural frequencies of the mechanics stipulate the limits for the control range of position and speed control loops and thus also for the achievable dynamics and accuracy of the machine.

For linear direct drives, the driving force of the motor directly impacts and drives the slide, resulting in the following advantages:

■ Simple, low-maintenance mechanical design with high rigidity

■ High achievable accuracy and no backlash

■ High dynamic movement due to high speed and high acceleration

■ No technical limitation of the travel path

Yet the following disadvantages should be noted:

■ There is limited feed force because there is no adjustment via a transmission.

■ No mechanical parts dampen load shocks; rigidity must be achieved by the control alone.

■ Often water cooling is required to carry process heat away from the machine.

■ Long traverse paths are expensive because of the high cost of permanent magnets of the secondary parts.

Given an appropriate design, linear direct drives can be more dynamic and accurate than electromechanical feed drives. Yet a simple replacement of a threaded spindle drive on a given machine with a linear actuator without consideration of the abovementioned requirements is not expedient. In addition, the high attraction forces between the primary and secondary parts of the guide elements must be safely dissipated in the machine bed; the presence of ferromagnetic chips mandates a tight seal of the secondary parts to protect the permanent magnets.

The regulatory bandwidth of feed drives with ball screws is usually determined by several natural frequencies of the mechanical system. But here the designer has more measures to improve identified vulnerabilities. It is easier to achieve an optimum for feed force, speed, and acceleration, that are determined by the following parameters:

■ Lead-screw pitch

■ Gear ratio

■ Mass moment of inertia

■ Greater choice of synchronous servo motors with more suitable motor constants

The parameters influencing the bandwidth of the control loops, such as tension, compression, and torsional rigidity of the lead spindle, and the rigidity of the spindle bearing are also subject to optimization. Thus factors of about 5 (m/min)/mm can be achieved with this well-proven drive.

The factor is one of the factors that determine machining accuracy of a feed axis. The factor indicates at which speed in meters per minute the lag, also called *following* between the position command value and the actual position value at the position controller input reaches 1 mm. It is also called the *velocity* In terms of control technology, it is the proportional coefficient of the position controller. The adjustable value of this parameter is determined by the

characteristics of the feed axis. Essentially these are:

■ The dynamic properties of the subordinate speed and current control loops, which depend on the sampling times and the possible rise and settling times or the their loop bandwidths, respectively.

■ The feedback of natural frequencies of the mechanical transmission elements, which is determined by mass and stiffness.

IMPORTANT POINTS TO REMEMBER

1. With each motion of an axis, there is a lag that is proportional to the speed of the movement.

2. The size of the lag is determined by the *KV* factor. This factor indicates the speed in meters per minute at which the axis can be moved until a following error of 1 mm has been reached.

3. If the control loop gain is too high, vibrations will occur in the position control loop that will affect the quality of the machined workpiece.

4. With digital drive controllers, the control of current (torque or force), spindle revolutions (speed), and position is performed digitally, by means of microprocessors. This achieves higher accuracies and reaction rates than with analog controllers.

5. The stiffness of the position-controlled feed drive is the quotient of the torque that is exerted on the drive shaft and the angular deviation of the shaft.

6. The dynamic of a position-controlled feed drive is the temporal behavior during changes of force, torque, speed, or acceleration. The shorter the settling time, the higher is the dynamics of the control circuits.

7. Feed drives on machine tools should meet the following requirements:

a. Speed adjustment range: ≥1:30,000

b. Good dynamic behavior in the speed control loop, including mechanics, with a control loop bandwidth ≥ 100 Hz

c. Low force or torque ripples; caused path ripple ≤ 0.25 mm

d. Linearity between target and actual values, high sensitivity on reversal of direction

e. High *KV* factor; for a linear drive, ~20 to 30 (m/min)/mm; for an electromechanical drive, ~5 to 6 (m/min)/mm

f. High resolution of the measuring system; for a linear drive, ~10 nm; for an electromechanical drive, ~1 nm

g. Low operation heat, small construction volume, and no maintenance

8. In most cases, water cooling is required for linear drives in order to keep operational heat out of the machine.

9. Linear direct drives and electromechanical drives with synchronous servo motors, both with digital position, speed, and

power (force or torque) control circuits, are state-of-the-art for feed drives on machine tools and in many motion-control applications.

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Basically, when configuring regulated main drives, the decision has to be made whether synchronous or asynchronous motors should be used. For this decision, it is decisive whether the motor is operated in a speed control loop, for instance, to power the spindles of drilling and milling tools, or in a position control loop, for instance, in a lathe with an additional drive. Speed-

controlled electric motors are used as spindle drives of machine tools to perform two main tasks:

■ To provide torque and speed for the work process

■ For interpolation of the main spindle rotation with the feed drives on lathes and machining centers that require the operation as a

Speed control of synchronous and asynchronous motors is generally done based on the voltage and frequency of the supplied direct current. This requires a special upstream frequency converter. A rotary encoder in the motor continuously measures revolutions per minute and rotor position and reports these values to the inverter. From this input, the control electronics determines the required *electronic commutation* to advance the rotary field and also the actual revolutions per minute.

REQUIREMENTS FOR MAIN SPINDLE DRIVES

The main drives of CNC machines must meet additional requirements for automatic operation that go far beyond those of conventional drives. These are in particular:

■ *Automated speed* Automatic operation requires programmable automatic speed change.

■ *Precisely stepped but preferably stepless speed* A CNC machines is an expensive production means with many hours of operation in a given time period. Therefore, it is important to make optimal use of modern tools. For example, stepless speed change is required on a lathe to maintain constant cutting speed when cutting a face or cone.

■ *Large speed control* CNC machines are universal machines that process different workpieces using various tools. For this, the work spindle must cover a large speed range without the use of a transmission. The entire speed range must be provided by the motor only.

■ *Very fast speed* Every speed change means a loss of time. This is especially evident in cases of frequent tool changes on machines with rotating tools, for instance, on machining centers. These machines have automatic tool changers, and for each tool change, the spindle must be stopped and accelerated again. This demands a quick acceleration and deceleration of the spindle motor.

■ *High drive* The automatic machining process of a CNC machine makes human intervention unnecessary. It allows for a completely closed workspace. Thus working speeds can be realized that make full use of modern cutting tools. This is accomplished with drives with a performance that is a multiple of that of conventional machines.

■ *High range of constant* The high drive power should be available over the largest possible speed range.

■ *High torque at low* In the lower speed range, the highest possible torque should be available.

■ *Small footprint and low* In many CNC machines, the main drive motor is part of a unit and is being moved with it constantly. This leads to the demand for a possibly low mass and size of the motor. In this way, the achievable acceleration of the unit will not be diminished.

■ *Low heat* The adverse effect of local heating of the machine on the accuracy of the machining process has already been mentioned (see Section 4.3).

TYPES OF MAIN SPINDLE DRIVES

Figure 11.1 shows a comparison of the three different motor principles. The same motor types that are used for feed drives are in principle used for the main spindle drives. Here a speed-controlled asynchronous motor is preferred because of its positive properties such as low price, simple and robust construction, low maintenance, and a frequency converter that provides for speed control. This type of motor is available in a variety of types. It has replaced the DC motor that was dominant for a long time. Depending on the main drive (see Figure motors can take the form of housed motors or kit motors with a hollow shaft

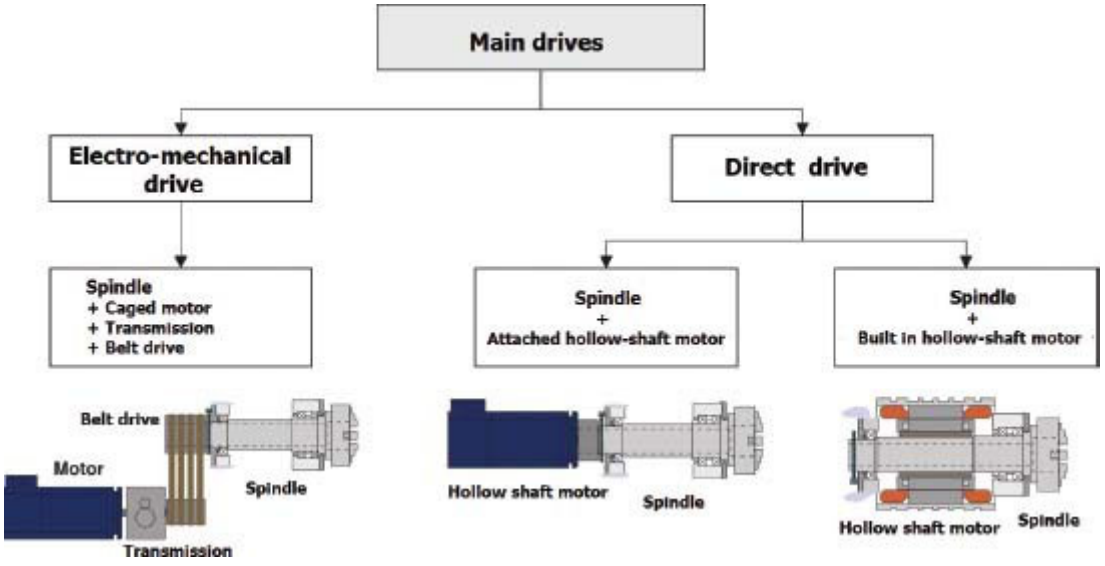

FIGURE 11.1 Kinds of main drives.

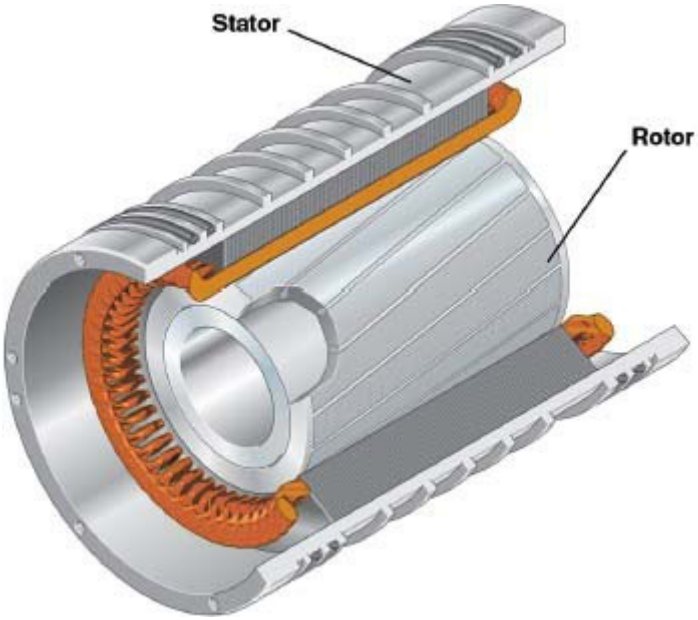

FIGURE 11.2 DC asynchronous motor as a kit with a hollow shaft.

In order to ensure full torque at low speeds and even down to a speed of 0 rpm, housed motors for main spindle drives are always designed with external ventilation or liquid cooling. Kit motors for direct installation in the spindle are, as a rule, always liquid cooled because it is necessary to ensure both high power density in a reasonably small space and a thermally neutral signature.

DESIGNS OF MAIN SPINDLE DRIVES

The classic design of the main drive used to be the coupling of a housed motor with the tool spindle via a geared and/or belt transmission, in some cases in multiple stages. This arrangement offers the advantage that the motor is thermally separated from the machining space and from the spindle. The motor can be connected outside the machining space; this means that main spindle motors with standard installation dimensions can be used. However, the belt drive limits the speed, stiffness, and dynamic characteristics of the drive and thus the productivity of the entire machine tool.

These disadvantages have led to the use of directly driven spindles. The belt or gear drive is eliminated—the torque is transmitted via the rotor of the drive motor directly to the spindle shaft. This makes the speed of the system very stable and allows high amplification factors and short acceleration and braking times. In order to clamp the workpiece, the motor is equipped with a hollow shaft. Because the heat input from the motor does not go directly into the spindle, the motor can have external ventilation. Liquid cooling is an option and can be used to further increase the motor's use. This arrangement is especially beneficial in machining centers.

Combining the drive motor with the spindle created the *motor* a design that generally requires liquid cooling. This type of main spindle drive design is increasingly becoming the standard in the modern machine tool industry.

In both these direct-drive designs, the lack of mechanical speed adaptation means that the following requirements become particularly important:

- High power density
- Large speed-adjustment range
- Large range with constant power
- High torque at low speeds
- High maximum speed

Three-Phase Asynchronous Motors

Speed-controlled asynchronous motors have become standard as main drives owing to their positive features, such as low price, simple and rugged design, and low maintenance requirements. The speed of a three-phase asynchronous motor can be changed over a broad range by changing the output frequency and output voltage of the converter that is supplying the power. The speed/torque characteristics of three-phase asynchronous motors operated with converters are provided in the form of characteristic curves This would indicate the speed range, purely mathematically speaking, up to the infinite. The behavior of the characteristic curves is determined by the strength of the DC link voltage and the corresponding motor-specific data, such as inductivity, resistance, motor constants, and tilting moment.

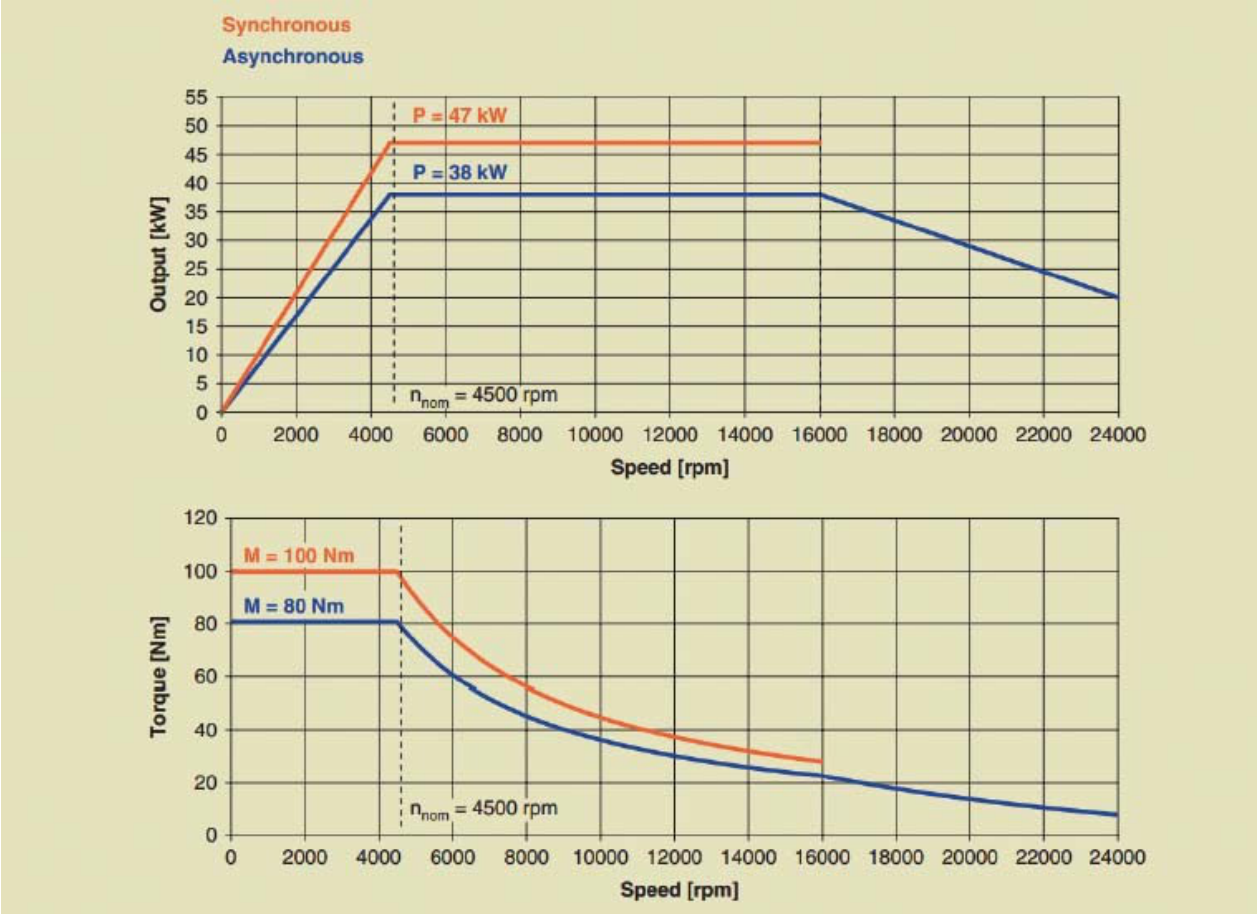

FIGURE 11.3 Rpm control range of synchronous and asynchronous motors with same power and same torque.

In the basic speed range, the voltage and frequency increase proportionally up to the rated speed. If externally cooled, the motor generates a constant torque. Once the voltage reaches its maximum value at the rated speed, it is only possible to increase the frequency. From here the so-called field-weakening range starts. The field-weakening range begins with a range of constant output in which the torque decreases hyperbolically, that is, inversely proportional to the frequency/speed If the speed/supply frequency is increased further, the tilting moment or tilting limit of the motor will be reached. The tilting moment of an asynchronous motor decreases to the square of the frequency or speed, respectively In contrast to operation on the

power grit, the tilting limit of the motor does not express an actual limit given the use of modern converters and an appropriate control system. This is because the stability of the motor, meaning the drastic reduction of torque to a possible standstill, is avoided. The maximum speed thus is limited only by hardware such as bearings, rotors, rotor mountings, and so on.

The characteristic curves generally are indicated for continuous operation (operating mode S1) and intermittent service (operating mode S6) with various operating times, often 25%, 40%, or 60%. The closed-loop control or the control structure, respectively, of main drive motors is largely the same as those of a modern feed drive. The main-drive controller encountered today merely has a few supplementary functions, for example, for special field control. Thus operation on a lathe, that is, the interpolation of the main spindle with the feed drive, as is often required today, can be accomplished.

Three-Phase Synchronous Motors

In machine tools, synchronous motors are used primarily as feed drives. In special applications with demands for greater power density and temperature stability, the use of permanent-magnet three-phase synchronous motors in main drives can be called for. Proven modern motor principles and closed-loop control methods have made it possible to implement such drives in series-produced machines. At present, speed-controlled synchronous motors are used primarily as main drives when the following requirements have to be met:

- Extremely high requirements as to machining quality and smooth operation

- Extremely short times for run-up or speed changes

■ Standstill torque

■ Small size

This is especially the case in high-quality lathes and lathe/milling centers when high-quality drilling and milling operations have to be executed on the end faces or lateral surfaces of the workpiece.

TYPES OF THREE-PHASE SYNCHRONOUS MOTORS

Two main types of synchronous motors are available:

1. *High-speed* High-speed motors are mainly four-pole synchronous motors that are used for milling applications. These motors have been optimized for speeds of up to 40,000 rpm and a wide speed-adjustment range. They are used mainly with closed-loop speed control via frequency converters. The speed adjustment range is about 1:3 in the field-weakening range. In purely mathematical terms, the overall speed-adjustment range reaches to infinity.

2. *High-torque* For high-torque applications six- or eight-pole synchronous motors are available. They have been developed for lathes, grinding machines, and rotary tables with moderate speeds and very high torque.

The high-speed synchronous motor is more dominant and prevalent than the torque motor. The complicated design and limited number of torque motors manufactured account for the high price.

ADVANTAGES AND DISADVANTAGES OF THREE-PHASE SYNCHRONOUS MOTORS

Synchronous spindle drives have the following advantages compared with lower-priced asynchronous motors:

■ High efficiency

■ Low moment of inertia and thus good dynamic characteristics

■ Low maintenance (in the case of rotors without slip-ring rotors)

■ Speed independent of load

■ No electrical power necessary for field excitation

■ Up to 60% higher torque and thus more compact machine designs

■ Extremely short run-up and braking times (50%) owing to the torque

■ High torque even during standstill and change of direction of rotation

■ Compact construction, for instance, for lathes and vertical milling machines, owing to the elimination of mechanical components such as motor mountings, belt drives, gearboxes, and spindle encoders

■ High power density when water cooled

■ Maximum rpm of 40,000 and torque greater than 820 Nm

■ Low rotor heating owing to equipment with permanent magnets. (The result is significantly less power loss in the rotor in the lower speed range and thus less warming of the bearing and spindle expansion.)

■ Extremely high precision on the workpiece thanks to smooth, uniform spindle operation even at extremely low speeds because there are no transverse drive forces

■ Interpolating operation with the feed drives, for example, in lathes

■ Larger internal rotor bores than cage rotors of asynchronous motors with the same external diameter (This is an advantage for the processing of bar stock on automatic lathes and for greater spindle stiffness to the greater shaft diameter for milling spindles.)

■ Increased stiffness of the spindle drive thanks to mounting of the motor components between the main spindle bearings

■ Less cooling necessary for the same power output compared with asynchronous motors. (This means greater efficiency.)

■ Only one encoder for detecting the motor speed and spindle position

■ Easy servicing by exchanging complete motor spindles

These disadvantages need to be considered:

■ Expensive magnet materials raise costs for permanent-magnet motors.

■ Elaborate closed-loop control requirements (use of frequency converters)

■ Possibly annoying whistling noise from the motor

■ Lower maximum speeds than asynchronous motors in order to avoid delaminating the magnets from the rotor

■ No field-weakening range as with the asynchronous motor, whose stable cage rotor allows higher speeds

IMPORTANT POINTS TO REMEMBER

1. The speed-controlled asynchronous motor, because of its positive properties such as low price, simple and robust design, and low maintenance, is preferably used as a standard main drive.

2. In order to have full torque at low speeds down to 0 rpm, cage motors always have added ventilation or liquid cooling.

3. Installation of a motor spindle typically requires liquid cooling. This design as a main spindle drive is increasingly becoming the standard in modern machine tool engineering.

4. The control of the asynchronous motor largely corresponds to that of a modern feed drive. Modern main-drive controllers are supplemented (e.g., for special field controls).

5. Main spindle synchronous drives offer highest accuracy on the workpiece due to quiet, uniform spindle run even at very low speeds because there are no transverse forces.

6. Synchronous main spindle motors are the preferred drive for position-controlled

7. Synchronous motors in tool machines are predominantly used as a feed drive.

8. Synchronous motors are available in two main versions: high-speed motors and high-torque motors.

9. The high-speed synchronous motor has a much greater importance and use than the expensive torque motor with its more extensive windings and low-volume production quantities.

10. Synchronous motors are designed for maximum revolutions of up to 40,000 min-1 and torques of greater than 820 Nm.

Nm. Nm. Nm. Nm. Nm. Nm.

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PROCEDURE

When designing an electric feed drive, the following main selection criteria should be considered:

■ Maximum torque of the application does not exceed the motor torque.

■ Maximum speed does not exceed the maximum speed of the motor.

■ Effective torque does not exceed the rated torque of the motor.

■ Motor design is based on operating conditions (e.g., degree of protection).

The conditions must be assessed separately for each individual axis. Figure 12.1 shows the basic procedure for dimensioning an electromechanical feed drive.

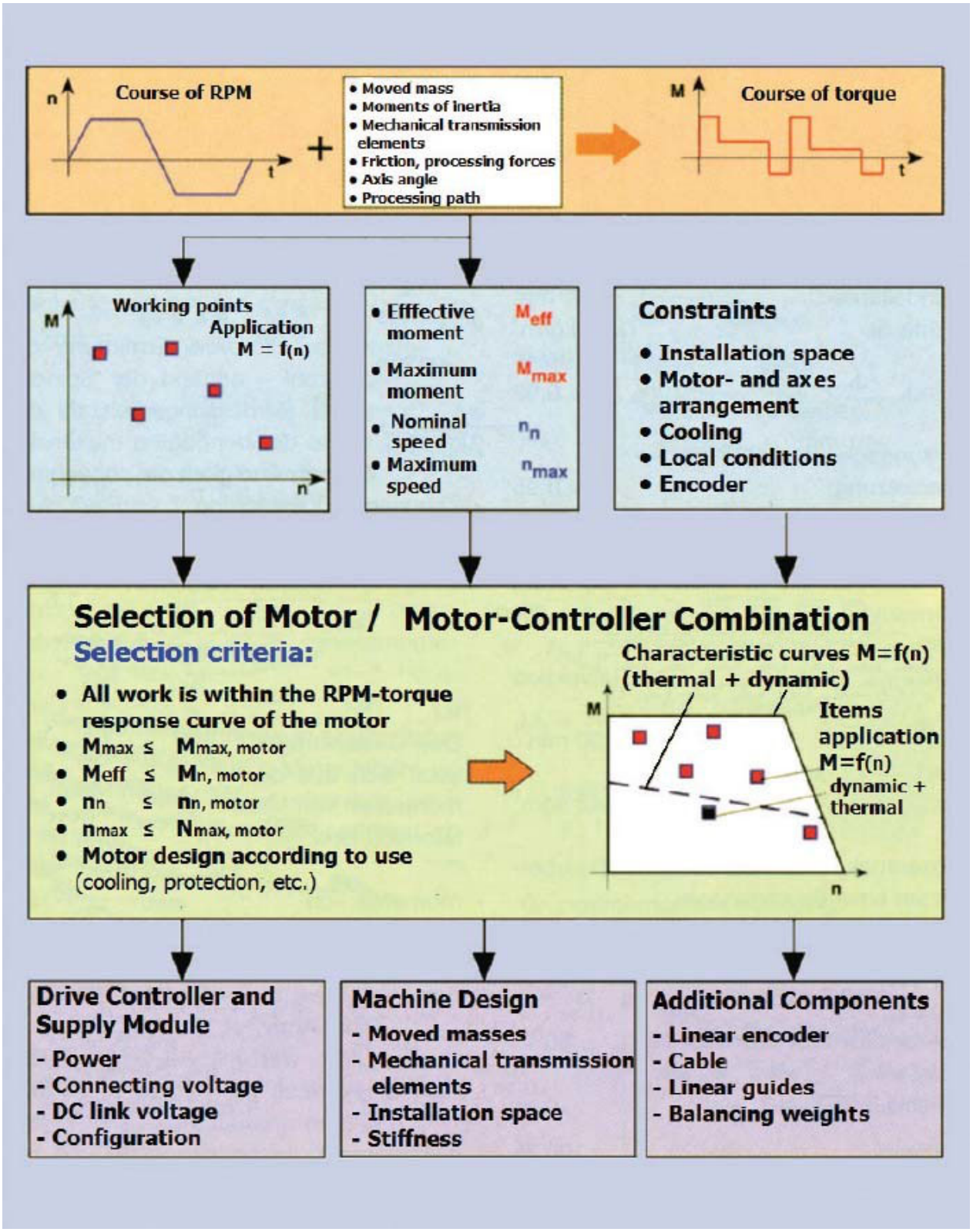

FIGURE 12.1 Procedure for dimensioning a feed drive.

The configuration and selection of linear direct drives are rather easy. The process-related feed forces, speeds, and accelerations can be used directly for drive selection without conversion. Several calculations are required, however, for the dimensioning of rotary drives. The advantages of CAD programs include:

- Fast and safe drive design
- Practice-oriented user guidance
- Easy and fast variation options
- Display of diagrams, such as traversing profiles, motor characteristics, etc.
- Clear documentation of the design
- Predefined input masks and examples
- Selection of motor/controller combinations
- Interfaces for programs for RFQ (request for quotation)
- Updating data via the internet

EXAMPLE

Detailed information about the travel cycle is mostly not known or not exactly possible for machine tools. This is because of the wide variety of parts and possible users that operate these machines. Drive dimensioning is done on the basis of the relative lengths of different operating phases; these are based on empirical values of the machine manufacturer or user. The following example explains the procedure.

The axis arrangement shown in Figure 12.2 was selected as a feed axis of a machining center with:

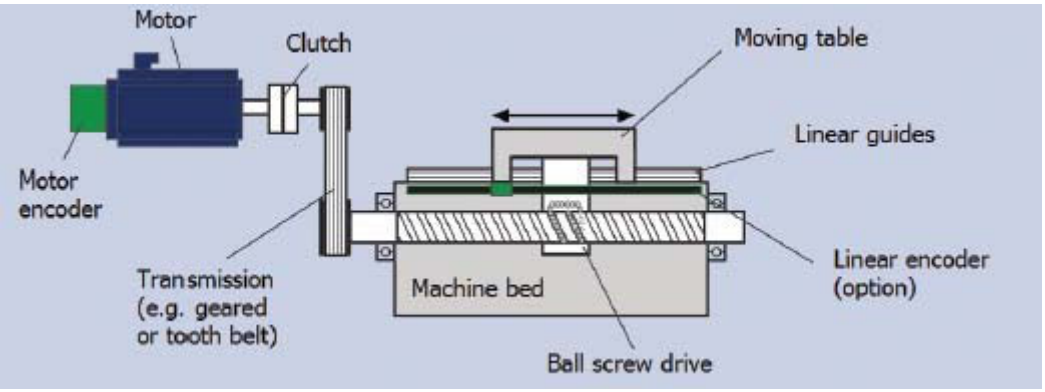

FIGURE 12.2 Design of an electromechanical feed drive with ball-screw drive.

- Rotary servo motor

- Ball-screw-driven spindle

■ Tooth belt between motor and spindle

An available motor based on the manufacturer's catalog must be examined for possible use plus a suitable transmission of the toothed belt for speed adjustment.

Given Data

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Available Motor

Motor Motor

Motor Motor

Motor Motor

Motor Motor

Percentage of Individual Processing or Movements

Movements

Movements

Movements

Movements

Movements

Movements

Movements

Choice of Toothed-Belt Transmission

The spindle speed results from the maximum feed rate and the spindle pitch

$$n_s = \frac{v_{ft}}{h_p} = \frac{40\ \text{m/min}}{0.02\ \text{m}} = 2{,}000\ \text{min}^{-1}$$

Given the rated motor rpm the gear ratio results in a toothed-belt ratio of

$$i = \frac{n_n}{n_p} = \frac{3{,}200\ \text{min}^{-1}}{2{,}000\ \text{min}^{-1}} = 1.6$$

Alternatively, the toothed-belt ratio *i* can be calculated given the spindle pitch, rated rpm of the motor, and required maximum feed rate:

$$i = \frac{h_s \times n_n}{v_c} = \frac{0.02\ \text{m} \times 3{,}200\ \text{min}^{-1}}{40\ \text{m/min}} = 1.6$$

Determination of the Moment of Inertia

The total moment of inertia of the axis consists of the individual moments of inertia of the motor, spindle, and translationally moved mass; in this example, the moments of inertia of the clutches, toothed-belt drive, and so on are neglected for the sake of simplicity. To achieve a simple drive dimension that satisfies the requirements of the drive, these individual moments of inertia are combined and specified for the motor shaft. Thus moment of inertia of the spindle is:

$$J_s = \frac{\pi}{32} \times l_s \times \rho_s \times d^4 = \frac{\pi}{32} \times 0.7\ \text{m} \times 7{,}850\ \text{kg/m}^3 \times 0.063^4\ \text{m}^4 = 0.0085\ \text{kg} \cdot \text{m}^2$$

The moment of inertia of the linearly moved mass is:

$$J_L = \left(\frac{h_p}{2\pi}\right)^2 \times m_{tot} = \left(\frac{0.02\ \text{m}}{2\pi}\right)^2 \times 500\ \text{kg} = 0.005\ \text{kg} \cdot \text{m}^2$$

The reduced loaded moment of inertia relative to the motor shaft is:

$$J_{red} = \frac{J_s}{i^2} + \frac{J_{red}}{i^2} = \frac{0.0085\ \text{kg} \cdot \text{m}^2}{1.6^2}$$

$$+ \frac{0.005\ \text{kg} \cdot \text{m}^2}{1.6^2} = 0.005\ \text{kg} \cdot \text{m}^2$$

There is also a control-related requirement to create an approximate ratio of 1 for motor and load moment of inertia for rotating servo motors. The value of 1 is seldom reached; typically, a ratio of 1 to 2 is targeted in practice. The motor parameters, which in modern servo motors are stored in a data memory within the motor encoder, are optimized for this ratio in the factory.

The present case shows a ratio of motor-to-load moment of inertia of 0.72. Total moment of inertia, meaning the reduced-mass moment of inertia, related to the motor shaft is:

$$J_{tot} = J_m + \frac{J_s}{i^2} + \frac{J_{tot}}{i^2} = 0.003\ \text{kg} \cdot \text{m}^2$$

$$+ \frac{0.0085\ \text{kg} \cdot \text{m}^2}{1.6^2} + \frac{0.005\ \text{kg} \cdot \text{m}^2}{1.6^2} = 0.008\ \text{kg} \cdot \text{m}^2$$

Calculation of Torque

Calculation of the torque in the individual operating phases is shown below. The objective is to determine the maximum torque and the effective torque. The indication is based on the motor shaft, meaning that the ratio and the effi ciency of the toothed belt are taken into account.

Acceleration torque is:

$$M_a = \frac{a \times m_{tot} \times h_s}{2 \times \pi \times i \times \eta_s \times \eta_z}$$

$$= \frac{3\ \text{m/s}^2 \times 500\ \text{kg} \times 0.02\ \text{m}}{2 \times \pi \times 1.6 \times 0.92 \times 0.95} = 3.41\ \text{Nm}$$

Torque during operation is:

$$M_b = \frac{(F_b + F_0) \times h_s}{2 \times \pi \times i \times \eta_s \times \eta_z}$$

$$= \frac{2{,}500\ \text{N} \times 0.02\ \text{m}}{2 \times \pi \times 1.6 \times 0.92 \times 0.95} = 5.96\ \text{Nm}$$

The basic torque (friction) is:

$$M_0 = \frac{F_0 \times h_s}{2 \times \pi \times i \times \eta_s \times \eta_G}$$

$$= \frac{500\ \text{N} \times 0.02\ \text{m}}{2 \times \pi \times 1.6 \times 0.92 \times 0.95} = 1.14\ \text{Nm}$$

See Table 12.1 for the resulting torque and speed values during the individual processing phases.

TABLE 12.1 Calculations of Torque Values for Six Individual Operating Phases

Phases Phases Phases
Phases Phases

Phases Phases
Phases Phases
Phases Phases

Phases Phases
Phases Phases

Note: See Figure 12.3 for the duration of each operation.

Maximum Torque

In this example, the assumption is made that during acceleration and breaking, there are no machining forces, and therefore, only the basic force is at work. The maximum torque is therefore determined by the torque during machining; it is 6.83 Nm.

Effective Torque

The effective torque determines the thermal load of the drive motor and must not exceed the rated torque; otherwise, the motor will be thermally overloaded. The resulting torque values in the individual operating phases are shown in Figure

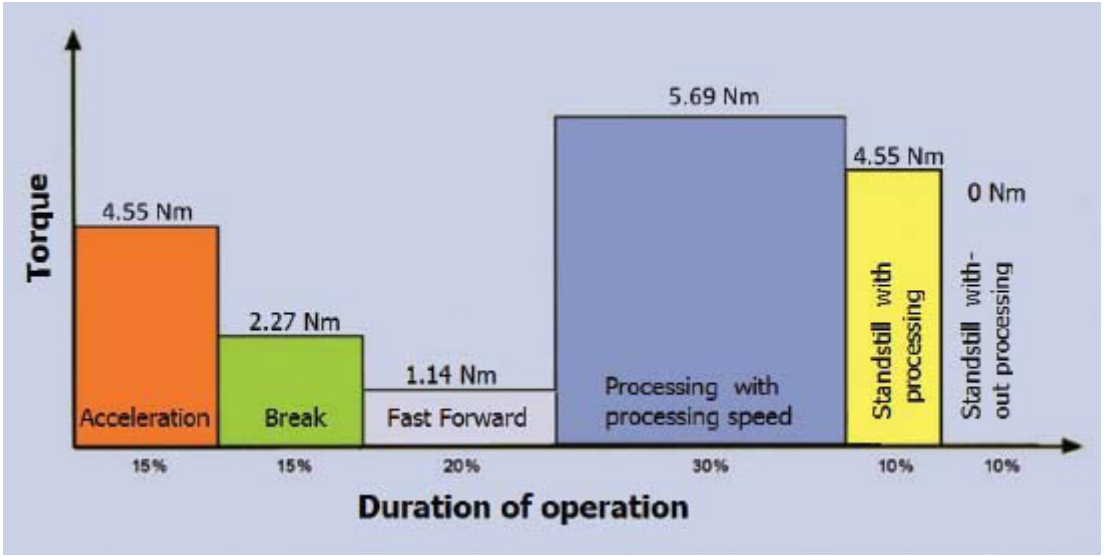

FIGURE 12.3 Torque values and switch-on duration of individual operations.

The effective torque can be calculated with the resulting torque values in the individual operating phases:

$$M_{eff} = \sqrt{\frac{\sum\left(M^2 \times DO_i\right)}{100\%}} = 4.62 \text{ Nm}$$

The effective torque is thus the root mean square of the resulting torque vales of the individual operating phases.

The average revolutions per minute are needed for the later calculation of the continuous power and are the arithmetic mean of the average revolutions per minute in the individual operating phases:

$$n_{avg} = \frac{\sum\left(v_i \times DO_i\right)}{100\%} = 1{,}360\,\text{min}^{-1}$$

Drive Power

The effective torque and the average revolutions per minute determine the continuous power of the motor and represent the operating moment within the thermal limit characteristic line. Calculation for the mechanical continuous power at the shaft of the motor is

$$P_{md} = 2 \times \pi \times \eta_{avg} \times M_{eff} = 2 \times \pi \times 1{,}360$$
$$\times 4.62 \text{ Nm/min} = 39{,}458.5 \text{ Nm/min}$$
$$P_{md} = 39{,}458.5 \text{ NM/min} = 657.6 \text{ Nm/s}$$
$$\text{m/min} = 39{,}458.5 \text{ Nm/min}$$
$$P_{md} = 657.6 \text{ Nm/s}/1{,}000 = 0.657 \text{ kW}$$
$$\text{(rounded: 0.66 kW)}$$

In the case of servo drives, the electrical power is generally specified as the dc link power of the converter. Concerning modular drive controllers, the dc link power of all drives determines the necessary power of the supply module.

The necessary dc link power results from the mechanical power and the electrical power dissipation of the motors and inverter. The required dc link power can be estimated with sufficient accuracy as follows:

$$P_{dc} = P_{md} \times 1.2 = 0.79 \text{ kW}$$

Checking the Motor Selection

Figure 12.4 shows the rpm/torque diagram of the motor in question and the most important operating moments of the

operating phases. All operating moments are within the S1 characteristic curve of the motor. *Conclusion:* The motor can be used, and it also has sufficient power reserve.

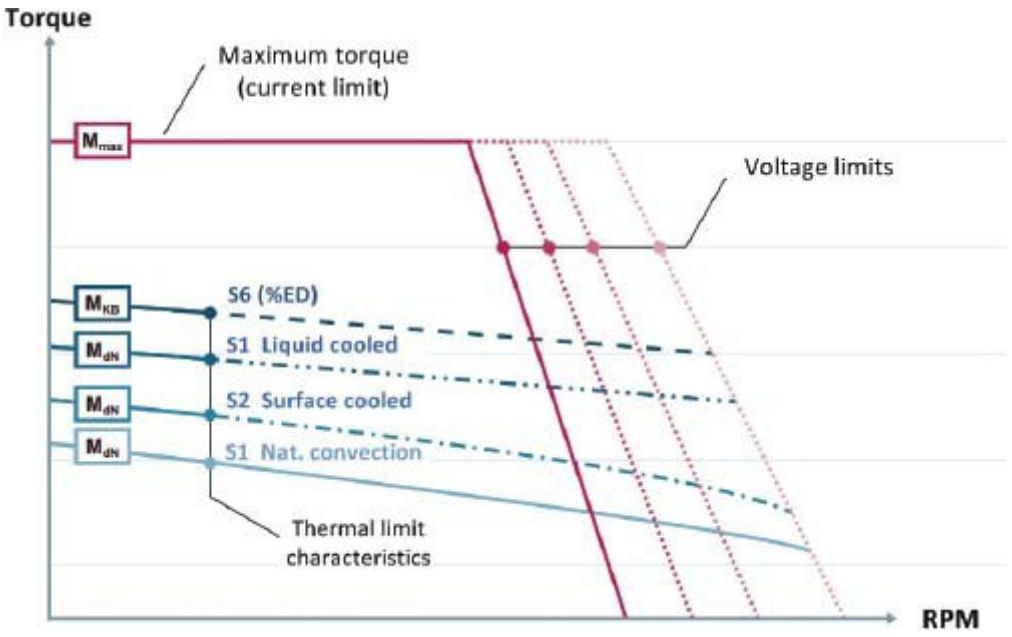

FIGURE 12.4 Rpm/torque diagram relative to the most relevant phases of the operation.

DIMENSIONING OF MAIN SPINDLE DRIVES

A main spindle drive basically consists of the same main components as a feed drive (see Figure except that the required drive power and speed are higher (see Figure and the design of the motors also differs from that of feed drives. The procedure for dimensioning main spindle drives essentially corresponds to that for feed drives. This is true especially when a load cycle determines the drive dimensioning.

In most cases, however, there are different speed and torque profiles corresponding to the cutting powers in question. These are mostly identical to the motor's characteristic curves (see Figure or are at least given as corresponding key data. Thus a simple drive selection is possible through a comparison of these basic data.

EXAMPLE

A built-in three-phase asynchronous motor should be used as a direct drive for the main spindle of a lathe. The lathe should accommodate workpieces with diameters of d = 35 to 95 mm at a cutting speed of 300 m/min. The cutting force is 2,800 N.

Problem: A suitable motor including an inverter must be selected. The necessary speed range is determined by the different workpiece diameters:

$$n = \frac{v_s}{\pi \times d}$$

This results in a maximum revolutions per minute of 2,728 for the smallest workpiece diameter and 1,005 for the largest workpiece diameter. The required torque also depends on the workpiece diameter:

$$M = \frac{F_s \times d}{2}$$

Sought: For the largest workpiece diameter, the highest moment needed. For a d = 95 mm workpiece diameter, the necessary torque of 133 Nm and for d = 35 mm, a torque of only 49 Nm is needed

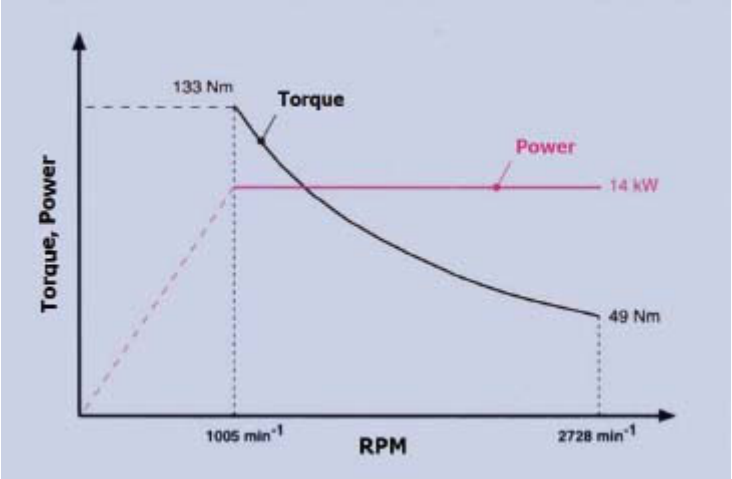

FIGURE 12.5 Required torque and drive power of

The required drive power is calculated using torque and speed:

$$P = 2 \times \pi \times n \times M$$

The entire speed range from 1,005 to 2,728 requires a constant drive power of 14 kW.

The diagram in Figure 12.5 shows the curves of torque and power above the revolutions per minute:

minute: minute: minute: minute:

minute: minute: minute: minute:

minute: minute:

minute: minute:

minute: minute:

minute: minute:

SUMMARY

Modern applications predominantly use feed drives consisting of a permanent-magnet three-phase motor with a ball-screw drive. This yields the optimum of speed, acceleration, accuracy, and service time through the following parameters:

- Spindle pitch
- Gear ratio motor/spindle
- Critical speed
- Moment of inertia
- Position-dependent stiffness and bending strength of the ball-screw drive

The control specific range of feed drives with ball screws is determined by the natural frequency of the mechanical system. The achievable factor is about 5 (m/min)/mm maximum. The factor is a measure of the achievable machining accuracy and dynamics of a feed drive and expresses the speed (in m/min) at which an NC axis can be moved until a following error, also called *axis* of 1 mm is reached.

The factor is determined by influences and system properties such as:

- Rigidity of mechanical components (bearings, transmission)
- Control dynamics (motor data, masses, moments of inertia)
- Nonlinearities of the system (friction, backlash)
- Direct or indirect distance measurement

Higher dynamics and accuracy are achieved with linear drives. When these drives are used, the machine design must meet the following requirements:

- Minimization of moved masses
- High rigidity and high mechanical natural frequency of the machine structure
- Consideration of attraction between primary and secondary parts, as well as of ferromagnetic chips

The control specific range of linear direct drives is only determined with the CNC. The achievable factor is up to 30 (m/min)/mm.

The directly driven motor spindle has largely prevailed for main drives. If additional positioning tasks, for instance, for the are required, then preferably three-phase synchronous motors are used.

IMPORTANT POINTS TO REMEMBER

1. Controlled feed and main spindle drives are the core components that determine the performance of cutting-machine tools.

2. Calculation of motor performance data is independent of the motor types, e.g., synchronous or asynchronous motors, and is determined later. The advantages of these systems are described in the previous two chapters.

3. In order to avoid greater collision damage, couplings with integrated overload protection are indispensable for rotary drives.

4. Sufficient acceleration and process forces also improve the accuracy of the workpieces that are produced on the machine.

5. When calculating the required torques, any holding forces to be applied must also be taken into account, for example, for the weight of the vertical NC axes.

6. The manufacturing and operating costs of a CNC machine are decisively determined by the type and size of the drives. On the other hand, underdimensioned drives reduce the subsequent productivity of the machine.

7. CNC machines usually involve several axes in the generation of the motion sequences. Therefore, it is also necessary in the drive calculation to match the dynamics (speed) of the CNC axes. Thus the axis drives are not necessarily uniform.

8. Main spindle drives increasingly have position control. For lathes, this makes operation possible, also allowing milling and drilling operations on the workpiece. For this, only synchronous motors can be used.

9. For simpler machines, variable-speed motors with squirrel-cage design are sufficient.

10. High-quality main drives basically contain the same main components as feed drives.

11. Linear drives are best suited for high feed rates. Because they do not contain mechanical transmission elements, they do require linear encoders.

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MOTOR SELECTION

Motor selection has a major influence to the correct functionality of the main spindle. In modern main spindles, the drive motor is integrated. The rotor is part of the spindle shaft and is carried by bearings. There is no need for mechanical coupling between motor shaft and spindle shaft. The elimination of additional transmission elements provides various benefits such as quiet running, small space requirement within the machine, higher precision, and improved control dynamics through less inertia. The transmission of torque is touchless, and mechanical wear does not happen. The electrical power is only induced into the fixed outer jacket of the motor. The rotor does not need its own power supply.

Generally, a motor spindle can be equipped with a synchronous or asynchronous motor, available in different speed classes. Both variants have certain requirements for the power converters that must be taken into account when designing the machine. In addition, different advantages and disadvantages, depending on the desired use, must be considered.

The control of asynchronous motors is less complex. The motor ramps up quickly and has a larger field-weakening range; thus it reaches the highest speed with smaller power consumption than comparable synchronous motors. Synchronous built-in motors offer high power densities through the permanent magnet, compact design, or use of comparatively large shaft diameters, respectively. The power loss in the lower speed range is low. For high-speed

motors, it might be indicated to deploy an additional inductance (choke) because of the structure of the motor. In addition, the use of a choke makes it possible to reduce voltage peaks by filtering out high-frequency signal components and thus to relieve the motor windings.

Motor spindles are generally designed with integrated channels for liquid cooling of the stator. The stator, because it receives the electrical drive power, is the main heat source of the spindle unit. The cooling system therefore must dissipate the heat, in addition with other heat sources. The spindle unit has connections for the supply and return of the cooling agent. An external chiller with a circulation pump will bring the coolant back to the initial process temperature. The machine builder will deliver the chilling unit as part of the motor spindle.

Sensors are used to monitor motor temperature and protect against overload during operation. Synchronous motors are required under special operating conditions, for instance, when under load during motor standstill, to provide additional monitoring of the motor phases to protect against overload. This is realized with a *positive-temperature-coefficient* triple-protective sensor, also known as or, optionally, with a *negative-temperature-coefficient* thermistor. These are used if the inverter does not allow the evaluation of the KTY sensors.

BEARINGS

The bearings of a main spindle must provide a highly accurate run and absorb the machining forces. The selection and arrangement of bearings vary depending on the required process parameters. Most of these bearings are roller bearings.

Roller bearings with a higher precision class are used almost exclusively for spindles in machine tools. The bearing types are mainly angular ball bearings, radial angular contact ball bearings, spindle bearings with 15- and 25-degree pressure-angled, double-sided axial angular contact ball bearings, radial and axial cylindrical roller bearings, and occasionally tapered roller bearings. Depending on the required speed range, the materials of spindle bearings are either steel or ceramic. Hydrodynamic or hydrostatically mounted spindles are used for extremely high requirements in terms of precision run and damping. Some characteristic bearing arrangements from a variety of potential machine tools designs have proven to be successful.

In applications with a focus on high cutting forces and low speeds, the bearings must provide high rigidity plus precise radial and axial alignment. This is accomplished with large shaft and bearing diameters. A rigid bearing housing with accurately applied preload produces the required accuracy. In applications with high speeds, the bearings must satisfy the thermal and dynamic operating conditions as well. Particularly suitable are hybrid spindle bearings with ceramic balls. Bearing pairs oppose each other on

the driving and driven sides and are set against each other by means of springs with a defined preload. This enables an unencumbered compensation of axial expansion due to thermal and dynamic factors. In addition, optional linear bushings enhance radial stiffness. Proper spindle cooling, observance of the permissible bearing load, and maximum allowed ambient temperature during operation ensure that the permissible bearing temperature is not exceeded.

LUBRICATION

A film of the proper lubrication must always be present in the contact area to ensure the appropriate live span and a wear-free operation of the spindle. Generally, one distinguishes between grease lubrication and oil-air lubrication. Grease lubrication is preferred at lower speeds. Low-speed spindles have the advantages of low friction, simplified spindle design, and comparatively low system cost. As long as the spindle load is in compliance, the presence of grease determines the life of the bearings. The right kind of bearing grease should be selected and in the correct quantity. Bearing design, spindle speed, operating temperature, and installation conditions also determine the useful life of the grease.

The second type of lubrication is oil-air lubrication. It is used when the spindle speed is too high for grease lubrication and has become standard. To lubricate a spindle bearing, it takes three to four drops of oil per hour, where one drop of oils measures about 30 It must be ensured that all affected contact areas have an oil film. Lubrication with the described quantity of lubricating agents results in low friction losses. Preferred oils have the designation ISO VG 68 + EP, that is, nominal viscosity 68 at 40°C with extreme pressure additives. It is advisable to use transparent hoses with an internal diameter of 2 to 4 mm to be able to monitor lubricant flow. Fine droplets form as a result of the passing air at 1 to 5 bar pressure and are ensured for hose lengths of 400 mm and more. Specific flow conditions in the bearing can change the amount of air consumed drastically.

MACHINING PROCESSES

Milling

The use of standardized tool holders is characteristic of milling spindles Standardization depends on adapting to the needs. It means that the manufacturer can deliver the spindle with the appropriate tool adapter. The same tool spindle can be equipped with a reception with or without coolant supply and with a hydraulic or pneumatic release mechanism. Rotary unions and release mechanisms are compatible and interchangeable.

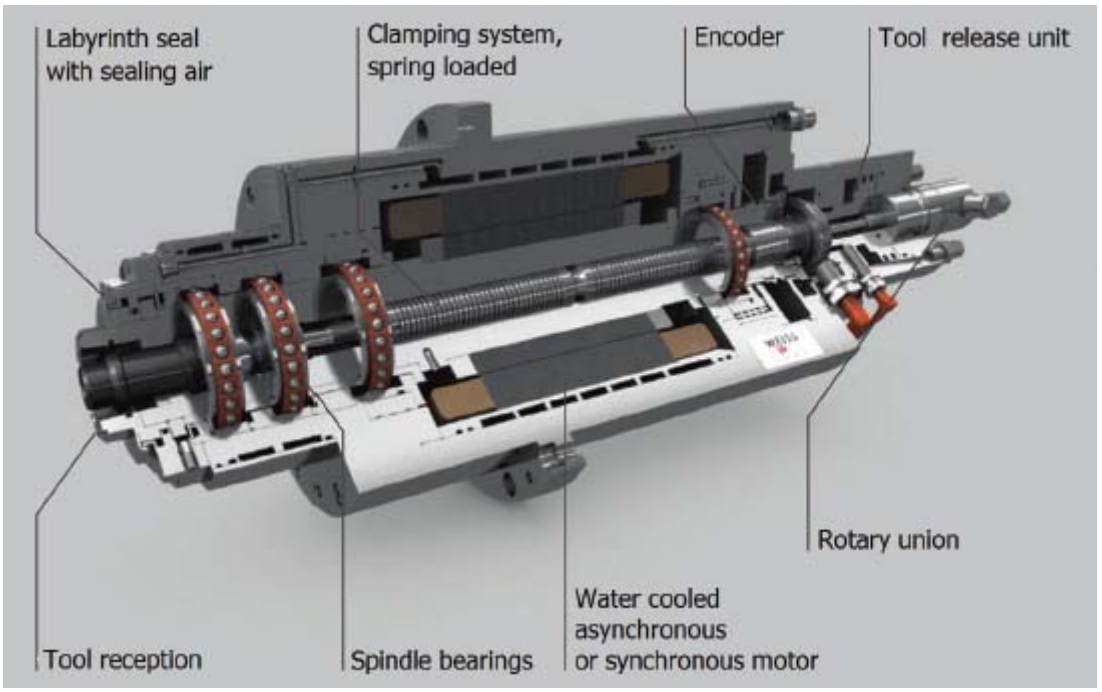


FIGURE 13.1 Design of a milling spindle. Weiss, Schweinfurt.)

Basically, there are two kinds of tool holders: the steep (SK, BT) taper and the hollow-shank (HSK) taper. Both have type-specific properties with pros and cons. For tool systems with spindle speeds of up to 10,000 rpm steep-tapered holders per DIN 69871, Part 1 are used; on request, the tool supplier can possibly provide hardware for still higher speeds.

Five-axis spindle units and overhead machining are supported. Safe machining is possible at any angle. It could be a disadvantage that the machine is not suitable for high speeds because the spindle widens as a result of centrifugal forces. The steep taper is being pulled in too deeply and might get stuck.

The acceleration of machining processes in the industry used in high-speed cutting (HSC) also requires solutions for faster tool changes. This is accomplished with HSK adapters. The main distinguishing feature of this type of adapter is the flat resting area on the face of the spindle shaft compared with the SK tool holder. This support detail provides additional bending strength and axial positioning accuracy in the micrometer range. Form-fitting, tight cone tolerances prevent concentricity errors.

A speed of 40,000 rpm is the maximum for the HSK-A63 tool adapter and 60,000 rpm for the HSK-A32 adapter. The fact that centrifugal forces will widen the spindle bore and pull the tool in deeper cannot happen when the tool rests on a flat step. Additionally, the clamping elements are arranged so that higher centrifugal forces may push the tool outward, but this will cause an increase in clamping force. The torque is transmitted through

the frictional engagement of the cones and additional carrying elements at the end of the shaft.

Nonproductive times such as tool changes become more relevant as spindle ramp-up times improve. A quick tool change requires an effective release system, which ejects the tool from the work spindle. For this, the rear of the spindle holds a piston that pushes against the clamping mechanism with an embedded spring. Release units are typically hydraulically or pneumatically operated, yet there are also electrical systems for hydraulics-free machines. The three concepts applied in modern tool spindles can deliver the same result.

Grinding

For grinding, common tool holders have inside or outside cones and cylindrical holders for manual mounting of the grinding wheel. In addition, receptacles with HSK taper are used for automatic grinding wheel change.

Grinding spindles are distinguished between inside cylindrical and outside cylindrical grinding. External cylindrical grinding spindles are also suitable for surface grinding. Depending on the procedure, different grinding wheel holders and grinding wheel diameters are necessary. The diameter and material of the grinding wheel determine the operating speed of the spindle. Carborundum, silicon carbide, and cubic boron nitride (CBN) are used as grinding agents; ceramic and artificial resin are used binding agents.

The uniformity of the surface is of utmost importance because grinding is often the last operation of a manufacturing process. Therefore, the arrangement of the bearings on the spindle is very important. A rigid arrangement of the bearings toward each other is preferred This arrangement severely limits the speed range, but at the same time the operating result is superior because of lower wave motion. High-speed spindles are used especially with inside cylindrical grinding. Here, however, the bearing arrangement must be adapted to the kinematic conditions. This compromises the stiffness of the spindle and thus possibly also the surface quality.

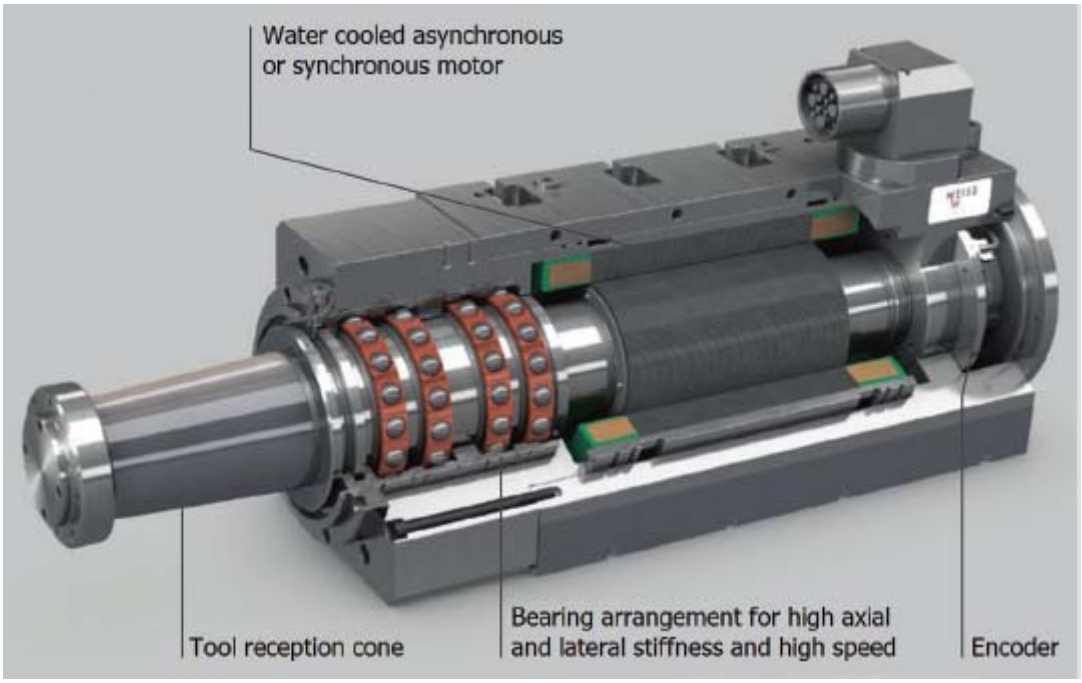


FIGURE 13.2 Design of a grinding spindle. Weiss, Schweinfurt.)

Grinding typically requires continuous spindle speed (S1). As stated previously, for this kind of operation, oil-air lubrication for the bearings is standard, and grease lubrication is not indicated.

For applications with a large-diameter grinding disk, the use of a balancing system is indicated. It compensates the residual imbalance of the grinding wheel during operation. A number of patented systems are available from different manufacturers. The hardware of the balancing system is usually placed in the spindle shaft center.

The motors used for grinding spindles can be of the synchronous or asynchronous type. With the asynchronous technology, there is often no encoder. Under these circumstances, the safety of the machine must be evaluated.

Turning

Spindles for lathes are characterized by standardized interfaces for workpiece chucks. The short cone reception A3–A20 according to DIN 55026 and 55027 is favored in Europe. DIN 55026 (ISO702/I) governs how the lathe chuck is attached at the face with Allen screws. The threaded holes are located directly in the spindle nose. DIN 55027 (ISO 702/III) chucks are clamped to the lathe, similar to DIN 55021 and DIN 55022 chucks. Asian machines often use DIN 55029 (ISO 702/II) interfaces, also known as Besides manual chucks, there are also many chuck designs with automatic workpiece clamping. For this, a hydraulic cylinder is mounted at the other end of the spindle that pulls in the chuck by means of a draw bar through a hole in the spindle shaft.

The nature of turning requires a spindle with high rigidity. The working side of the spindle must run very precisely under high

axial and radial stress. On machines that operate with moderate speeds, the design therefore requires rigidly braced bearing arrangements and highly exact bearings Bearing arrangements with radially active cylindrical roller bearings in combination with axial bearings are used for increased machining forces. Bearing arrangements with tapered rolls that face and brace each other are seldom used. For high-speed requirements, spring-loaded bearing systems are used, yet compared with rigid bearings, these lack stiffness, reducing permissible tensile strength. Bearing units in lathe spindles are predominantly lubricated for life. Thus the lifespan of the bearing is defined by the life of the grease lubrication. operation in lathe spindles requires a rotary encoder with high resolution, such as optical or magnetic encoders.

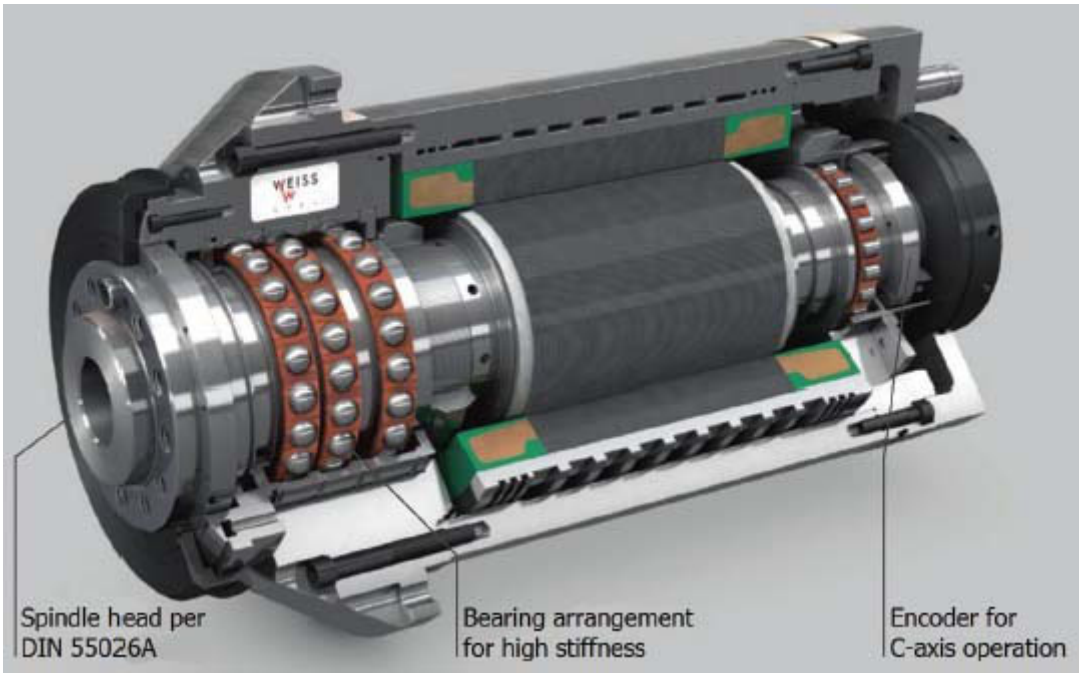


FIGURE 13.3 Design of a lathe spindle. Weiss, Schweinfurt.)

Some spindles have an enclosure with open cooling cartridges. This concept uses the headstock of the machine as the housing, and O-rings for sealing are placed on the spindle.

REQUIREMENTS FOR THE MAIN SPINDLE IN TERMS OF INDUSTRY 4.0

The term *Industry 4.0* is used to explain all forms of connecting product development, production, logistics, and secondary tasks of a factory. The basic idea of the fourth industrial revolution is to use information and communication technology to increase productivity, quality, and flexibility in production.

The requirements for the main spindle derive from the holistic approach of all processes that are involved in product manufacturing. In essence, the demands on the quality of the main spindle, such as accuracy, service life, thermal stability, and availability, will increase. In order to achieve full integration of the machine into the intelligent network with upstream and downstream processes, it does not suffice to add any number of sensors for monitoring. The intelligent, self-controlling machine tool can only function if all parameters in the process are under control. In order to have a machine available 24/7, all individual components must fit together. For example, tools should be well balanced, the spindle well aligned in two orientations, and fluctuations of the workpiece should be brought into tolerance with appropriate tooling and processes. Otherwise, predefined limit switches are triggered, resulting in machining interruptions and downtimes.

It is also worthwhile in individual and contract manufacturing with small batch sizes to perform an intelligent simulation of the

process to check the production process without manual intervention. One of the main machine accidents is a crash of the main spindle. If a problematic machining contour can already be detected in the simulation stage, the program can prevent a crash. If redundant process steps can be left out, a productivity increase is possible.

So far, data captured on main spindles have been limited to speed, some analog or digital proximity sensors, and temperature; occasionally, vibrations have been monitored with an acceleration meter. These data were then compared with previously entered warning and shutdown limits; exceeding the values led to warnings or, in the worst case, machine shutdown. The machine operator then had to find the cause given a number of more or less meaningful error messages issued by the CNC system. It is a common practice that main spindles are sent to the manufacturer for checking, although the cause of the error lies somewhere else. A significant improvement could be realized if the signals of the individual sensors were networked with the CNC system, for instance, via CAN bus systems.

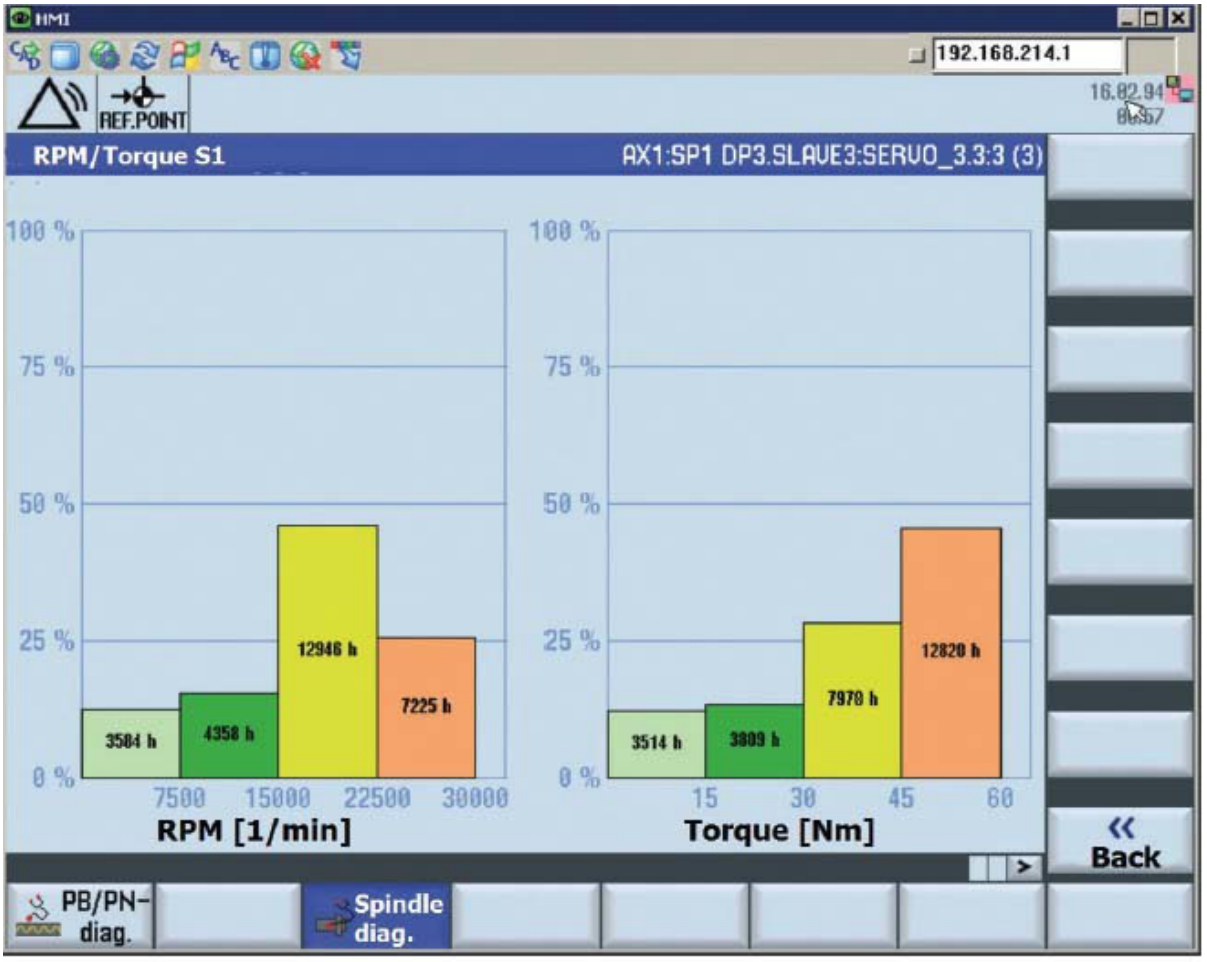
Quite frequently the signals in the machine are corrupted by a multitude of electronic components. Cables often lead several meters from the machine to the CNC system along with heavily used power lines; these can easily result in *electromagnetic compatibility* problems. Such factors can lead to incorrect information in the CNC system and, consequently, to false interpretations. Modern main spindles, for these reasons, are built with integrated sensor modules. These collect analog sensor signals in the spindle, convert them to digital signals, and send them over a network cable to the CNC system The digital signal

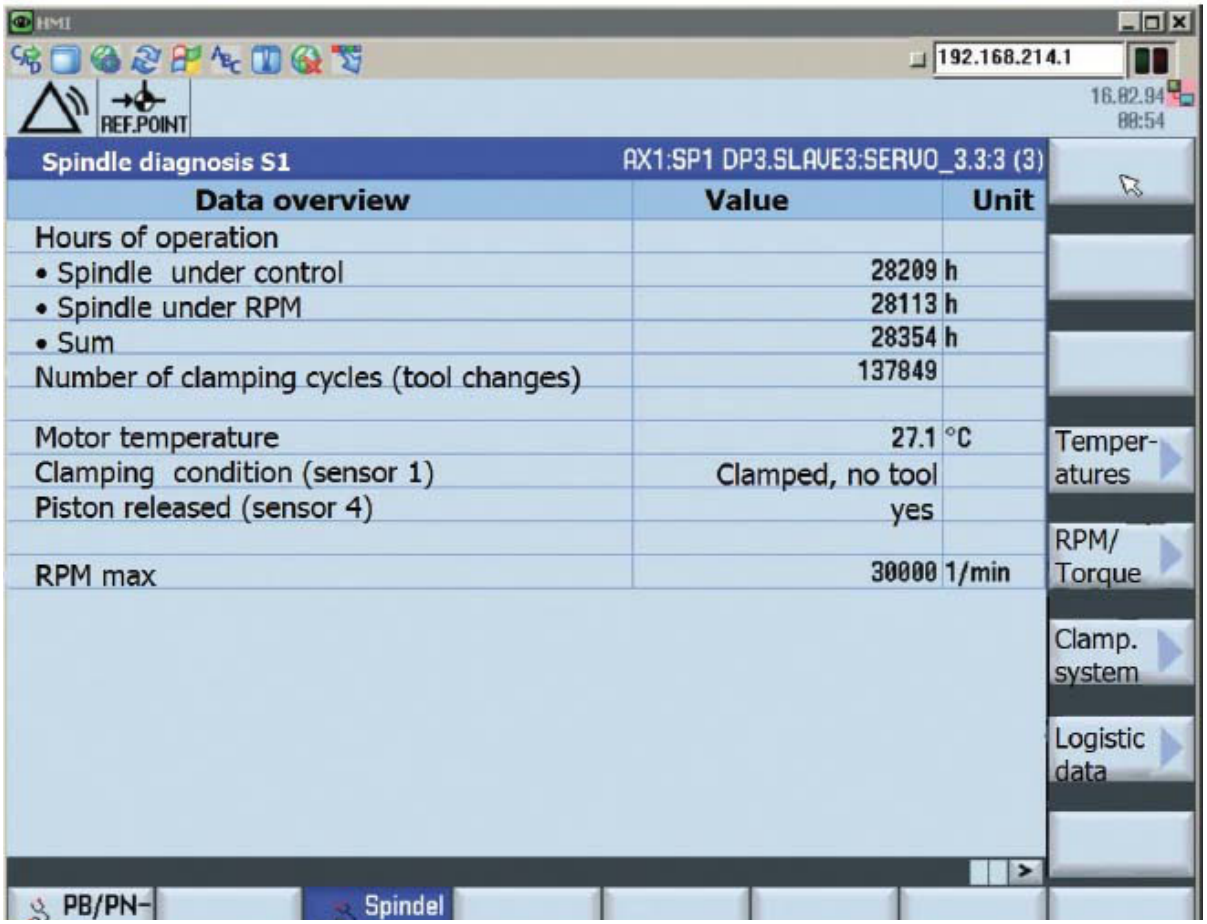
transmission takes place without interference and thus avoids the corruption of information.

FIGURE 13.4 Spindle with sensor module. Weiss Spindle Technology GmbH.)

It is another advantage of integrated sensor modules that existing data can be stored in the spindle and can be evaluated by the spindle supplier, machine manufacturer, or service person. Thus the actual use data of the spindle (i.e., speed, performance, and torque) can be checked and optimized. Furthermore, it is possible to detect early changes in the spindle's performance and better plan for maintenance or exchange.

Modern CNC systems also offer an integrated user interface for spindle diagnosis. The above-mentioned information such as speed, power and torque clusters, tool clamping conditions of milling spindles or actual spindle operation times are displayed in a user-friendly way





Data overview	Value	Unit
Hours of operation		
• Spindle under control	28209	h
• Spindle under RPM	28113	h
• Sum	28354	h
Number of clamping cycles (tool changes)	137849	
Motor temperature	27.1	°C
Clamping condition (sensor 1)	Clamped, no tool	
Piston released (sensor 4)	yes	
RPM max	30000	1/min

FIGURE 13.5 User interface integrated spindle monitor (ISM): the CNC system provides an interface for monitoring and evaluating spindle conditions. Siemens).

IMPORTANT POINTS TO REMEMBER

1. Asynchronous motors are easier to control and provide a large field-weakening range to reach very high speeds with lower power consumption than comparable synchronous motors.

2. Synchronous built-in motors offer high power densities through the permanent excitation. They allow compact designs or comparatively large shaft diameters.

3. Motor spindles are generally designed with integrated channels for liquid cooling of the stator.

4. The bearings of a main spindle must lead it with high accuracy and absorb the machining forces. Depending on the required process parameters, bearing selection and arrangement vary. Most bearings are roller bearings.

5. Grease lubrication is preferred for motors that operate at lower speeds. The advantages are low friction, simplified spindle design, and the comparatively low system cost.

6. The minimum oil lubrication is used when the spindle speed is too high for grease lubrication.

7. Basically, there are steep taper (SK, BT) holders and hollow shank cone (HSK) holders. Both have type-specific properties with

advantages and disadvantages. Tool systems for spindle speeds of up to 10,000 rpm often employ steep taper holders according to DIN 69871, Part

8. The maximum speeds of clamping systems are around 40,000 rpm for an HSK-A63 tool holder and up to 60,000 rpm for HSK-A32 holders.

9. A significantly higher bending strength is achieved because of the flat resting area on the face of the HSK holder than with comparable steep taper tools. In addition, the face provides an axial positioning accuracy in the micrometer range.

10. The machining process on a lathe usually requires high rigidity of the main spindle. The working-side bearing must lead the spindle with a high accuracy and must have very little "give" considering its high axial and radial impact.

11. The main spindle motor is equipped with sensors for monitoring. The measured values or error causes are displayed in a table on the CNC screen. The sensor converts analog signals into digital signals and transfers them via a network connection to the CNC system.

12. The existing data on integrated sensor modules are stored in the spindle and can be accessed by the maintenance department.

13. Modern CNC systems additionally offer their own integrated user interface for spindle diagnosis.

diagnosis. diagnosis. diagnosis. diagnosis.

14 CNC Machine Tools

15 Additive Manufacturing Processes

16 Flexible Manufacturing Systems

17 Industrial Robots and Handling

18 Energy-Efficient, Cost-Effective Fabrication

Fabrication Fabrication Fabrication

Fabrication Fabrication Fabrication

MACHINING CENTERS, MILLING MACHINES

Machining centers are machine tools that arose only as a result of the development of *numerical control* systems. They were developed based on machines with rotating tools such as milling, drilling, or boring machines. The goal was to perform as wide a range of machining operations as possible automatically in a single setup. The definition therefore is the following: a *machining center* is a machine tool that is numerically controlled in at least three axes and is equipped with an automatic tool-changing system and a tool magazine. Milling machines without automatic tool-changing systems are an exception. Simple, smaller machines of these types are produced today for training purposes.

Machining centers are categorized by the position of the main work spindle as horizontal and vertical machines. An important difference is the following: on vertical machines, the is horizontal; on horizontal machine, it is vertical. Thus, for horizontal machines, a column-type construction with a roughly cubical workspace predominates (see Figure for vertical machines, are used most often, or for large workspaces, the gantry or portal construction can be found (see Figure 14.1f and The preferred machine in highly interlinked installations is the horizontal machine because the overhead kind of machining provides for a better handling of the chips.

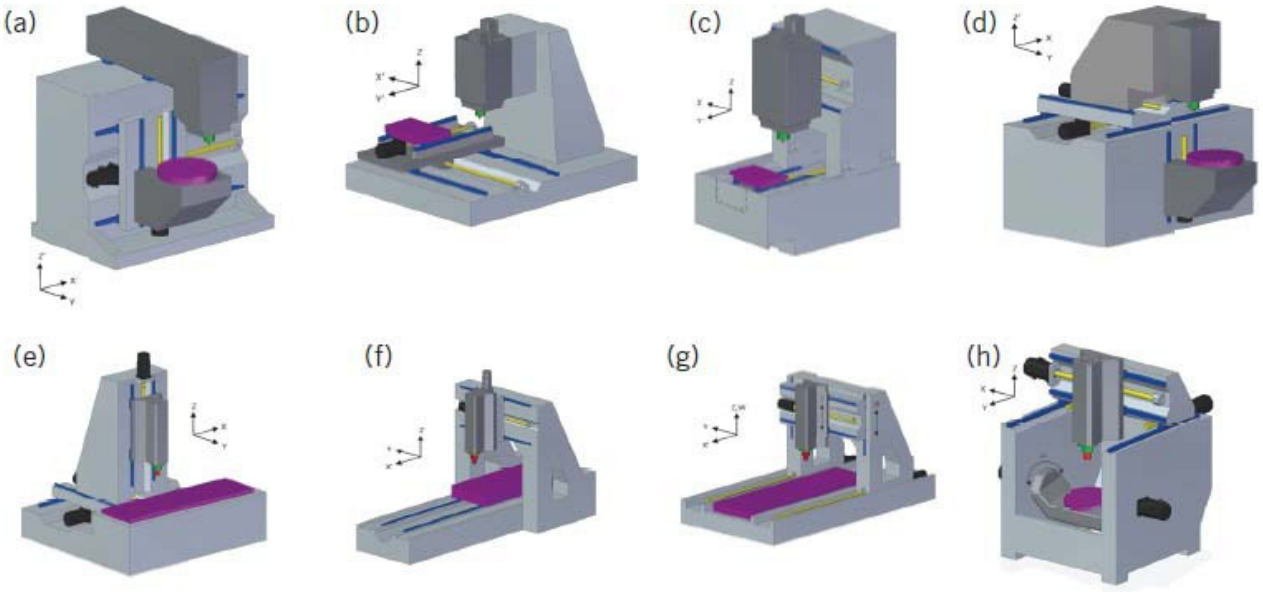


FIGURE 14.1 (a) Console-column design. Because workpiece table drive must carry the workpiece weight, the console design is used mostly for smaller universal machines in tool- and die-making applications. (b) Cross-table design. The workpiece is clamped onto the cross-table, and the table then performs the *X* and *Y* movements. The column is often laid out as a frame construction, within which the tool spindle box is guided in the (c) Table design. In this machine, the workpiece is clamped onto the machine table. It has two linear axes in the tool and one axis in the workpiece. (d) Console bed design. The machine shown has two linear tool axes and one workpiece axis. The workpiece table is usually equipped with rotary motion and also moves vertically on the machine bed. (e) Mobile column design. The design is distinguished by the three feed and drive axes on the tool side. The column undercarriage is placed behind the fixed workpiece table and moves on the on the machine bed. The column sits on this undercarriage and moves in the The tool spindle assembly is placed on the front side of the column and performs the motion. If the machine is equipped with an NC rotary table, a five-surface operation in one clamping can be performed. (f) Portal table design. This design is suited for machining heavy and

large-surfaced workpieces. The machine has a table that can be moved on the Therefore, the machine must be twice as long as the longest workpiece. All other movements are performed by the tool. (g) Portal machine, gantry-type design. In contrast to the table machine, in this design the crossbeam with the tool slide moves, and the workpiece remains in place. Here the worktable for the workpiece must only to be as long as the longest workpiece that must be machined. Given a certain machine size, the portal is moved on the with two feed drives, one on each side of the portal. Incline monitoring through the CNC and measuring systems on each side prevents tilting of the portal. A portable control unit for setup work is essential. These machine types have 3D path control systems with all configuration levels, such as parallel axes, inclined position monitoring, and temperature compensation. (h) High-gantry design (see also Figure On a U-shaped base frame with high rigidity, the crossbar moves in the A cross-slide moves on the beam in the X-direction; it carries the headstock on a vertical slide. This design is often found on smaller machines. Both pictures show a swivel axis that carries a rotary table. Thus five-surface simultaneous machining with one clamping is possible.

Figure 14.1 provides an overview of the construction concepts involved in vertical work spindles.

Figure 14.2 shows machines with horizontal tool spindles.

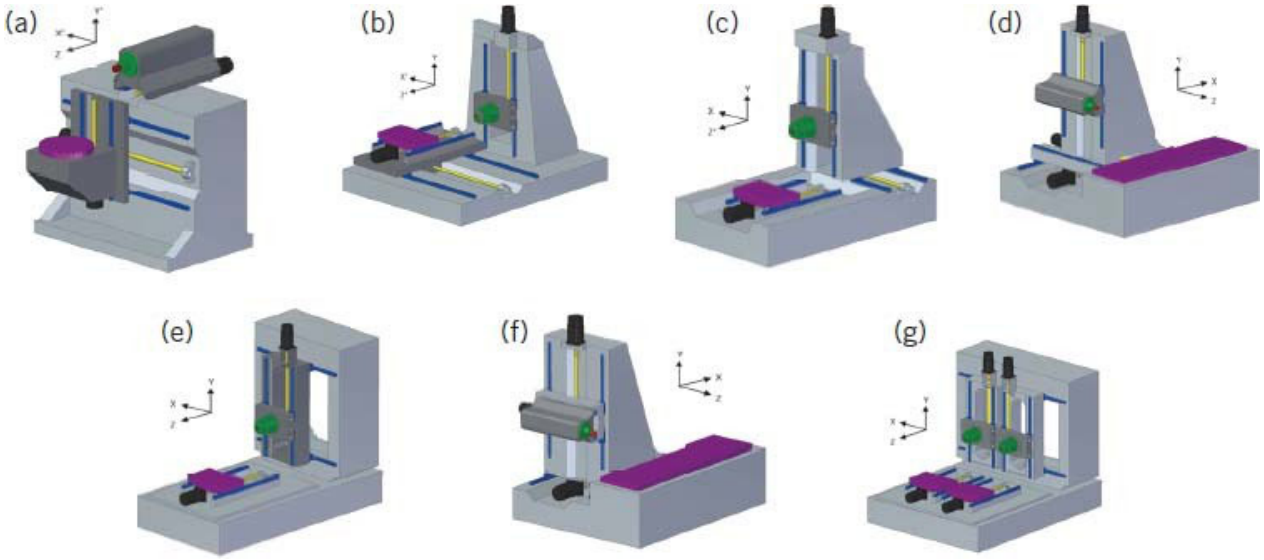


FIGURE 14.2 (a) Console column design. Similar to vertical machines, this design can also be applied on machines with a horizontal tool spindle. The workpiece is clamped on the console and performs the horizontal or on the cross-slide. The cross-slide itself moves vertically (i.e., on the The tool carrier is a horizontal quill that performs the machining in the This design is found on rather small machines. (b) Cross-table design. The workpiece is clamped on the cross-table that performs the The column is often laid out as a frame construction, and the tool spindle head moves in the (c) Cross-bed design. The workpiece is clamped on the machine table that performs the The column moves perpendicularly in the and the tool head performs the (d) Mobile-column design. In this design, the three in-feed and feed axes are placed on the tool side. The cross-slide sits on the machine bed, moves in the and carries the column that moves in the The headstock performs the vertical on the column. This machine type is suitable for the processing of heavy and long workpieces. Alternatively, pendulum processing is possible at double the table length. (e) Frame-column machining center. The column is significantly different from the classic traveling-column design. The column is firmly connected to the machine frame. An integrated cross-slide moves within the column in the *X*- and The holds the

tool spindle head. (f) Boring-mill design (see also Figure This design is similar to the mobile-column machine, but with a difference: the headstock holds a long quill as a superimposed It is for boring jobs with deep holes. Heavy-duty milling jobs are performed directly with the headstock when the quill is retracted. (g) Double-spindle machining centers. Two horizontal main spindles positioned side by side are used in predominantly horizontal machines to increase productivity. The two spindles can operate independently ≠ so each spindle has a separate tool length correction.

Differentiation Based on the Number of Feed Axes

Three-Axis Machines

The three-axis (milling) machine with three linear axes is the basic design of a machining center.

Four-Axis Machines

Four-axis machining centers usually consist of three linear CNC axes and one rotation axis. The rotary axis is used for round surfaces. On horizontal machines, these take the form of a turntable; on vertical machines, that of a clamping cube for machining of cylinder jacket surfaces or for three-sided machining of small workpieces

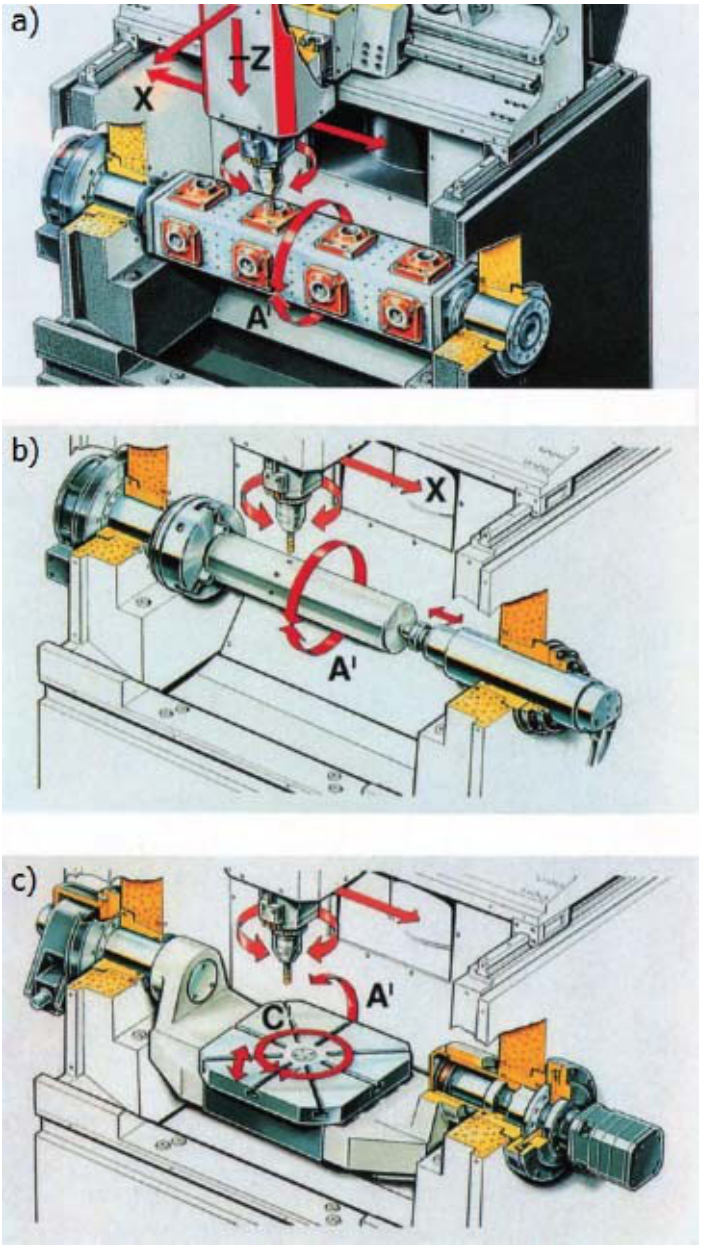


FIGURE 14.3 Options of workpiece processing on milling machines with a vertical main spindle: (a) four-axis machine with multiclamping bridge for three-sided machining of small workpieces; (b) four-axis machine with indexing clamp for machining cylinder outside surfaces (c) five-axis machine with swivel table for five-sided processing and

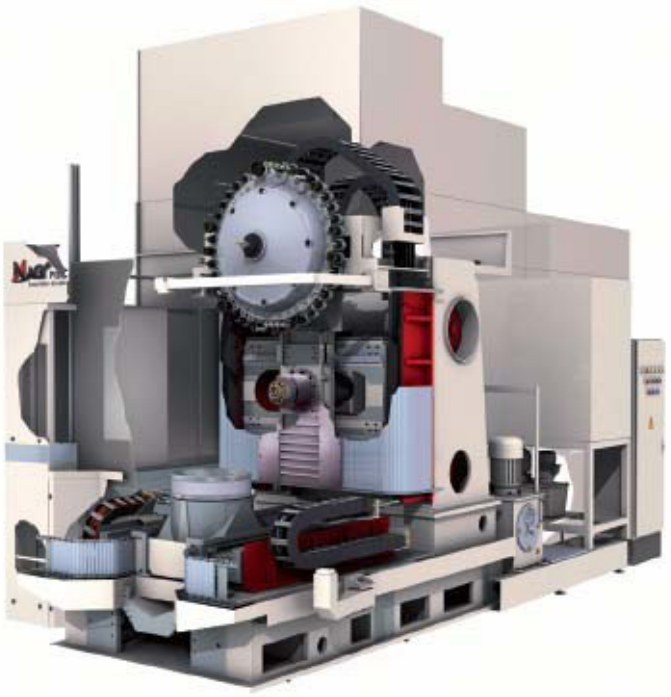


FIGURE 14.4 Modern processing center with linear motors on the and MAG IAS GmbH.)

Five-Axis Machines

Five-axis machining centers 14.4 and consist of three linear and two rotary axes. This allows for positioning of the tool in any direction. Thus milling surfaces or drilling holes is possible in any given orientation in space. Both rotary axes can function as workpiece and tool axes, which results in a large number of different machine configurations.

Without exception, machining centers today have path control systems with spatial (simultaneous) interpolation in all axes. The programming therefore is typically done using computer-based programming systems and machine-specific postprocessors. For simple machining tasks and better work-shop flexibility, users often opt for *shop-floor programming* Programmable milling and drilling cycles, graphically supported input of contours, graphical simulation

of the machining sequences, and technological programming aids are standard today.

Tool length and cutter diameter compensation, automatic or programmable tool monitoring, and (usually for larger machines) temperature compensation measures today are considered indispensable CNC functions. Ease of use of the CNC machine also is an important consideration so that the restart after an interruption, data entry, and the entire handling of the equipment do not turn into a time-consuming and expensive endeavor.

All possible types of cutting can be performed, such as milling, drilling, boring, tapping, and, with some machine modifications, contour milling, oblique drilling, and thread turning. Speeds and feeds must be programmable for each tool.

The tools are stored in an attached magazine. The appropriate tool is automatically located by the program and inserted into the work spindle. Design and capacity of tool magazines can be very different. Most common are chain, plate, and cassette magazines.

Additional workpiece changers, usually pallet changers, shorten the downtime of the machine when changing the workpiece. Here clamping and unclamping the workpieces take place outside the workspace while the machine is operating.

More complex centers are equipped with more hardware, for instance, a second rotary table, a pivoting device for the workpiece, or a horizontal/vertical infinitely controllable angular tool head. When using a pivoting tool head, three axes must interpolate linearly for an

oblique hole. For facing heads, one or two additional axes are used. Standard on CNC machines are correction value tables for tool length, cutter diameter, remaining service life, and cutting properties. The CNC system also should store tool weight, identification (ID), contour, and additional information to provide the best possible tool management.

These machines are used in mass production and in chained systems in the automobile industry. Their market share has risen disproportionately in the recent years compared with other machines. Machining centers with five numerically controlled axes can place the tool engagement at any point on the workpiece and move along the surface at any desired angle to the workpiece surface.

This universal relative movement between tool and workpiece can be achieved in principle in three ways

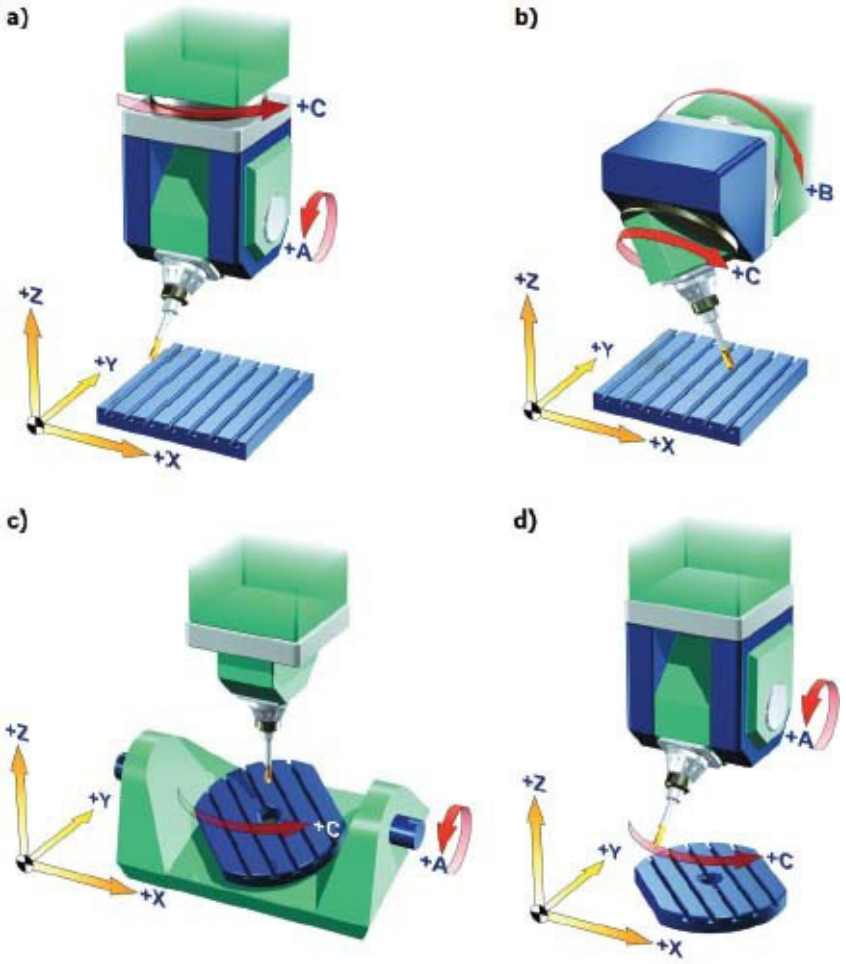


FIGURE 14.5 (a–d) Three-dimensional (3D) processing options of the kinematic five-axis machining center.

1. With a fixed workpiece and two swivel axes of the tool 14.5a and

2. With a fixed tool axis and a double-pivoting movement of the workpiece (e.g., a pivotal rotary table; Figure

3. With a pivoting movement of the tool axis and the workpiece, where both are 90 degrees offset to each other

Such machines can be used both for geometrically complicated parts and for curved surfaces using special cutting heads for higher material removal rates instead of the usual finger or ball end mills. It takes a powerful programming system to program a five-axis system with simultaneous movements. The machine-specific postprocessor still needs to calculate the kinematics of the machine so that the tool performs exactly the desired movements. Therefore, the actual length and diameter of the tool must exactly match the values used in the programming.

Multispindle Machining Centers

All the machines described so far can be designed as two-, three-, or four-spindle machines to process several identical workpieces simultaneously. Especially in mass production, two-, three-, and four-spindle machines are in use, which also requires appropriate multiclamping fixtures.

For multispindle machines, all tools must have uniform dimensions. The exact length is achieved via tool presets or individually adjustable spindles. In automatic operation, the length compensation of the individual spindles takes place via sensors or adjusted load cells. The more elegant solution in new machine designs is a compensation for the tool length in the

Trends in Modern Machining Technology

High-Speed Cutting

The definition of *high-speed cutting* is based on the cutting speed. Here the cutting speed is 5 to 10 times higher than in the conventional range. However, the speed is material dependent. High-speed milling uses a relatively small effective diameter on the tool,

resulting in significantly higher spindle speeds than conventional machining. Thus the definition of HSC for milling is amended by the factors for high tool speeds and high feed rates

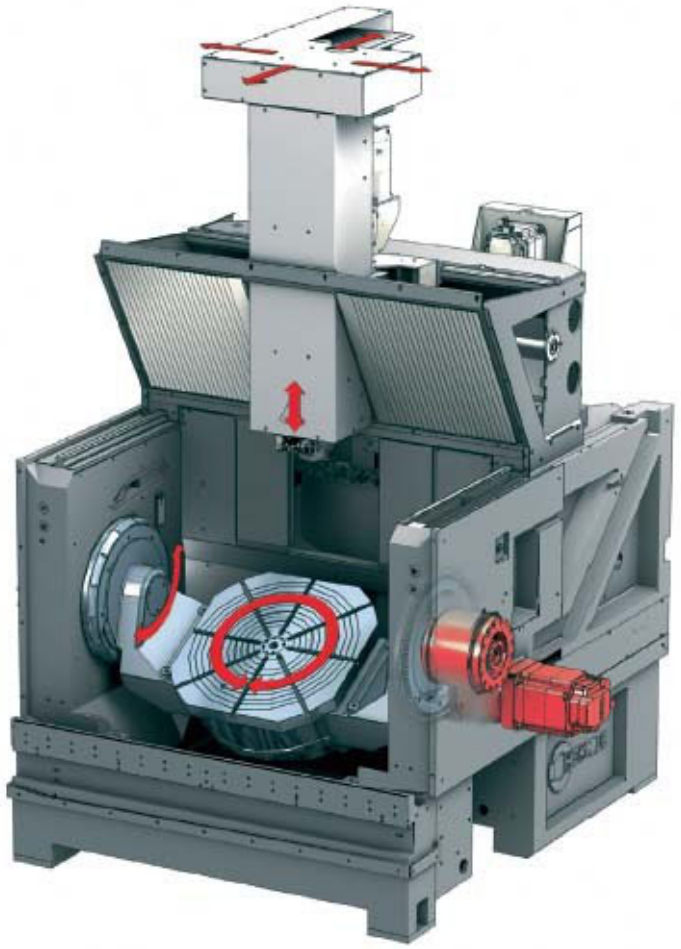


FIGURE 14.6 High-speed processing center. Hermle.)

High-Performance Cutting

High-performance cutting strives to reduce costs by cutting machining times in some cases by over 50% compared with previous technologies. Increasing the chip volume in a given time by means of new tool types and optimized machine components increases the availability of the machine tool.

Requirements for the machine tool include:

■ High rigidity and maximum possible damping to avoid vibrations and resonances, which requires short overhangs and slides with high rigidity

■ Vibration-free spindle drives to the extremely high rotational frequencies

■ Low masses to reach acceleration values of up to and factors of 2 to 4

■ Suction devices, especially for HSC machines for aluminum processing

Requirements for the CNC system include:

■ Short block cycle times in the range of 1 ms, meaning a processing speed of about 100 blocks per second, because at high feed rates the times for reading and implementing the blocks are very short

■ Look-ahead function to recognize corners and edges in time (In order to avoid contour violations, the feed rate should be automatically reduced in the short term, with simultaneous adjustment of the spindle speed.)

■ High rigidity of the feed drives with a high factor in order to achieve the required accelerations and accuracies

■ Axis lag = 0 (Axes should be moved without a following error to achieve good contour accuracy despite the high feed values.)

The increased use of CAD systems has recently added another requirement, namely, the direct processing of geometry data generated by CAD systems. These are essentially Drawing eXchange Format (DXF) data, nonuniform rational B-splines (NURBS), or Bezier formulas. This means that these mathematical data no longer have to be converted by a postprocessor into linear vector elements because they are taken over and processed by the CNC directly. This makes for a much smoother machine behavior despite the high accelerations and speeds. The result is improved surface quality on the workpiece.

Dry Machining

In terms of environmental compatibility, dry machining is becoming increasingly important. Research projects investigate the possibility of using more environmentally friendly consumables, for example, minimal quantity lubrication. Additionally, tools for dry cutting are developed. In particular, the automotive industry and its suppliers realize the increased potential of dry machining.

Hard Metal Cutting

The importance of hard machining is also growing. Tools and technologies have been developed to perform high-precision machining operations with geometrically determined cutting tools. Thus it became possible to turn and mill workpieces with a hardness of approximately 62 HRC in grinding-like surface quality.

Machining CFRP Materials

The processing of carbon fiber–reinforced plastic (CFRP) materials creates new demands on the design of the machine tool. Due to the aggressive nature of the dust particles, added precautions need to be taken for the protection of operating personnel and the machine. In addition to already existing precautions, a suction device must be installed as well as added protection of the guides and measuring systems.

LATHES

Lathes are machine tools for the production of rotationally symmetrical workpieces. The cutting movement is generated by rotation of the workpiece. Lathes are available in different types and designs:

■ *Flatbed lathes* These are generally used as universal or shop lathes. As a CNC machine, they are often equipped with joystick and automatic cycle control. The synchronization of workpiece speed and feed rate during thread cutting is performed by the CNC system. These machines are usually used in single-part or small-series fabrication.

■ *Inclined-bed lathes* This design combines the advantage of the high rigidity of a flatbed machine with good accessibility, better chip removal, and automatic loading capability. These machines can be used universally both in the shop and in production.

■ *Vertical* These can be of two kinds: (1) large vertical lathes (carousel lathes) with easy clamping of unstable workpieces with a large diameter and (2) pickup lathes that have smaller dimensions and a high degree of automation. The principle realizes a cost-effective variant by picking up the raw part and unloading the part after processing.

FIGURE 14.7 Cycle-controlled precision lathe. Weiler Machine Tools.)

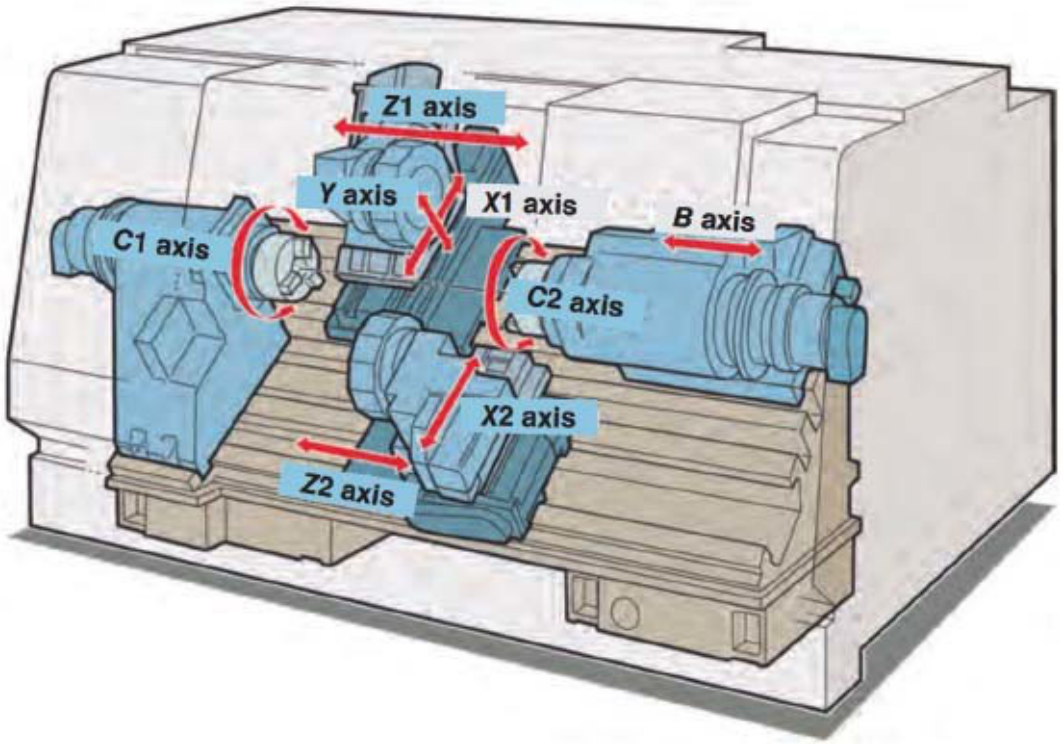


FIGURE 14.8 Lathe with spindle and counterspindle. Mori Seiki.)

Example of a Pickup Lathe

The machine shown in Figures 14.9 through 14.12 is designed for the production of high-quality workpieces manufactured in medium to

large series, such as gear shafts, rotor shafts, pump shafts, motor shafts, or Cardan shafts. The machine bed is made of mineral cast, which ensures better tool life and high surface quality. The vertical structure ensures a free falling of chips. This is particularly important for the machining of soft materials that produce a large volume of chips. Compared with the horizontal position of the spindle and tail stock, the vertical concept has the advantage of a smaller footprint. Automation takes place via the revolver. The gripper in the revolver picks up the blank from the storage bin and inserts it into the clamping position. After machining, the workpiece is unloaded and returned in the same fashion. In order to minimize downtimes from tool changes, twin tools are employed.

FIGURE 14.9 Vertical lathe for shaft production. EMAG.)

Long or Swiss-Type Lathes

These are machines for processing parts that are long and sleek, such as screws, nuts, and threaded pins. Usually, the workpiece is clamped into a collet in the spindle and guided in a guide sleeve (bezel). Different from other lathes, here the spindle with the part is moved relative to the tools. Depending on the machine configuration, it has one or more tool slides. Given the relatively high setup effort, these machines are preferably used for the mass production of small and medium-sized workpieces.

FIGURE 14.10 Work area of machine shows tool revolver that picks up part from magazine and inserts it in clamping fixture. EMAG.)

FIGURE 14.11 Typical array of parts from a shaft-processing lathe: shafts for transmissions, rotors, pumps, or Cardan drives.

FIGURE 14.12 Crankshaft fabrication on a vertical shaft processing lathe. EMAG.)

Multispindle Lathes

In a spindle drum with a diameter of up to 1,000 mm, several spindles, usually two, six, eight, or more, are arranged to hold and process the workpieces The work area has a variety of tool slides and accessories. These machines require a relatively high setup effort and are only used in mass production.

FIGURE 14.13 Multispindle automatic lathe; manufactured parts.

These rotary indexing machines are particularly suitable for the mass production of small, complex, high-precision parts. The workpieces, either blanks, bar stock, or ring stock, are successively clocked to 14 processing stations and processed in simultaneously running operations.

Because of the simultaneous processing at all stations, the total processing time is reduced to one cycle time. Special swivel chucks enable five or more surface-finishing operations on the workpieces. Except for material removal, other operations might be inserting screws, mounting parts, flanging on disks, or pressing in pins.

Until a few years ago, all these operations were performed predominantly on cam-controlled conventional machines. For single-purpose machines or correspondingly large series, this can still be an economical solution. But this type of production becomes problematic for smaller batch sizes, that is, with frequently changing setups. Long setup times quickly make these highly productive machines

unproductive. After converting to CNC production, many conventional machines with cam disks become obsolete. With CNC technology, feed path, feed rates, and spindle speeds are freely programmable. Further advantages are the processing of different diameters on one station and the cutting of radii, edges, and cones.

When loading a new program, up to 20 CNC axes will be converted within minutes for the fabrication of a new part. The mandate for quick setup changes is supported by the use of exchangeable processing units at the individual stations.

Lathes with Two and More Tool Slides

Long before the introduction of CNC machines, parts were processed on large lathes with two or three tools at the same time 14.14 and For the advantage of saving fabrication time, the small disadvantage is tolerated that not all tools operate with optimal cutting speed.

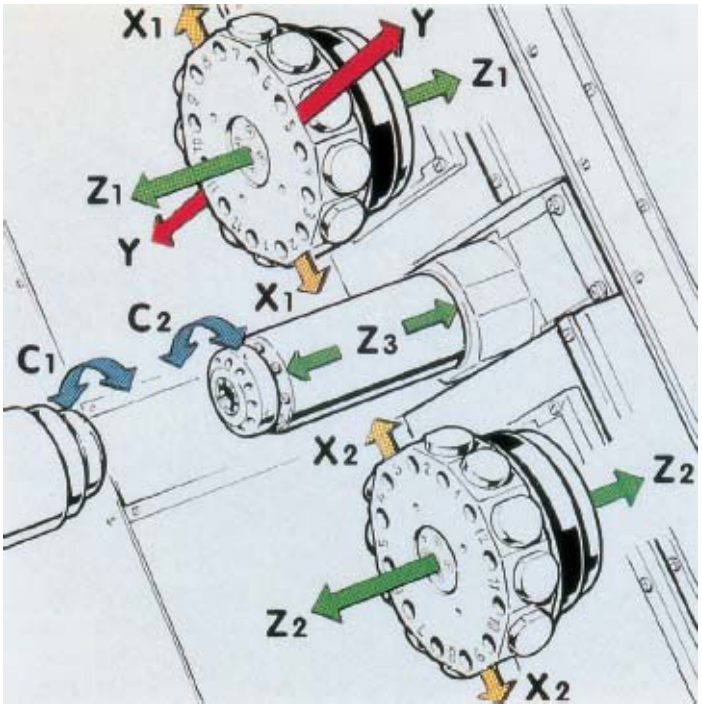


FIGURE 14.14 Lathe main spindle, counterspindle, two revolvers; one revolver has a for cylinder outside processing. Altogether the machine has eight CNC axes.

FIGURE 14.15 Vertical lathe with two processing units and automatic parts feeder. MAG-Hessapp.)

Lathes with two CNC axes are not suitable for simultaneous use of two tools. Therefore, they were soon equipped with two separate tool slides and thus four axes. In this way, two tools could work independently of each other. In today's CNC lathes, two revolvers are designed and arranged for supposedly collision-free simultaneous operation. This means that both shafts and chucked parts can be machined simultaneously with two tools. In order to prevent a collision of the two revolvers, corresponding safety precautions are provided by the software.

The control of these machines requires special CNC systems that can interpolate 2 × 2 axes independently. If, at one specific point,

one tool slide must wait for the other, a special will be issued. The programming is thus much easier because both tool movements are programmed independently and only have to wait for each other at critical points.

In summary, it can be stated that multiaxis lathes are mainly suitable for the production of medium-sized and large series. Whether programming in the workshop makes sense depends on the performance of the programming system (see Figure

Automation of Lathes

The degree of automation of lathes can also be very diverse. For example, the following automation components are available:

- Workpiece magazine with automatic workpiece change
- Tool magazine with automatic tool exchange between revolver and magazine
- Live tools, usually in conjunction with an additional CNC axis and controlled spindle as
- Automatic tool monitoring
- Automatic change of jaws in the chuck
- Numerically controlled tailstock and lunette
- Equipment for linking several similar or different machines

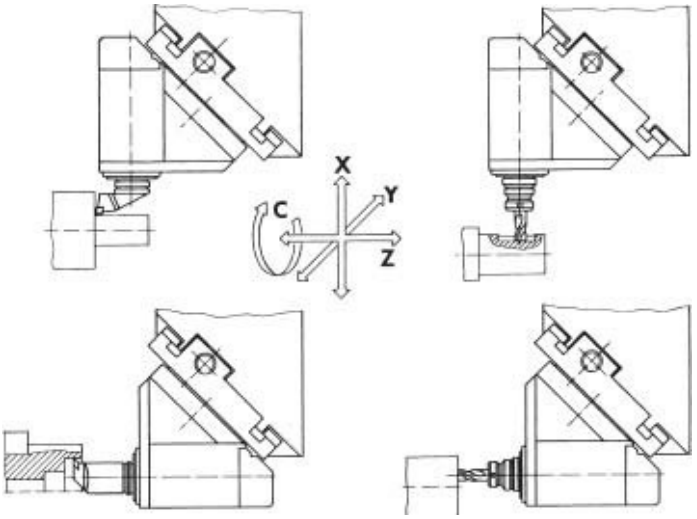


FIGURE 14.16 Ninety-degree swivel head on lathe for axial and radial processing with both fixed and live tools.

CNC Systems for Lathes

The diversity of lathe types and designs is also transferred to the numerical controls (see Figure The basic equipment today must satisfy very high requirements:

■ Two to seven CNC axes, with multispindle machines having up to 30 axes

■ 2 × 2 or 3 × 2 independently interpolatable axes for multislide machines

■ Spindle potentially controlled as

■ Additional CNC axes for loading robots

■ Constant cutting speed by automatically adjusting the spindle speed to the turning diameter

■ Tool offset and cutting radius compensation for all turning tools

■ Cutter diameter and length compensation for live tools

■ Free assignment of the correction values to the tools, in order to assign different corrections to a tool if required

■ Simultaneous monitoring of several tool correction values, such as tool offset, cutting radius, and tool wear

■ Tool edge monitoring and tool breakage control

■ Tool life monitoring and automatic tool change at end of tool life

■ Feedback of measured data to the tool data memory and automatic readjustment

Another very valuable function of a CNC lathe is thread cutting. For this, the main spindle needs to have a measuring system, usually an incremental encoder, for feedback of the spindle speed and the exact angular position to the CNC system. An additionally issued reference pulse per revolution causes the feed always to engage at a certain position of the main spindle, and the subsequent cut follows the preceding one. Also, conical threads, multiple threads, and progressive and degressive pitches can be cut with numerical control with no need for tapping hardware and the associated setup time. The CNC machine provides for absolutely synchronous motions

between spindle rotation and feed drive by processing the pulses of the spindle encoder accordingly.

Programming a Lathe

As can be seen from the preceding by no means exhaustive list, the lathe of old became very quickly a very complex CNC machine. A new focus was the development of a simple, understandable, and easy-to-learn programming option. This effort was supported by the advancement of powerful desktop computers. The color display contributed to the quick user acceptance. Today, the programmer no longer has to learn an "artificial language" to program a CNC machine; rather, the person takes part in a dialogue, answers the questions of the system without any math knowledge or and sees the result of his or her input immediately as a graphic on the screen. Thus the user enters the target and blank geometries; the system simulates the process for any given stage and displays it on the screen. Errors can be corrected quickly, and the result is checked again, until error-free processing is complete. Next, the system generates the CNC program and makes it available on any chosen medium for any suitable machine. The computer automatically calculates drives and motions, correction values, and other special features. Errors are largely excluded. Shop floor programming (SFP) can be performed directly on the machine.

GRINDING MACHINES

Designs and Requirements

Grinding is considered the classic fine- and hard-machining process and is used for diverse tasks. Grinding machines satisfy high demands in accuracy and surface quality in tool and mold making, process the hardest materials in the fabrication and conditioning of tools, produce highly accurate and complex tooth geometries in gear fabrication, and perform short cycle times in automated series production.

Today, predominantly CNC machines are produced. Contrary to conventional grinding machines, where an operator can intervene to carry out corrective actions, it is expected that the CNC machines will fulfill the quality requirements in automatic operation and do so largely shielded from interference and variable process values. For example, given the high demand for precision, all possible sources of deformations must be limited. These can be variable grinding forces, warming up of machine elements, coolant, or the environment.

The grinding processes are differentiated according to the form of the surface processed and the appropriate machine types assigned to the job. Machines for flat, profile, round, and tool grinding 14.17 through are the most common. Furthermore, there are special machine designs for particular purposes such as for grinding threads, gears, worm gears, curves, and eccentrics.

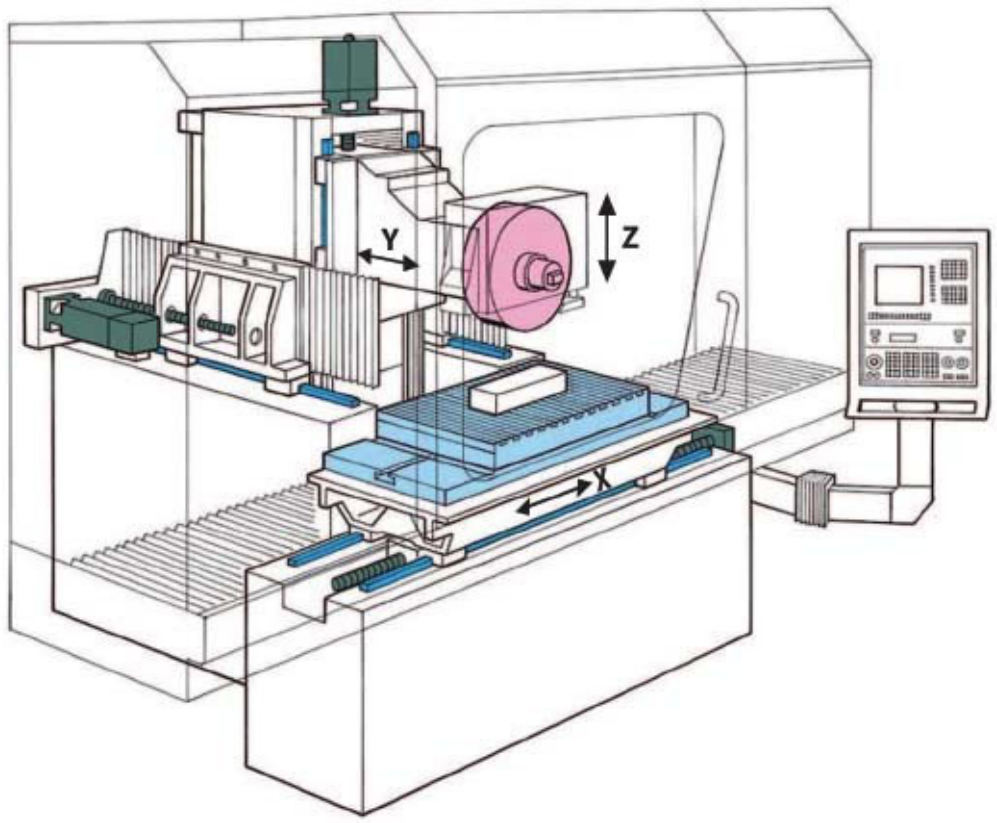


FIGURE 14.17 The Planomat surface-/profile grinding machine, table design with three CNC axes. Blohm-Schleifring.)

The high-precision operation and special operating conditions of grinding place particular demands on the stiffness of the frame and slide components. In addition, the grinding machine is characterized by a very precise work spindle, guides, and measuring systems that guarantee precise positioning and exact feed paths. Depending on the application and the required axes speeds, different guide principles are used. These are mostly low-friction, no-play roller guides; well-dampened, plastic-coated low stick-slip sliding guides; or frictionless hydrostatic guides. Servo motors and ball-screw spindles dominate for feed drives. Increasingly, torque motors are used for these axes. These motors do not need any backlash-prone transmission elements and allow very quick and accurate positioning. Linear encoders are

mandatory, at least for the measure determining axis directions; these are the for surface grinding and the for cylindrical grinding.

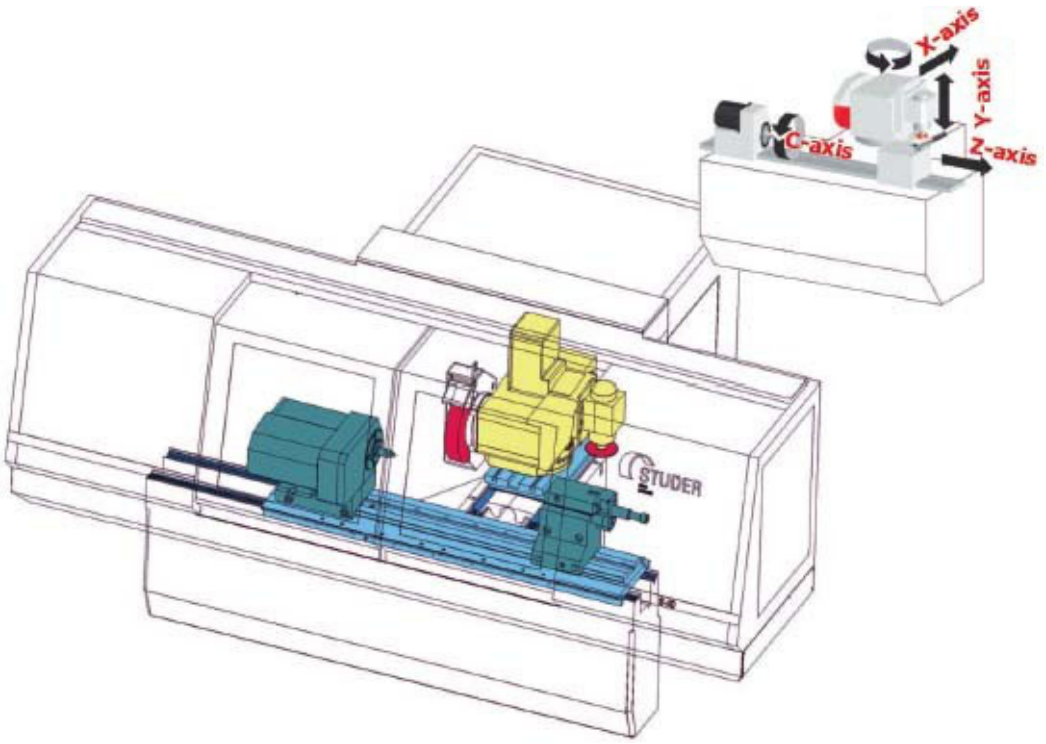


FIGURE 14.18 Universal cylindrical grinding machine S40, table design, with grinding head with and several grinding spindles. Studer-Scheifring.)

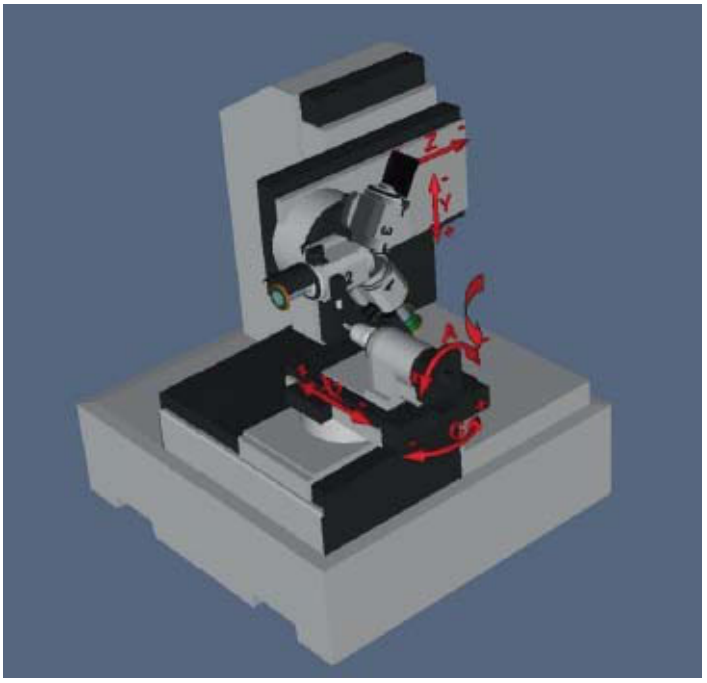


FIGURE 14.19 Tool-grinding machine with three grinding spindles and six CNC axes. Walter-Schleifring.)

Low vibration of all moving components and good damping properties of the machine structure are important requirements for unblemished surfaces. Because cooling or lubrication is used for most grinding operations, spindles, guides, and measuring systems must be protected against intrusion of water, oil, and solid contaminants. The whole work area must be shielded.

Control Tasks for Use of Grinding Wheels

There are special requirements for the CNC system given the peculiarities of the grinding tools and grinding processes. Grinding tools are predominantly disks, also called *wheels* and, less frequently, The peripheral speed is a dominant process value for optimization of the process. Most grinding machines are equipped with adjustable-speed spindle drives. The usually very high spindle speeds require the tools to be balanced to avoid vibrations in the grinding process. This

can be done by means of automatic devices that are integrated into the grinding spindle or tool holder.

Grinding wheels—with the exception of single-layer coated disks—are dressed and prepared for the job after they have been clamped onto the work spindle. Thus they will get the required concentricity, true run, appropriate profile, and sharpness. Sharp-edged abrasive grains can cut even the toughest technical materials. In the process, the tools wear and become dull. If profile and sharpness of the tool have been lost and the required tolerances cannot be achieved anymore, a dressing operation will reconstitute the initial conditions.

Dressing the tool and conducting the regular grinding operation are two distinct cutting processes. The CNC machine must capture both, as well as respond to the changed tool sharpness and diameter. With adjustable spindle drives the CNC can adjust the spindle speed and keep the peripheral speed constant.

Protection of the machine operator and the integrity of the process demand a safe limit of the peripheral tool speed. The key datum to be entered into the CNC system is actual tool diameter. After dressing, the new diameter will be automatically calculated based on the position of the dressing tool.

Dressing a grinding tool takes place predominantly with diamond-tipped tools that can either rotate or be stationary. A profile can be generated with a path-controlled motion whereby the dressing tool is controlled by two axes as it passes by the grinding wheel. To provide a high degree of flexibility and to also reach opposite flanks, some dressing tools can pivot as an option. Figure 14.20 shows a suitable device in which the dressing tool, provided with a radius profile, is

exactly aligned on a pivot axis. Unavoidable residual misalignments and deviations from the radius profile can potentially be measured and compensated for through process control. The overall objective is to improve the tool profile and optimize workpiece accuracy.

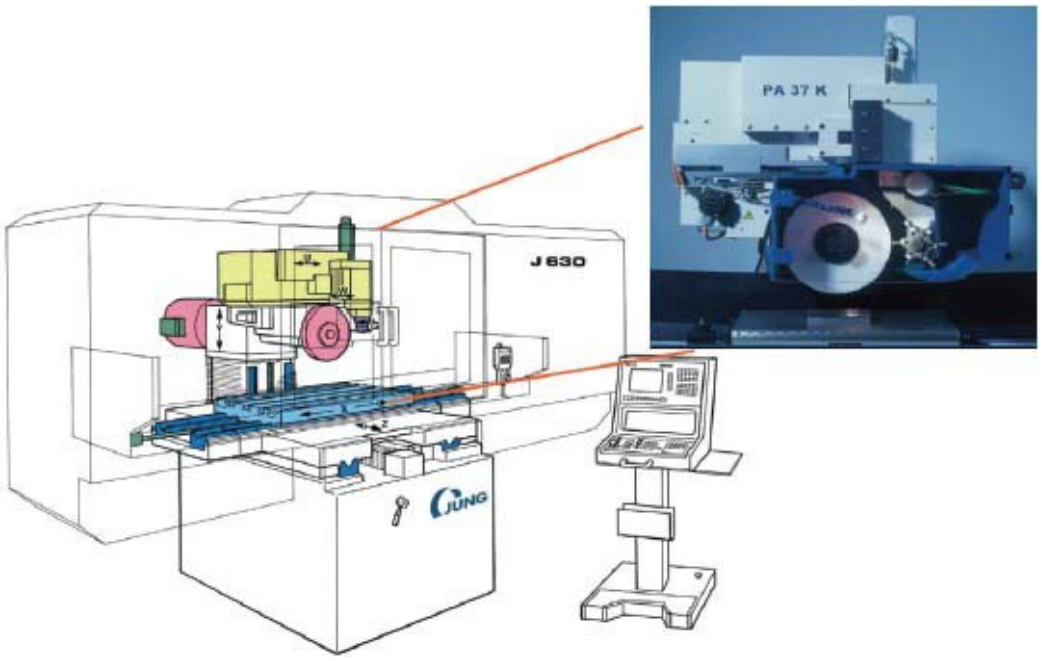


FIGURE 14.20 Profile grinding machine, tool slide design with CNC dressing module mounted on grinding head. The machine is controlled in three axes.

Alternatively, grinding wheels can be dressed with profiled diamond rolls in a plunge-cut motion. Diamond profile rollers are expensive and tailored for a specific workpiece, but they pay for themselves in mass production through time savings. Using diamond profile rollers, the grinding wheels can be kept continuously dressed during operation. When machining high-strength materials that cause excessive wear and thus require especially sharp edges, continuous dressing of the grinding wheel allows for a larger material removal rate and consequently shorter cycle times. The CNC system is tasked with compensating for the diameter change by adjusting the spindle

speed to keep the cutting speed constant. Also, these high-performance processes require adjustment of the coolant nozzles

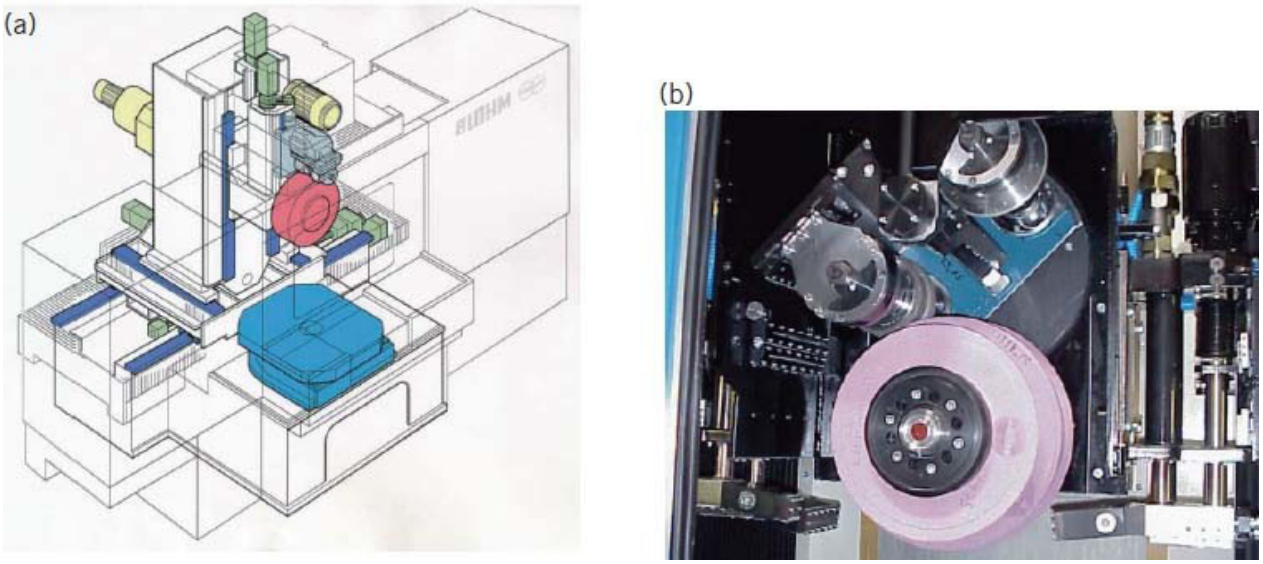


FIGURE 14.21 (a) Profile grinding machine with diamond roll dressing module mounted on the grinding head; it can be mounted and dismounted as needed during operation. Blohm-Scheifring.) (b) Dressing module with diamond profile rolls. The coolant nozzles are controlled.

Tasks of the CNC Machine during Setup, Programming, and Optimizing Grinding Processes

User-oriented controls support machine setup, operation, and process optimization. It is part of the operator involvement to manually intervene during automatic operations; this can be to manipulate the motion reversing points for the oscillation, to superimpose feed-in values for variable excess amounts, or to initiate a dressing cycle for a dull grinding wheel.

When setting up, the positions of workpiece, dressing tool, and grinding wheel are precisely determined in the work area. Measuring

can be supported by the CNC machine by processing signals from probes and other sensors, for example, impact sound sensors, which can recognize the contact between the grinding wheel and dressing tool and workpiece. The automatic conversion into machine coordinates is especially advantageous for machines with swivel axes and several grinding tools and reduces the risk of errors

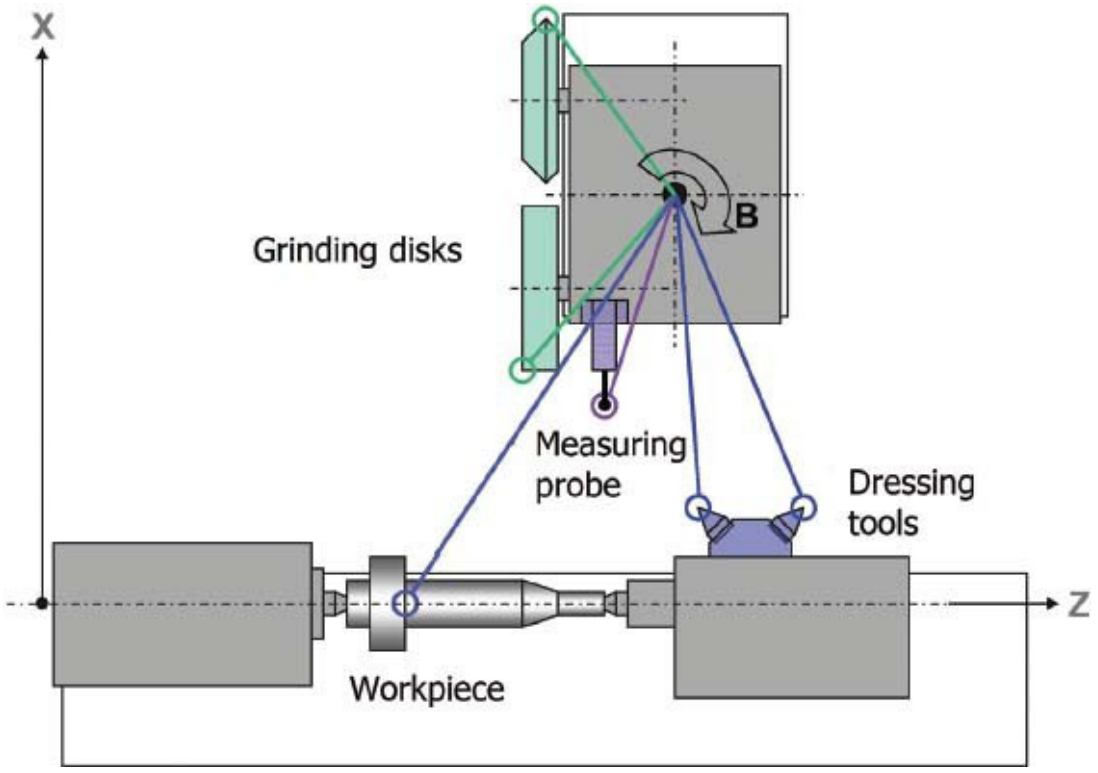


FIGURE 14.22 Supporting the CNC machine by instructing the software to find the reference points of the workpiece, grinding disk, and dressing tools. Studer-Schleifring.)

Programming of dressing and grinding cycles can be supported with software in a variety of ways. For the profiling of grinding wheels, geometric data must be taken from drawing files, and dressing paths must be calculated. Programming systems manage the grinding wheels, choose suitable dressing tools, and optimize the dressing settings in dialogue with the programmer. In addition, they

can perform calculations for collision monitoring and form error compensation.

When grinding out-of-round shapes, variable engagement conditions can occur. These can cause force fluctuations and result in form errors in the part. These effects and other system inherent errors can be minimized through adjusted speed profiles and by extra allowances in path correction. For high-precision work, after the grinding operation, the form deviations must be measured and compensated for in further optimization steps

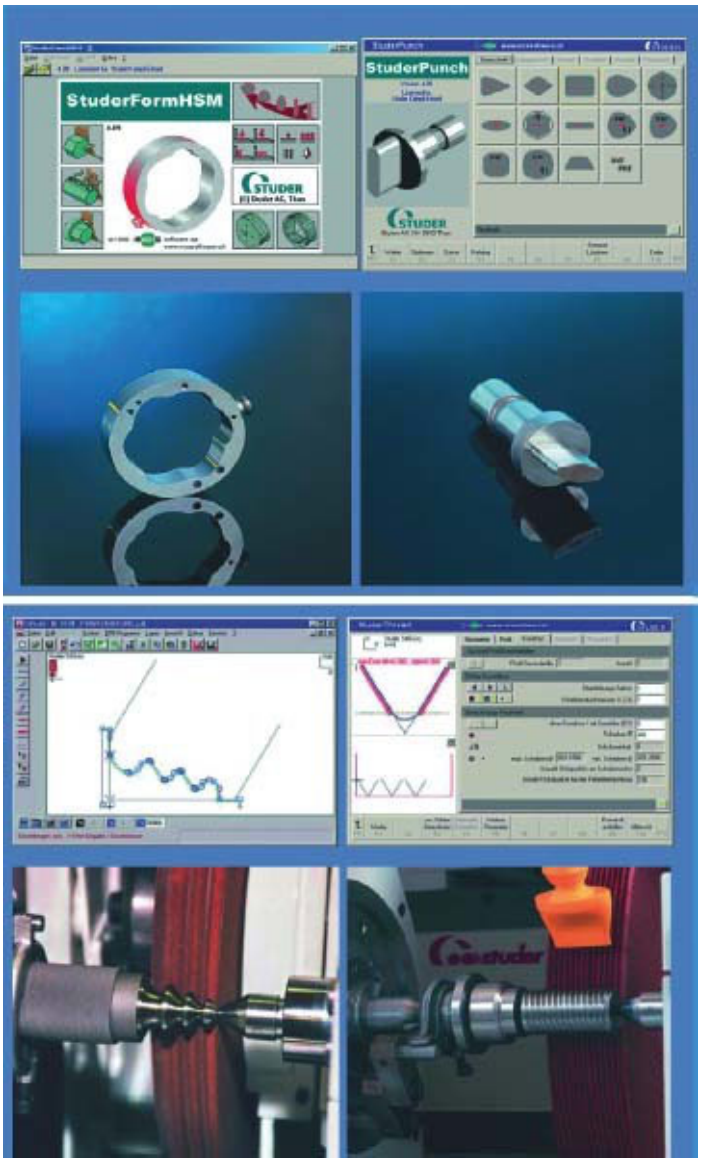


FIGURE 14.23 Programming system for round and out-of-round grinding. Studer-Schleifring.)

The great variety of drilling, counter-boring, and milling tools with high geometric complexity places the highest demands on the programming of a tool grinding machine. Advanced programming systems perform the complex calculations for feed paths; they also check the engagement geometries and analyze the generated workpiece profile. A review of the programs on the screen shows optimization potential and alerts to possible errors. Thus possible collisions in the work area can be detected before the programs become "live" on the machine

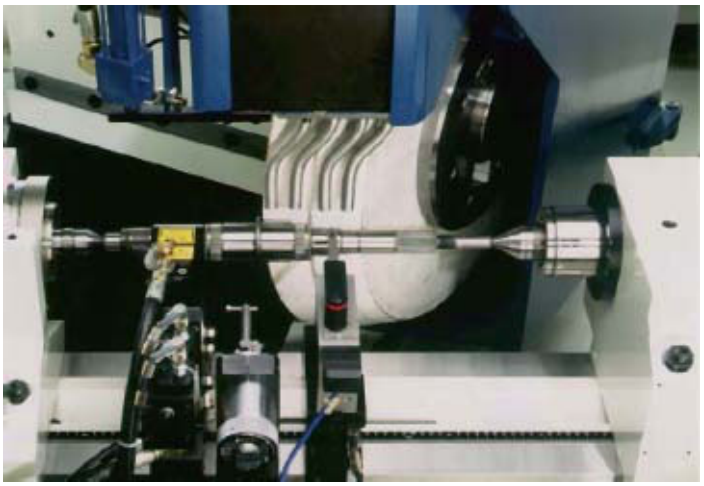


FIGURE 14.24 Computer-controlled grinding of a shaft. Staudt-Schleifring.)

Different amounts of excess material, disk wear, and heat deformations are possible causes of dimensional and form errors. Their influences during cylindrical grinding can be eliminated with the

use of measurement control devices. Here the feed-in during the grinding process switches from roughing to finishing at a set value and turns off when the target value is reached. With grinding, the feed-in motion, different from with turning and milling, can be reduced to near zero. This decreases the grinding forces and largely reduces deformations. At the same time, the workpiece roughness improves as a result of greater cutting edge coverage

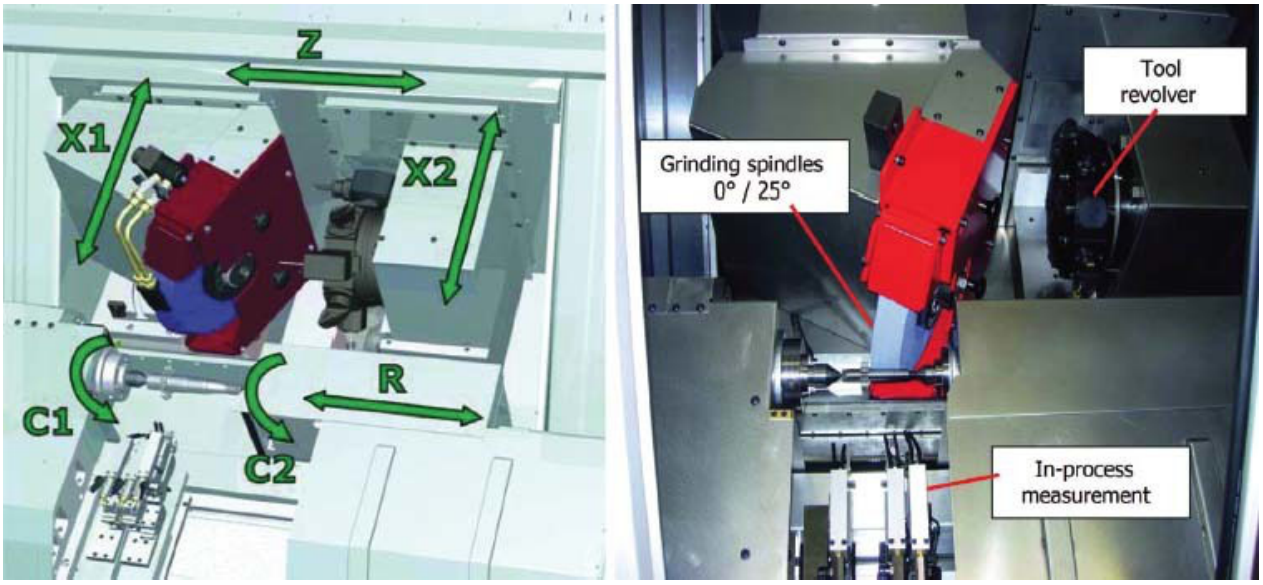


FIGURE 14.25 Complete processing: turning, grinding. Staudt-Schleifring.)

A typical plunge grinding process consists of several stages: a greater feed rate brings the tool close to the contact with the workpiece to reduce unproductive times. Contact can be recognized by means of force, power, or impact sound detection. At this time, the feed rate will be reduced within fractions of a second to a roughing feed rate. It is the objective, when rough grinding, to take advantage of the machine and tool power to remove excess stock quickly. Next, when finishing, the feed rate will be reduced to improve surface quality and bring the dimensions within tolerance.

Automatic Workpiece and Tool Change

In series production, the workpieces are mostly changed automatically. Variable and prismatic workpieces often can only be changed automatically by means of clamping pallets. Shafts, in contrast, typically can be gripped and clamped directly with a portal loader or robot. Components held in chucks can be picked up directly from the workpiece spindle and put down in a magazine.

Clamping in cylindrical grinding depends on machine type and workpiece form. The part can be held between centers, in a chuck, or centerless using bearing rails and support rollers. For slim workpieces that need additional support, lunettes, or steady rests, are used. If they have to be supported at points that are also going to be ground, a controllable design that compensates for the stock removal must be used.

Workpiece magazines and automatic loading devices allow a tool-grinding machine to work fully automatically. A number of profiled disks are required for the complete machining of a tool. These can be mounted on the grinding spindle side by side. As an alternative, grinding wheels can be changed automatically. The relevant coolant nozzles must be connected and adapted.

GEAR-CUTTING MACHINES

Basics and Applications

Gear-cutting machines are understood to be a group of machine tools whose purpose is to create very precise tooth flanks. The design of these machines can be very diverse and depends on the workpiece type, such as bevel gears, spur gears, and straight or helical gears, and the technological process, such as cutting/noncutting and soft/hard material. For this reason, this account will first focus on the fundamental requirements and resulting types and properties of gear-cutting machines. As an example, it uses the most common gear-cutting machine, the gear-hobbing machine for the manufacturing of spur gears. Later on, the description touches on the particularities of hard finishing machines and on machines used to produce bevel gears.

Tooth flanks are curved surfaces. In spur gears, the gear profile is an involute, also called and the gear profile is straight or helical. It is formed based on the tip of a taut string that is unrolled from a base circle. In the final state, the tooth flanks are only allowed to deviate from the ideal condition by a few micrometers. In many cases, both evolvent and tooth direction must be corrected for conicity and crowning. In addition to the tooth flanks, the pitch, that is, the distance between the teeth of a gear, is of vital importance to the quality of the part being produced.

Tooth flanks can basically be manufactured in two process variants:

■ *Shaping* These can be noncutting processes, broaching, form milling, and form grinding.

■ *Hobbing or hollow-cut* These can be hobbing, gear shaping, hob peeling, hob grinding, and generation of gears by planing.

The simplest variant of gear manufacturing, considering the kinematics of a machine, is the form processes and includes almost all noncutting processes. In the process, cutting tools are used that are formed like a tooth gap. With these tools, the excess material between gears is removed on an indexing head. A similar process is broaching; here an entire ring gear is generated in a single operation. It uses a tool with the negative shape of the gear to be formed.

The more complex hobbing processes in the generation of the involute are based on the reference profile. This reference profile has the form of a rack; that is, it has straight flanks, and in some processes it is a direct part of the gear-cutting tool (e.g., for hobbing), generating gears by planing and hob grinding. In other methods, the reference profile can be thought of as a toothed rack that can mesh with both the workpiece that is produced and the tool (e.g., gear shaping and hob peeling). In all these cases, the involute is created with a large number of profiling cuts that always start as a tangent to the involute. Figure 14.26 shows the theoretical principle for the generation of an involute using rack-shaped tools and its technical implementation in a gear-cutting machine.

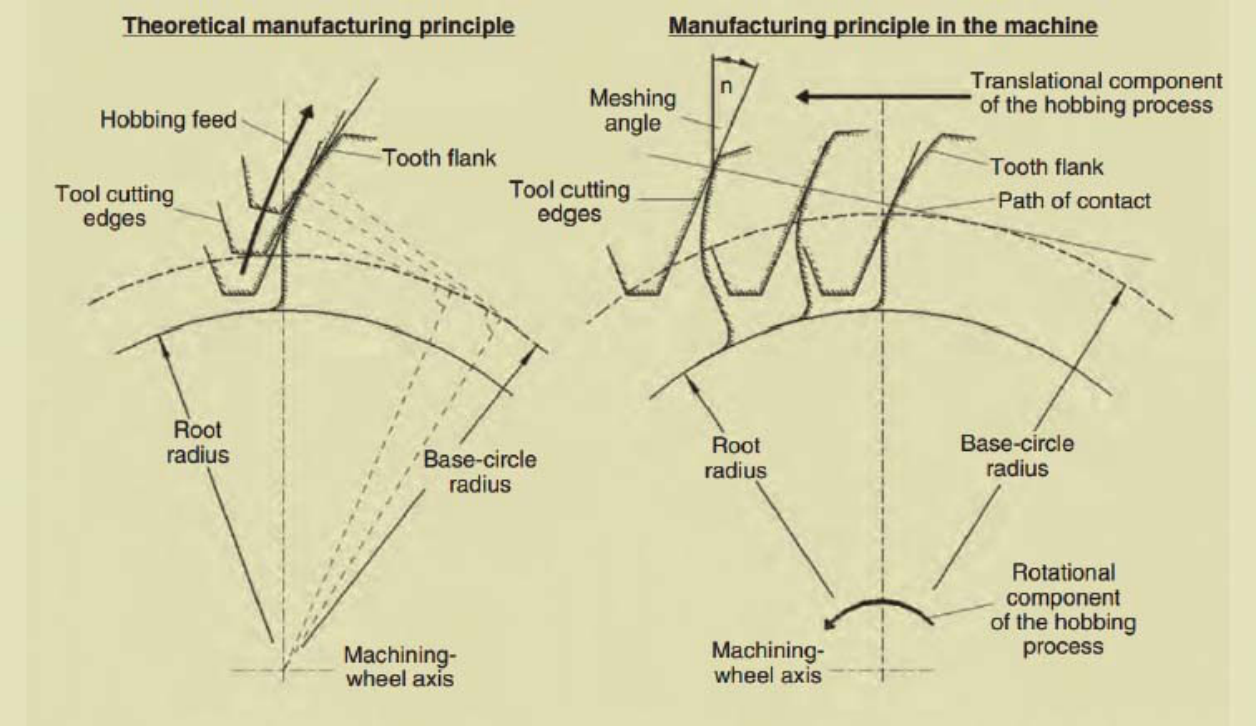


FIGURE 14.26 Manufacturing principle of an involute flank. Beck.)

The left-hand part of Figure 14.26 shows three cross sections of a straight-flanked tool that are always positioned tangentially to the involutes, thus creating them in a hollow-cut process. This relative motion between the tool and workpiece is implemented in a gear-cutting machine, as shown in the right-hand part of the figure. Here two individual motions are combined so that together they generate exactly the same relative motion between the workpiece and the tool. It consists of:

■ The rotational component of the hobbing as a rotation of the workpiece

■ The translational component of the hobbing as a linear advance of a rack-shaped tool

Using this motion characteristic, it is possible to create involutes in a continuous hobbing process. Creating gear teeth, however, requires some additional simultaneous feed motions. Thus the teeth are cut from top to toe by advancing the tool radially. What is more, the axial feed means that the tool is guided over the entire width of the gear workpiece, which means that the entire wheel is toothed. If a helical gear is being produced, the axial motion must be coupled with rotation of the workpiece in such a way that the workpiece is always cut in the direction of the tooth; that is, the workpiece table is subjected to an additional rotation on top of the hobbing rotation that depends on the angle of inclination and the axial position of the tool.

The demanding requirements regarding workpiece quality when four or more axis motions are being executed continuously have forced design engineers to find even more special solutions for gear-cutting machines. Thus, from the beginning, synchronous motions of multiple axes were implemented by means of mechanical gear couplings, so a single motor could drive a number of motions by means of gear branching. Changes in the gear ratio, for example, to produce a gear with a different number of teeth, were accomplished using changeable gears. In this regard, the mechanical-axis couplings meant that gear-cutting machines were always automated machines.

Preparations for Soft Material Processing of Spur Gears/Gear Hobbing

Figure 14.27 shows the most common hobbing processes of soft material using the reference profile of a gear rod. For better understanding, it is helpful to imagine the gear workpiece to the left three more times: in the second figure for the operation hob milling, in the third figure for the operation of hob shaping, and in the fourth figure for hob peeling. The cases of hob milling, shaping, and

peeling are continuous processes because of the practically unlimited tool length, where the part will be completely formed. The planing operation has a limited tool engagement, and the operation takes place in many partial motions.

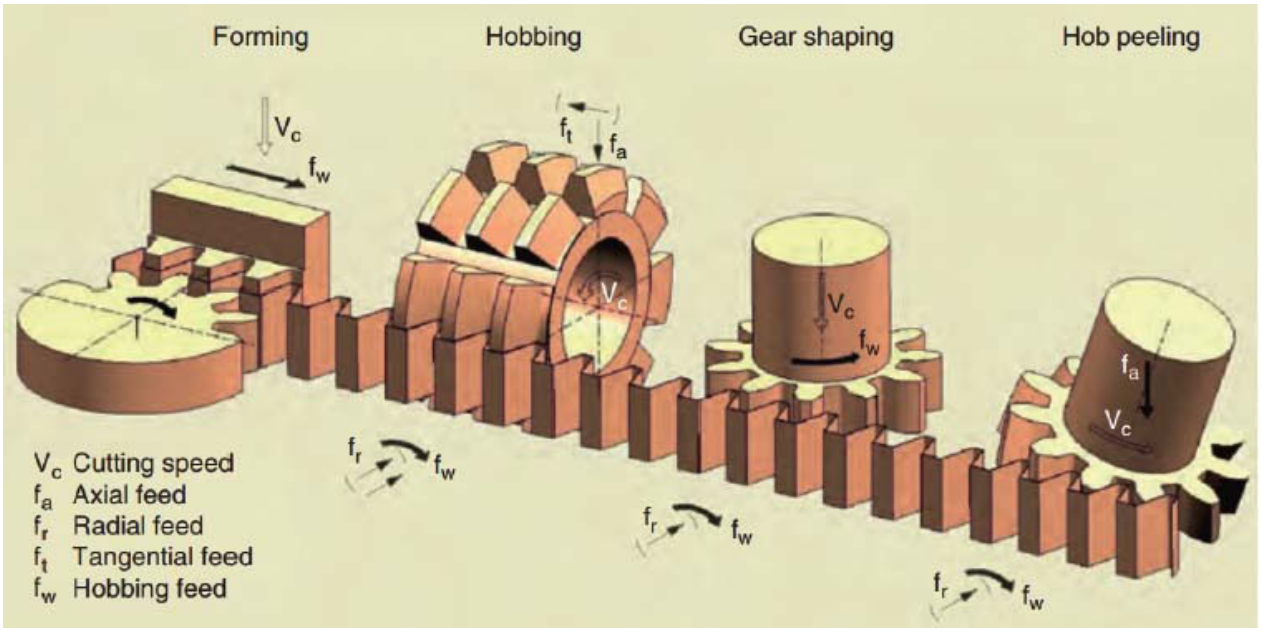


FIGURE 14.27 Principle of the four hobbing methods for soft machining.

Considering also the forming of the gap between an existing tooth and an emerging tooth, the two processes of hob milling and hob peeling and the two processes of hob shaping and hob planing reveal distinct differences. The latter two work with straight cutting motions, removing material in the direction of the tooth. During hob milling and hob peeling, the spinning tool, advanced by an axial carriage, is moved in the lateral direction of the tooth. It leaves marks in the direction of the tooth from the slow tool rotation and depending on the axial feed. The previously described cuts of the involute profile leave a facet-like pattern on the tooth flank. The chips of hob milling and peeling are always short, the chips of forming

and planing have the length of the entire gear width. Hobbing tools can basically be used with the same module for the fabrication of various numbers of teeth.

Gear-hobbing machines are continuously working machines. The tool used is an involute snail, from a geometric point of view, and the snail gears are interrupted by flutes. The flanks and heads of the cutting teeth are undercut to create the clearance angle needed for material removal. Tool and workpiece are rolling off each other as in a worm gear. The rotation of the milling cutter generates not only the cutting motion but also the translational component of the hobbing process via a tangential screw motion on the tooth flanks.

The production of straight-toothed gears is governed by the following parameters:

■ The gear hobber and workpiece engage at crossed axes in a similar manner to a worm and a worm gear.

■ The axis of the gear hobber is inclined by the helix angle of the milling cutter relative to the transverse plane of the workpiece.

■ The gear hobber and workpiece are positioned opposite each other according to the tooth depth.

■ The gear hobber and workpiece are rotated according to the ratio between the number of teeth of the workpiece and the number of cutter threads.

■ Either the gear hobber or the workpiece is moved at a feed rate parallel to the workpiece axis, and chips are removed.

■ After enough passes have been made around the workpiece, all the tooth gaps will have been cut out along the entire length of the workpiece.

With helical gears, the milling slide also moves parallel to the axis of the workpiece. Therefore, in this case, the axis of the gear hobber has to be inclined by the milling helix angle and by the spiral angle of the teeth that are cut. In order to ensure that the gear hobber always cuts in the direction of the teeth during the axial feed motion, the workpiece, in addition to the rolling motion, is given an additional rotational motion by means of a differential gear unit. In modern machines, this is always implemented using an electronic system.

The axial feed of the tool during gear hobbing creates feed marks. The distance between two marks shows the distance traveled by the gear hobber during a single rotation of the workpiece. There is an interrelationship here between quality and machining time insofar as higher axial feed rates reduce the machining time but, on the other hand, lead to more pronounced feed marks and thus a lower quality.

During gear hobbing, only a few teeth of the gear hobber are involved in the creation of a gear because the teeth are guided parallel to the workpiece axis over the complete width of the gear. In order to ensure even loading of the milling cutters and to reduce wear, it is possible to shift the tool either continuously or at certain time intervals in the longitudinal direction of the milling cutter, that is, tangentially to the workpiece. This motion is called The module and meshing angle are defined for each individual gear hobber. By varying the machine settings, the same milling tool can be used to

create all the required workpieces with different numbers of teeth, profile offsets, and spiral angles.

Figure 14.28 shows a state-of-the-art CNC gear-hobbing machine for use in mass production. Such a machine requires a minimum of five numerically controlled axes, which in some cases have to operate simultaneously. This involves the following axis motions:

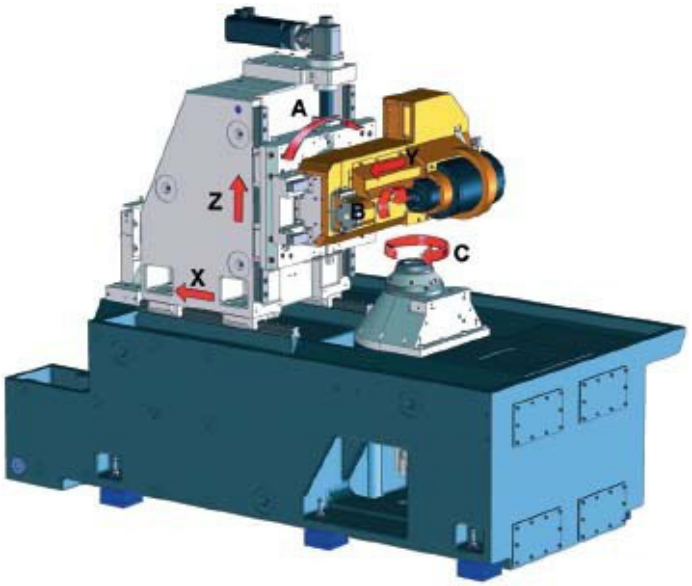


FIGURE 14.28 Modern CNC gear-hobbing machine for mass production. Liebherr.)

- tangential motion of the tool (shifting)
- rolling motion of the tool (cutting motion)
- rolling motion of the table or the workpiece
- radial motion of the tool

■ axial motion of the tool

As a rule, both rolling and axial motions are coupled by means of electronic gears. If greater flexibility is required, for example, to mill different workpieces or to correct the angle of inclination, then swiveling of the milling head can be used as the sixth CNC axis.

Play-free table drives are very important in producing high-quality gears. The manufacturers of gear-hobbing machines have taken various approaches when it comes to minimizing play. As a result, duplex worm drives, double worm drives, tensed cylindrical gear drives, and drives with hypoid gears are in use. However, the future definitely belongs to direct drives, which provide, among other things, high speeds and are thus also suitable for other technologies, such as gear-flank grinding. With the exception of very large machines, all new machines have direct drives for all their hobbing axes.

The trend toward dry machining led to new machine concepts with changed axis configurations. The common goal of these conceptions is to allow the free falling of chips. For this reason, the workpiece spindles are arranged either horizontally or vertically. The advantages of this design are counterbalanced by the disadvantage that these axis positions are not suitable for universal platform designs that could be used on the same basis to implement various types of workpieces or even different technologies, for example, gear hobbing and gear shaping. As such, these products have to be regarded as single-purpose machines whose use is limited in various ways.

Figure 14.29 shows a modular product system for the gear-hobbing, gear-shaping, and hob-grinding processes. It is also possible to perform the associated shaping process on these machines. All the hobbing drives are implemented as digital drives. The uniform machine basis means that workpiece feeding, automation, and other auxiliary functions such as deburring and coolant cleaning are performed independently of the tooth-generating process.

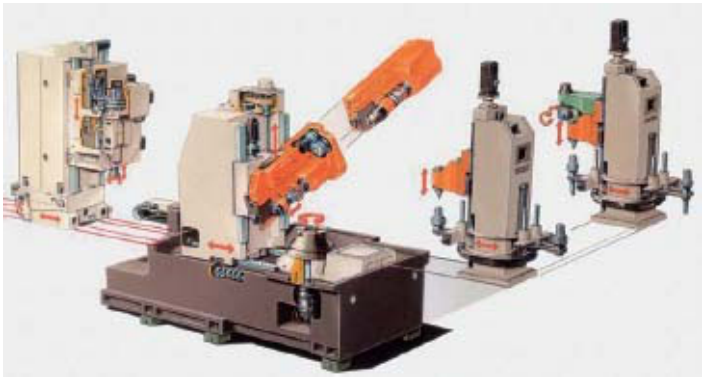


FIGURE 14.29 Modular gear machine arrangement for spur gear processing. Liebherr.)

Hard-Fine Machining of Spur Gears

The machining of hardened tooth flanks basically follows the same principles as soft machining. The goal of hard-fine machining is to eliminate the deformation created during heat treatment and to generate any necessary flank corrections. The processes created for this include hob grinding, profile grinding, honing, skiving, peeling, and broaching of hardened materials. Hard machining requires additional machine and control functions. These are decisive for the quality of the tooth flanks.

The teeth already exist, and the tool must be guided into the existing tooth gaps with great precision to hard-finish the flanks. The

orientation of the workpiece is detected with the aid of a sensor that has been marked with the set-point position based on the first workpiece, and that will bring all subsequent workpieces into the same position by correcting the angular position of the workpiece table. Various geometries of the individual tooth gaps are averaged out. For this reason, these are called *threading* or *centering*

For working with adjustable tools such as worm-grinding wheels made of carborundum, dressing devices are integrated into gear-cutting machines. These can themselves be multiaxis devices, and they can return a tool to its original form according to certain strategies, for instance, after the production of a certain number of workpieces or when a certain level of wear has been reached. Dressing tools are diamond coated.

Fabricating Bevel Gears

Whereas the generation of involute spur gears can be described as engagement of the straight-flanked reference profile with the workpiece, the production of spiral-toothed bevel gears involves the meshing of the workpiece with the so-called generating crown gear. Both wheels of a bevel-gear pair are based on the same crown gear. The center point of the crown gear is identical to the common tip of the two-pitch cones In the production process, the cutting tool generally represents only one tooth or one gap in the crown gear.

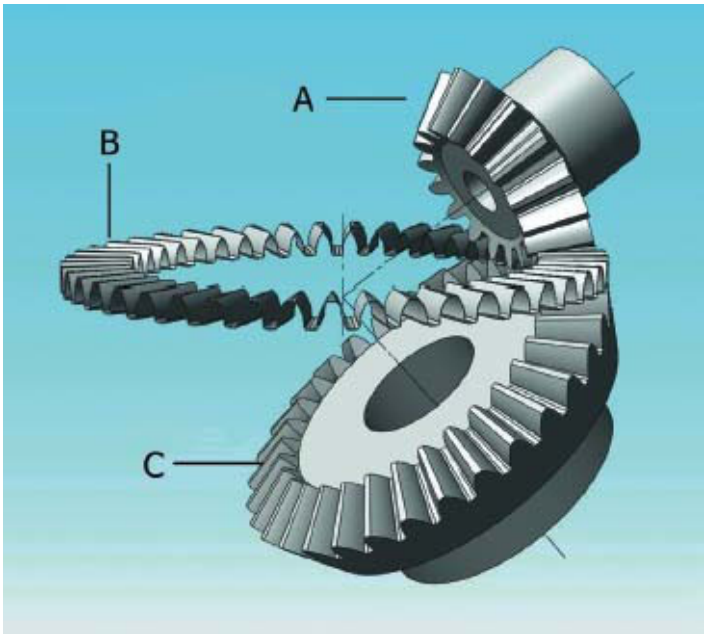


FIGURE 14.30 Gear pairings with intersecting axes: (a) drive gear; (b) generating planar gear; (c) driven gear.

The methods for creating bevel gears basically can be subdivided into the same categories as the methods for creating cylindrical gears. Bevel gears also can be produced using hard and soft machining processes. Soft machining can be further divided into cutting and noncutting processes; cutting processes, in turn, are subdivided into shaping and hobbing processes. In hard-machining processes, a distinction is made between processes with geometrically defined cutting edges and geometrically undefined cutting edges. Besides the manufacturing methods, bevel gears are also differentiated based on whether the tooth depth remains constant over the width of the tooth face or increases from a smaller to a larger one, that is, conically. The continuous production processes generate involutes or cycloids as a longitudinal curve and teeth with a constant tooth depth.

Conventional bevel-gear milling machines have from 10 to 12 axes. The axes are coupled by means of mechanical gear trains. The creation of the flanks involves three main elements with mutually associated motions: the roller drum, the cutter head, and the gear workpiece.

The kinematic basis for the bevel-gear production process is engagement of the generating gear with the workpiece. The axis of the roller drum is identical to that of the generating gear. The rotation of the roller drum brings about the rotary motion of the imaginary generating gear.

The actual cutting motion is performed by the cutter head. The path of the cutter in the area of engagement between the workpiece and the cutter head describes a tooth in the generating gear. The cutter head's rotary axis is positioned eccentrically and is not always parallel to the rotary axis of the roller drum. Both the milling cutter axis and the generating axis are rotated during the cutting process. The gear workpiece rotation is composed of the gear ratio between the gear workpiece and the generating gear and a relative motion that takes into account rotation of the roller drum.

The increased use of CNC technology has led to machine concepts with simpler mechanical designs and more flexible applications. These machines no longer have a roller drum but still use cutter heads as tools. They only have six CNC axes. The complex relative motions between the tool and workpiece are implemented solely through the use of complex control systems and drive technology. Such state-of-the-art CNC machines can be used for all the usual processes, such as the dividing method and the continuous method and tooth shapes such as arcs and cycloids, provided that

suitable tools are employed. Figure 14.31 shows an example of this type of machine. The following axes are involved in the production process:

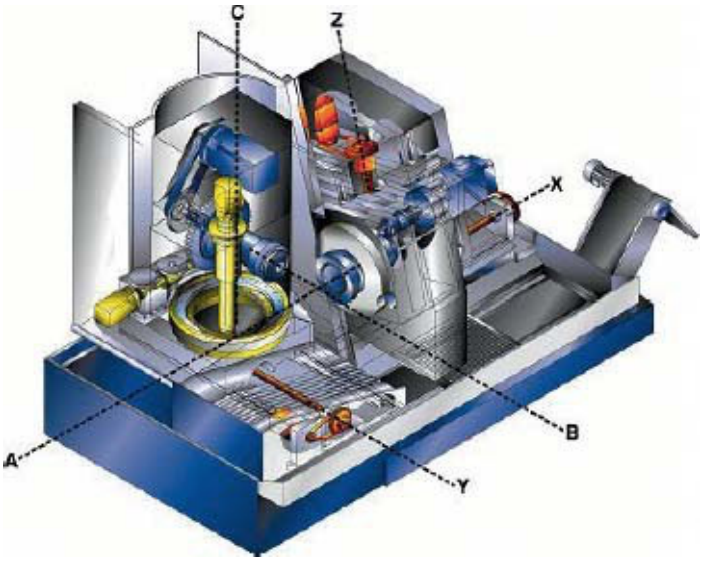


FIGURE 14.31 Gear-hobbing machine for bevel gears. Klingenberg.)

- rotation of the cutter-head spindle
- rotation of the workpiece spindle
- workpiece swivel axis
- milling depth in-feed
- workpiece positioning
- tool positioning

The production of bevel gears does not involve just a single machine or tool. Today, this almost always involves a special type of manufacturing organization that functions similarly to a closed-loop control process. Thus it is not just the gear-cutting machine itself that is important in achieving the necessary level of quality but also the gear-measuring machine and the tool-sharpening machine.

Programming Systems of Gear-Cutting Machines

Fundamentals and Basic Characteristics

The gears generally represent a repeated arrangement of the same geometry elements according to defined duplication specifications. A geometry element, for example, is understood to be a tooth of a gear that is positioned in a centrally symmetrical arrangement at the base of a circle. Concerning a tooth rack, the element duplication takes place in a plane. Concerning a worm, duplication takes place as a tooth or as number of gears.

As described earlier, a number of processes exist for fabricating or finishing gears, such as continuous hob grinding, hobbing, gear shaping, bevel-gear milling, and worm-gear grinding. Based on the duplication of CNC fabrication of gears, processes with a cycle character can be derived. This means that all movements of individual motion elements and the repetition of those motion elements can be structured as overall motion sequences. Modern CNC controls provide all instructions for programming such cycle sequences.

Generally, a distinction is made between control software and application software. The application software is usually created and supplied by the machine manufacturer. The control software provides

the firmware for the respective control system with the required instructions for cycle sequences. For turning and milling technologies, the various CNC machine manufacturers deliver specific solutions based on the respective control software. For gear technology, the machine manufacturer exclusively develops CNC programming systems as a user application. The main components are composed from the following areas:

■ CNC: Procedural and auxiliary procedures of the tool and machine movements

■ PLC: Control and switching sequences for guidance and support of the procedures

■ GUI: Procedures for entering and calculating all process preparatory data with machine and process-specific interactions and process customizations

Other components such as CNC sequences or communication of the control system in a network can also be components of the machine software.

Procedures are movements such as hobbing, in-feeding, tool stroke, workpiece stroke, and such and are essentially stored in NC programs. Control sequences act on the machine procedures in the form of interactions to directly or indirectly influence the machining process. They are located in the programmable-logic controller (PLC) program or at various process interfaces as quick inputs of the CNC system.

The acting level is understood to be the CNC, PLC, and GUI including their sublevels. The CNC programming system for gear-cutting machines allows the integration of a variety of gear processes up to practical preparation according to the stated basics and features.

Main Components of the NC Programming System in Machine Control

A user application based on the named major components requires a topology of components with a variety of:

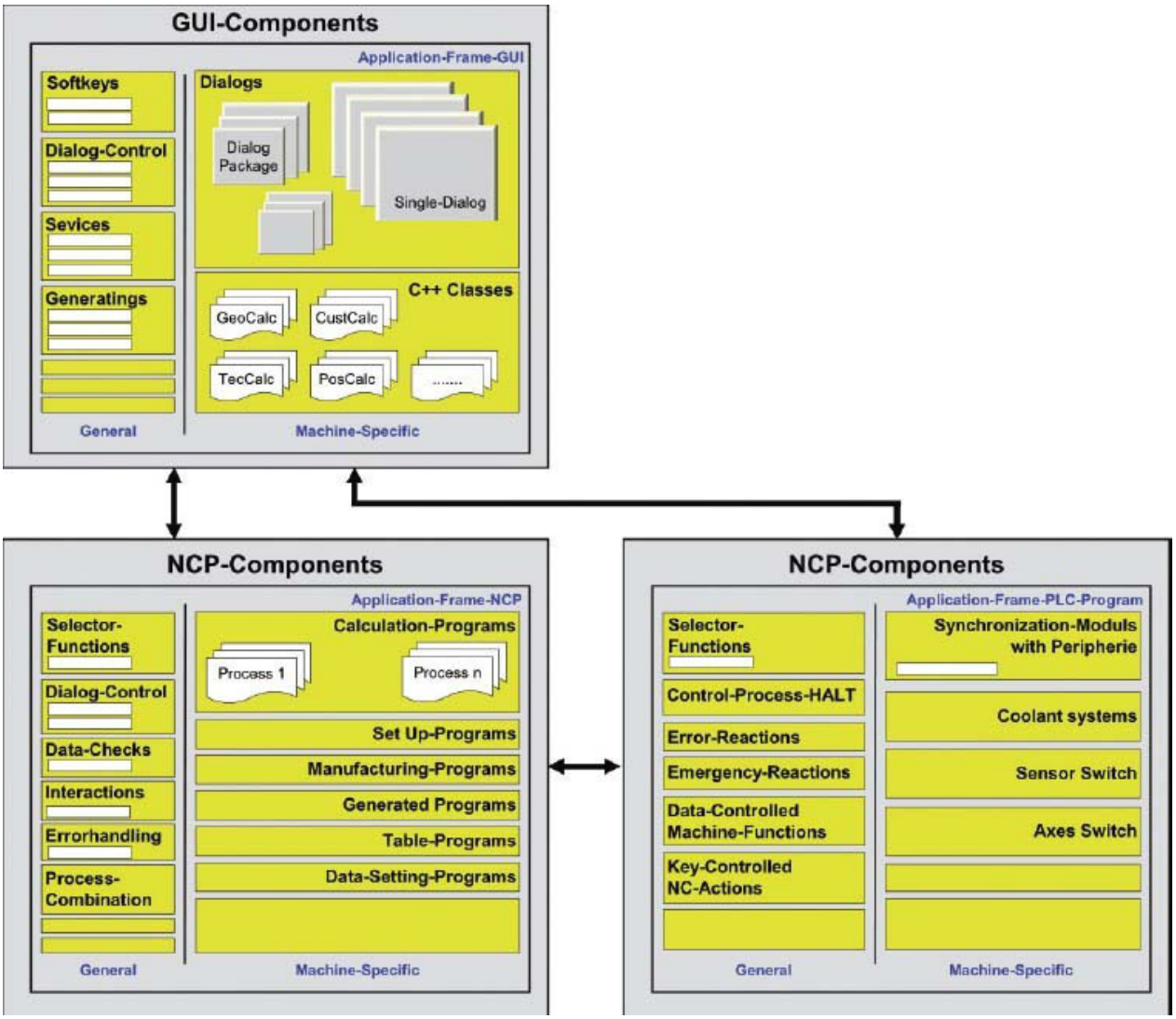


FIGURE 14.32 Topology of the main components of the NC programming system of a CNC machine for gear cutting.

- Fixed program sequences with continuous and cycle character

- Integrated calculation and generation modules for intermediate and final results and NC programs

- Communication channels for data and file transfers

- Modules for context-sensitive creation and deleting of GUI components

- Management modules

The motion-generating modules, preferably CNC programs, are implemented in the CNC machine, if necessary in the drive amplifier or in the PLC, respectively. These modules control processes such as setting up, machining, measuring, and loading/unloading. The use of the existing CNC functions for the processes offers advantages such as uniform data management in variables and files and fast synchronization of processes. The use of functions via the PLC has, or is supposed to have, only a supplementary role.

Generally, the system is characterized through a holistic file structure. The main criteria for the file organization are:

- Guaranteed clarity concerning the programs and data for the procedures, workpiece, tool, technology, and control processes

■ Fast and modular interchangeability and modifiability of procedures, workpiece and tool data, and processing technologies

■ Repeatability with high performance

Regarding the process technology, the distinction is made between workpiece, tool, process, and process combinations. This applies equally to the GUI and for the CNC area. Calculations and data and file generation and transfers are event driven.

As an entity of the overall organization, the differentiation of basic geometry data, modification data, and calculated data is done separately for workpiece and tool. This structuring clearly creates and programs causality into the geometry generation on the workpiece, tool, and sequence of processing.

An exchange of data and programs with workpiece, tool, and machining technology is guaranteed. For example, in the area of the GUI, the machining technology of profile milling contains files:

■ With limit values for the individual technological data such as in-feed or cutting speed

■ As manual jobs to generate NC programs in the form of data and program assignments

■ As automatic jobs to back up data of the NC in the current project file and, if necessary, with subsequent generation of NC

programs and automatic downloads

■ With texts in various foreign languages

The NC programming system is event driven. This means that all processes can be, for example, started by an event, stopped, activated, deactivated, aborted, or restarted. The NC programming system is prepared in all components for the event evaluation, for example, via data or interrupts.

Typical events are the manual pressing of soft keys or keyboard keys at the machine control panel. Other events can be generated in the PLC or NC system. Typical events are, for example, the writing of parameters of the NC program by the PLC, the error reaction on devices, and the sequence reaction on counter limits. The processes in the GUI, NC, and PLC can act by themselves or react on each other through direct or indirect influence in the form of an event generation.

The event handler in the PLC is of central importance for the NC programming system. Within the PLC program, data from the PLC itself, the GUI, the NC system, and peripheral inputs are processed. In a consistent consequence, the PLC controls the processes automatically and interactively.

Setting Up and Editing with the NC Programming System

The operation of a gear-cutting machine occurs primarily in the setup and production operating modes. It uses the usually available CNC operating modes *manual operation* (jog and continuous mode) and

automatic operation as submodes and the *reset* and *halt and wait* states.

Including the CNC operating modes, the machine operating modes are defined as:

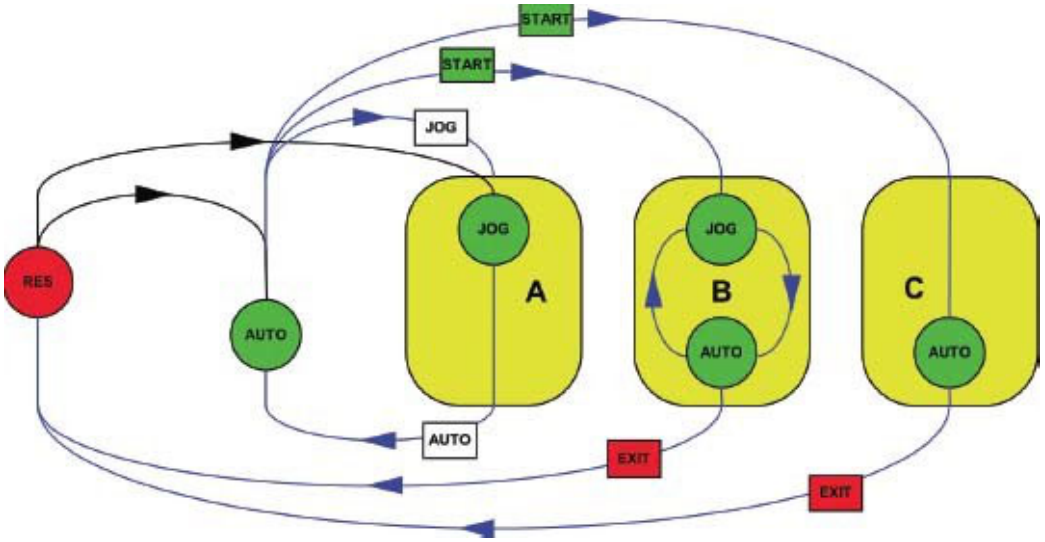


FIGURE 14.33 Machine operating modes for gear-cutting machines with status transitions.

■ (a) Manual operation with jog and continuous mode without an NC program run

■ (b) Setup mode with the NC program running and with jog and continuous mode

■ (c) Production operation with the NC program running and optionally with jog and continuous mode

The status can be changed using the keys "Start," "Reset," "Exit," "Jog," and "Auto." The setup and the production operation generally

take place as sequence steps with embedded sequence, star, and cycle functions. There can be differences between the operating modes:

■ In setup mode, the number of steps with the number of individual functions is higher.

■ In setup mode, run functions with short movements or data handling when opened or closed workroom doors are active.

■ In production mode, run functions and cycle functions are active, and the process functionality has primarily cycle character.

■ In production mode, a startup and end stop are active.

■ In the respective setup and production modes, different security levels are activated.

In all operating modes, the status transitions are initiated with the keys or soft keys “Start,” “Stop,” “Forward,” and “Back.” The follow-up functions are specific depending on the program location.

Process Mathematics and Technology in the Components

Especially in an NC programming system for gear-cutting machines, a number of tasks must be performed, such as data entry, plausibility checks, calculations, crosschecks, data selection, and data generation for the workpiece, tools, and processes. These tasks take place in varying degrees within the GUI, NC, and PLC based on the same rules.

With regard to clear operating sequences, compelling causality in data preparation, easy interruption, high performance, and other criteria, a splitting, for instance between the areas GUI and NC, is required. A high degree of flexibility in terms of customization to changed process conditions or even exchange of procedures itself is required. In this way, the processes are executed in the GUI and in the NC program alike as a sequence or sequence function with all the features, such as sequence abort and return to last menu item (see Figure

The overall sequence consists of the steps in the GUI area and steps in the NC area (examples are listed in Table This structure and organization are described as applicable for multiple procedures, for example, for continuous hob grinding and cyclopalloide milling. There are fundamentally different calculation algorithms, formulas, and couplings of NC axes during process execution for both methods. Yet the sequence arrangement in both processes is governed by the same rules (see Table Figures 14.34 and

FIGURE 14.34 Gear-cutting machines for bevel-gear cutting and hobbing from SERWEMA Company using a G-COTEC gear system.

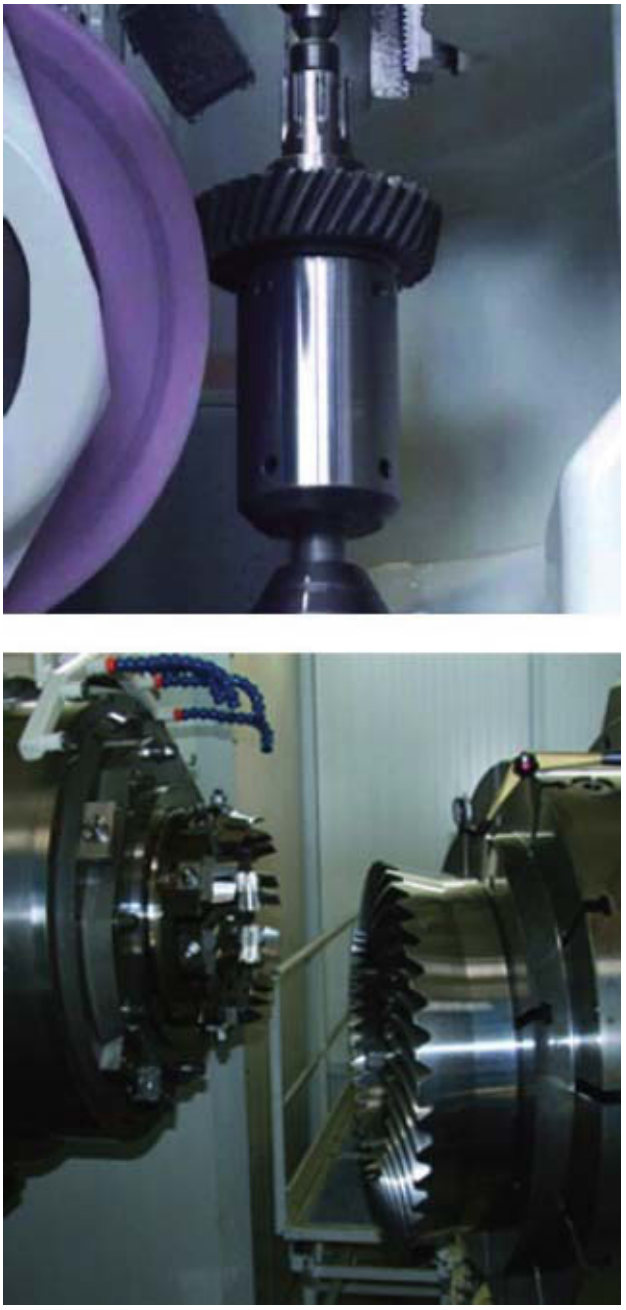


FIGURE 14.35 NC programming system used for continuous hob grinding and cyclopalloide hobbing.

TABLE 14.1 Steps for the Sequence Functions for Continuous Hob Grinding and Cyclopalloide Milling with Input of Process Assignment

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Application Examples of the NC Programming System

Machinery

The NC programming system is used for a variety of procedures such as continuous hob grinding of conical gears, cyclopalloide milling of bevel gears, and hob planing of internal and external spur gears. In addition, different CNC control systems are used as a basis for employing the NC programming system.

Technical Data Input

Technical data for all processes are entered as tables. Technical levels can be combined, displayed, or hidden

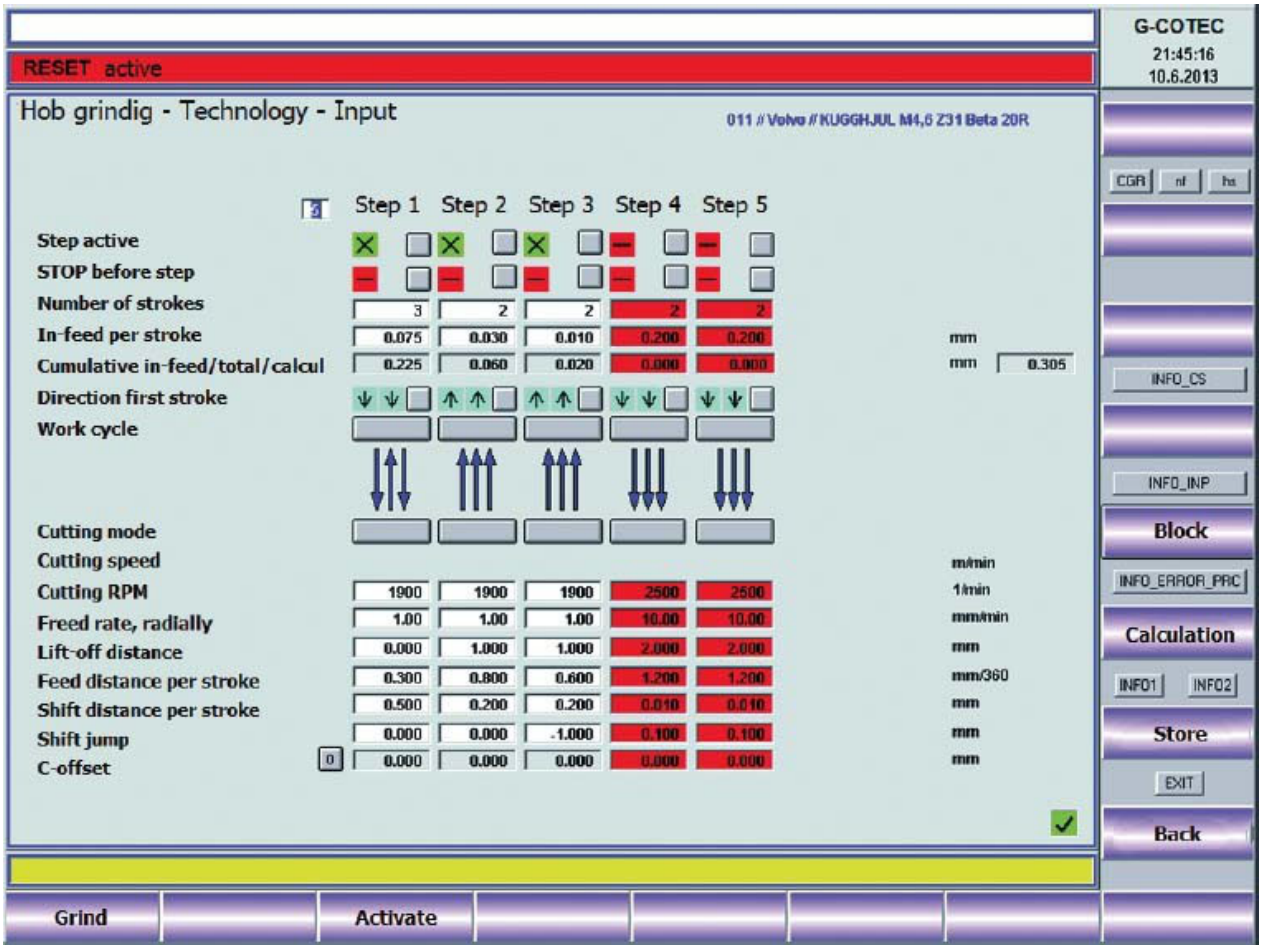
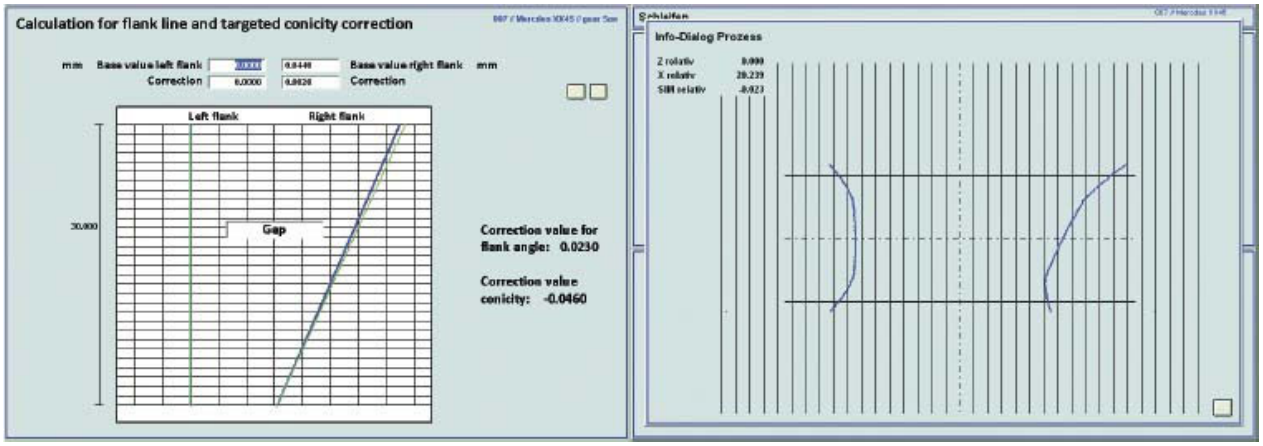


FIGURE 14.36 Technical data input through matrix control.

Modification Input and Graphic Process Feedback

For continuous hob grinding of conical gears, for instance, separate procedures are implemented. These can be for creating modifications of the crowning with the superimposition of flank line corrections separately for the left and right flanks and for offset correction During the process, generation of the flank line will be visualized as shown in Figure 14.37 (right).



FIGURES 14.37 Correction on one side of the flank line as a superimposition of an end correction of the tooth width.

DRILLING MACHINES

When drilling, the chips form via a rotary cutting movement of the tool. The feed movement is done either by the tool or by the workpiece in the direction of the axis of rotation of the tool. In addition to drilling with spiral drills, drill presses are used for reaming, tapping, counterbore, countersink, and boring applications. Drilling machines are available in different types and designs.

Column Drilling Machines

Drill presses with a vertical spindle assembly are typically used in metalworking shops. They are designed as tabletop or stand-alone models. These machines are easy to use and maintain and are therefore widely used.

Arm Drills

Many shops use arm drills, also called *radial drilling* for drilling larger workpieces. The drill head is mounted on a swiveling radially movable arm. To adapt to workpiece height, the arm also can be moved vertically and clamped.

Deep Drilling Machines

These machines are used for the fabrication of holes whose ratio between drilling depth and drilling diameter is greater than 10 mm and smaller than 150 mm. During operation, the chips are flushed out of the cavity because of the high pressure of the coolant. Column, arm, and depth drilling machines are included here for the sake of completeness because they are not CNC

machines. Drilling centers and boring machines do have CNC systems.

Drilling Centers

Customers often desire to achieve a higher degree of automation without forgoing the special advantages of a drilling machine. This led to the development of drilling centers An additional rotary or indexing table with a horizontal axis allows the four-sided machining of cubic workpieces. To reduce nonproductive times, especially for larger lot sizes, these machines are additionally equipped with two multiple clamping jigs and a swivel table. This allows manual or automatic loading and unloading of workpieces outside the enclosure during a production run.

FIGURE 14.38 The fast operating cycles of drilling and tapping centers are supported with a tool changer that clocks at 0.9 s. The dynamic in the linear drives is and axis speed is 60 m/min. DMG MORI.)

Boring Mills

Boring mills are usually very large machines with a horizontal main spindle. A typical feature of these machines is the addition of a quill in the as a This means that the quill moves on the and can be used in addition to the movement of the moving column. This results in a higher dynamic in the motion, as would be achievable via the mass inertia of the moving column alone.

The additional integration of a fully automatic tool changer can expand the functionality of a boring mill to that of a machining center.

Modern boring mills usually have controlled ways with up to seven axes. These features are indispensable for boring mills:

■ Teaching complete drilling patterns with mirror function [In this way, the hole pattern of a housing can be programmed, and the matching cover will be fabricated congruently

■ Slope correction to compensate for clamping tolerances

■ Hole milling

■ Thread milling

■ Measuring cycles for the use of switching probes

■ Programming supported with graphics and simulation of the processing

FIGURE 14.39 A boring mill with moving column and horizontal tool spindle. Union.)

Special machining tasks can be accomplished with custom cycles. The cycle is loaded, and the required parameters are entered and modified as needed. Typical examples for cycles are hole patterns, rows of holes, and form or pocket milling. The simple operation of the control is important in order to interrupt a running program to resume it later or to exchange worn tools (including the associated correction values). In addition, the CNC system should give the user the opportunity to create specific subroutines, including auxiliary graphics and parameterization. Linear encoders are used as measuring systems. For higher levels of precision, the encoders have error compensation in the CNC system.

An increased level of flexibility of large horizontal drilling and milling centers can be achieved with the following extensions:

■ Exchangeable additional heads for drilling, milling, thread whirling, and facing

■ Pickup stations for special tool heads

■ Portable control units

■ Rotating and movable clamping tables

■ Combination with other large machines, for instance, a second boring-mill stand, a carousel lathe, or a moving-column machine on a large workpiece plate

SAWING MACHINES

Machine tools with sawing functions are used to cut materials such as bar stock, plates, sheets, and the like. Sawing is regarded as cutting with tools that have multiple geometrically determined cutting edges according to DIN 8580/8589. Sawing also can be considered as a kind of prefabrication in the context of the manufacturing organization.

For a long time, many users in the metal-cutting industry have assigned the sawing operation to a lesser role in comparison with other production processes. One possible reason is that sawing is not considered part of the production process but part of warehousing. This attitude has undergone a fundamental transformation in view of the comprehensive rationalization of production processes and the development of tools and machines in the field of circular and band saws.

Circular Saws

Circular sawing machines are available in various kinematic designs for the use of high-speed steel (HSS) and carbide-tipped saw blades. What is more, some circular-saw models can perform miter cuts. Because, generally speaking, only a third of the actual tool diameter can be used effectively, large cross sections require overproportionally large tools. Thus, today, circular-saw machines generally are used for material diameters less than 150 mm. They are used as universal saws with the ability to perform miter cuts, for quick repetitive cuts, or as a production-to-order saw with a high degree of automation.

Band Saws

In heavy-duty production applications, a parallel arrangement of several broad saw blades is preferred. Horizontal machines with a stiff two-column design and modern linear guide elements are used most often. The use of mineral cast in saw slides also provides a performance boost for band-saw machines.

Band saws with high stiffness, high performance, and bimetal or carbide-tipped blades are now available for production. Given an appropriate machine and that the material is suitable for a carbide band saw, the sawing performance can be increased by a factor of two or three.

Designs and Variants

The core of every sawing machine is the sawing unit used to lead and drive the sawing tool. The important point of the design is to achieve a maximum of stiffness. For this, the circular-sawing machine is equipped with a compact gear unit with hardened and ground gears. The unit must be guided precisely and with low vibration either by a swivel bearing or by a linear guide. Depending on the specific operation, the cut can be performed from below, from the side, diagonally from above, or vertically from above. In the case of high-precision production band-sawing machines, the usual practice involves a linear feed motion. When it comes to smaller work areas and longitudinal cutting machines, vertically operating saw blades are used. In other areas, horizontal saw blades are more common.

Control and Technology Settings

Significant progress has been made not only with regard to mechanical systems but also in terms of CNC systems, drives, and technology in general. Classical contactor controls now have been replaced with modern high-performance CNC control systems. For simple automated machines, series-produced CNCs are available with a liquid-crystal display (LCD), function keys, manual control functions, and plain-text diagnostic functions. These CNC machines can be programmed to be compatible with Siemens PLCs; a large number of data sets, such as length/quantity combinations, can be entered and activated via a keyboard. At the same time, the saw-feed technology can be set up directly on the operator display

FIGURE 14.40 Modern CNC sawing machine. Kasto.)

When feed magazines and cut-off sorting equipment are used, they are combined with PC-based high-quality monitors with touchscreen control and a wide range of functions. CNC sawing machines for highly automated applications use the Windows operating system, an interface to higher-level computer systems, and extensive options for visualization and diagnostics. An important feature is technology control, which makes it easy for the operator to set the desired cutting and feed parameters.

LASER MACHINING SYSTEMS Definition and Physical Principles

The word *laser* is an acronym for "light amplification by stimulated emission of radiation." The function of the laser is based on the property of electrons of a laser-active medium to emit a photon when they go from a higher energy level to a lower one. The practical implementation of this principle is to place a laser-active material in a resonator between two mirrors and then excite it using an energy source

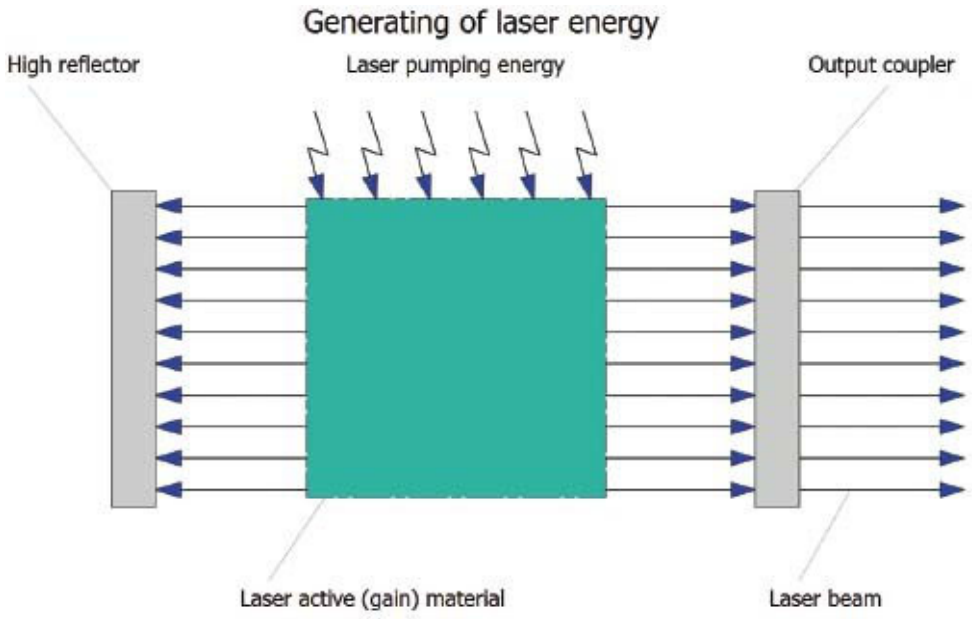


FIGURE 14.41 Creating laser energy.

The laser beam is a contact-based tool that can be used to machine almost any material. The major functional components of a laser machining center are:

- Laser beam source

- Beam guidance system, including the machining head
- Motion axes for relative motion of the laser beam and workpiece
- Workpiece support surface
- Extraction and filtering system
- Protective booth

Beam Sources

Carbon dioxide and neodymium: yttrium-aluminum-garnet (Nd:YAG) lasers are used primarily for the machining of materials because of their high output power. Diode lasers are becoming more common for surface finishing, such as hardening, coating, alloying, welding, and brazing applications.

Lasers

lasers are gas lasers. The gas for this laser consists of carbon dioxide, nitrogen, and helium. The nitrogen molecules are excited by electrodes and pass their energy on to the carbon dioxide molecules. The carbon dioxide is the actual laser-active material that emits laser light when excited. The residual energy of the carbon dioxide is released in the form of heat. Therefore, the gas has to be cooled continuously during operation. The power can range anywhere from a few hundred watts to 20 kW of laser power. lasers generally are used in the welding and cutting of metals

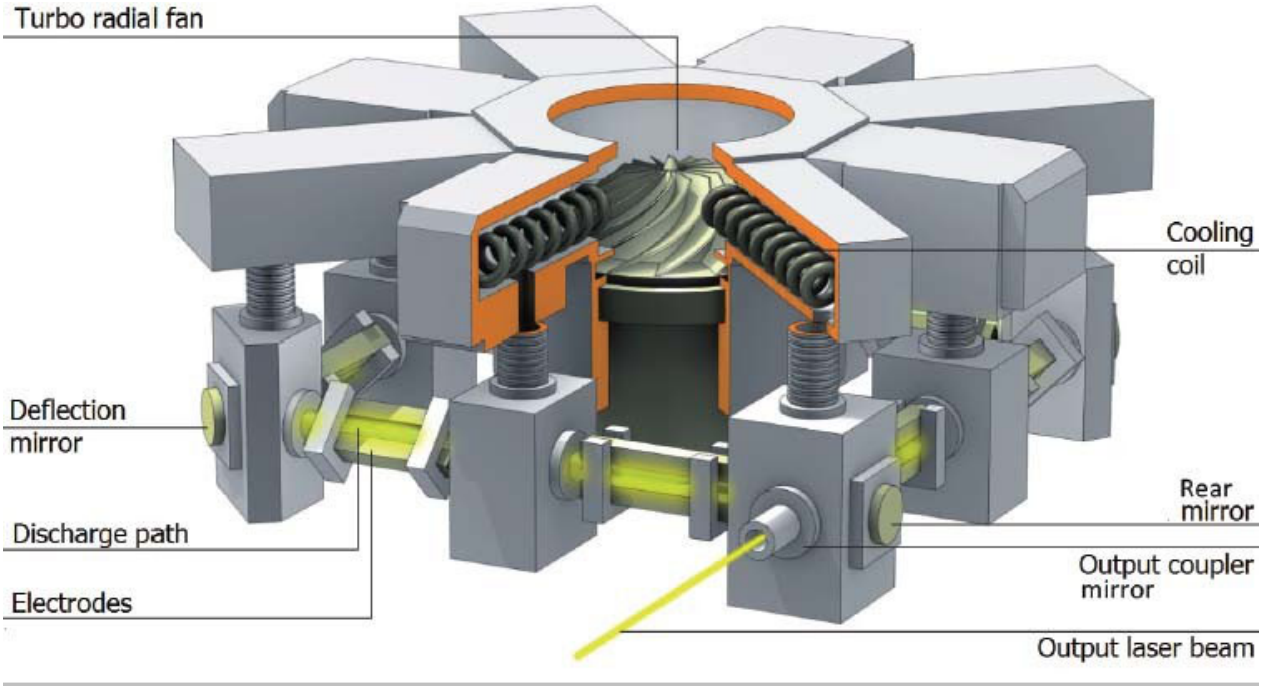


FIGURE 14.42 Section of a diffusion-cooled laser. Trumpf.

Nd:YAG Lasers

Nd:YAG lasers are solid-state lasers. The laser-active body is an artificially created monocrystal made of yttrium-aluminum-garnet (YAG) in which a portion of the yttrium atoms is replaced with atoms of neodymium (Nd). The crystal rod is excited via flashtubes or diodes

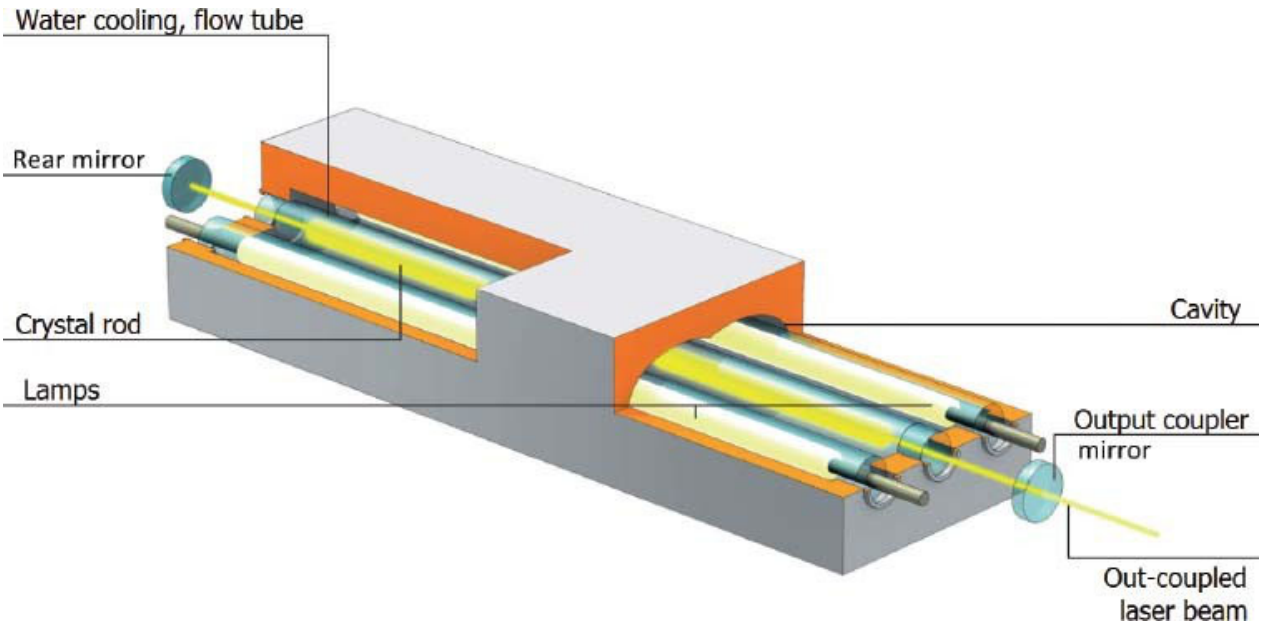


FIGURE 14.43 Nd:YAG laser as a rod laser. Trumpf.)

Disk Lasers

Disk lasers are a type of solid-state laser that is playing an increasingly important role in the metal-working industry. Their advantages include high efficiency and good beam quality. The laser-active material is Nd:YAG; the crystal rod has the form of a thin disk. The advantage of this disk geometry is that efficient cooling is possible

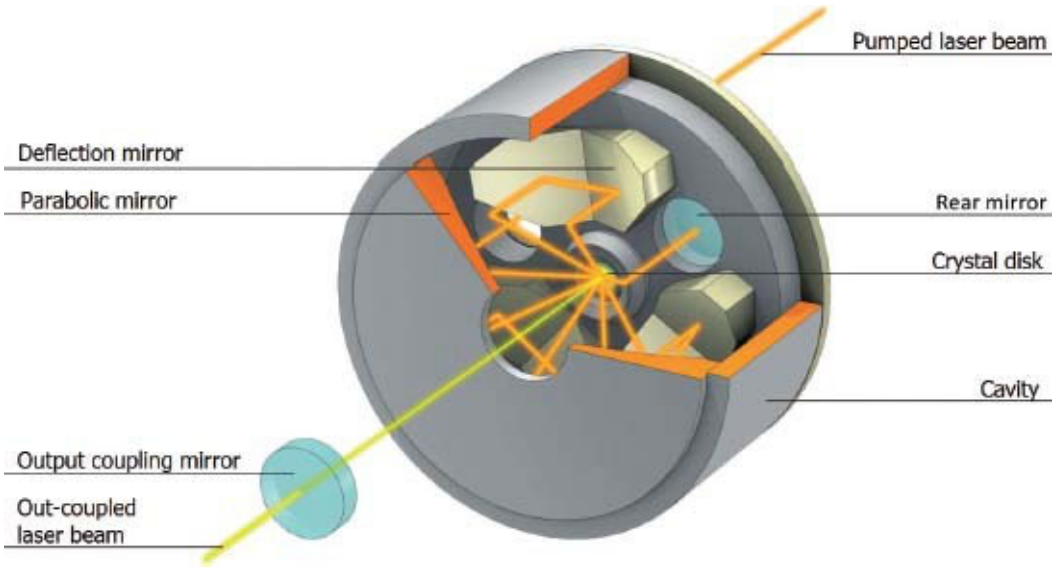


FIGURE 14.44 Cut-away view of a disk laser. Trumpf.)

Fiber Lasers

The fiber is also a Nd:YAG laser; instead of a rod, it uses thin fibers. The advantage here is that fibers, unlike rods, do not require elaborate cooling systems. Because their surface is very large compared with their volume, heat emission to the surrounding air

provides sufficient cooling. Ideally, the resonator of a fiber laser consists of only a single long, thin quartz-glass fiber. The beam source can be attached directly to a transport fiber, for example, to the glass fiber of a laser-light cable. Beam sources for metal machining can achieve a power of up to several kilowatts by coupling many individual fibers in parallel.

Diode Lasers

The laser beam in a diode laser is generated by diodes made of the semiconductor material gallium-aluminum-arsenide (GaAlAs; Figure In order to obtain the power required for the specific production technology, the individual diodes are bundled into so-called diode laser bars. These generally consist of 10 to 20 diode lasers To boost the power into the kilowatt range, multiple diode laser bars are connected in parallel, thus forming diode laser stacks. The laser beam is transmitted via an optical fiber and is available after it passes through the output coupling optics. The advantages of diode lasers are compactness, low weight, and low maintenance requirements.

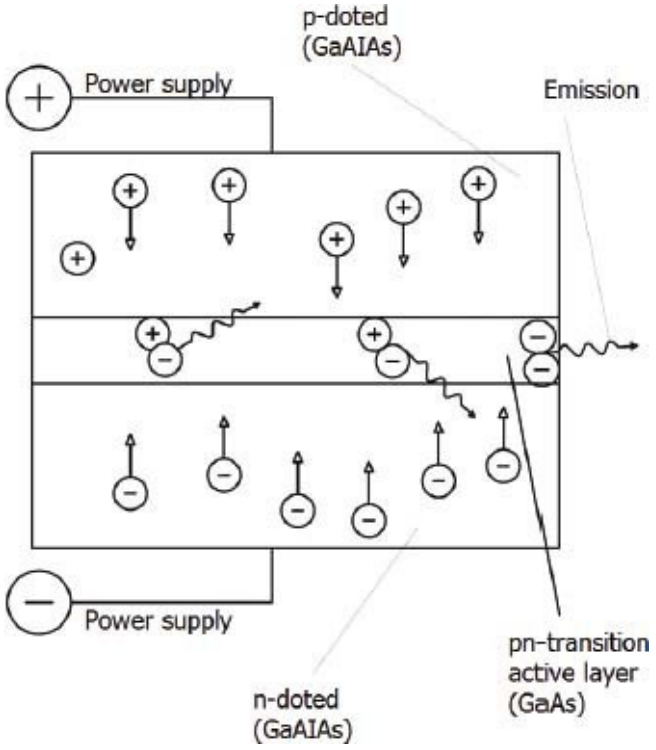


FIGURE 14.45 Schematic of a semiconductor laser.

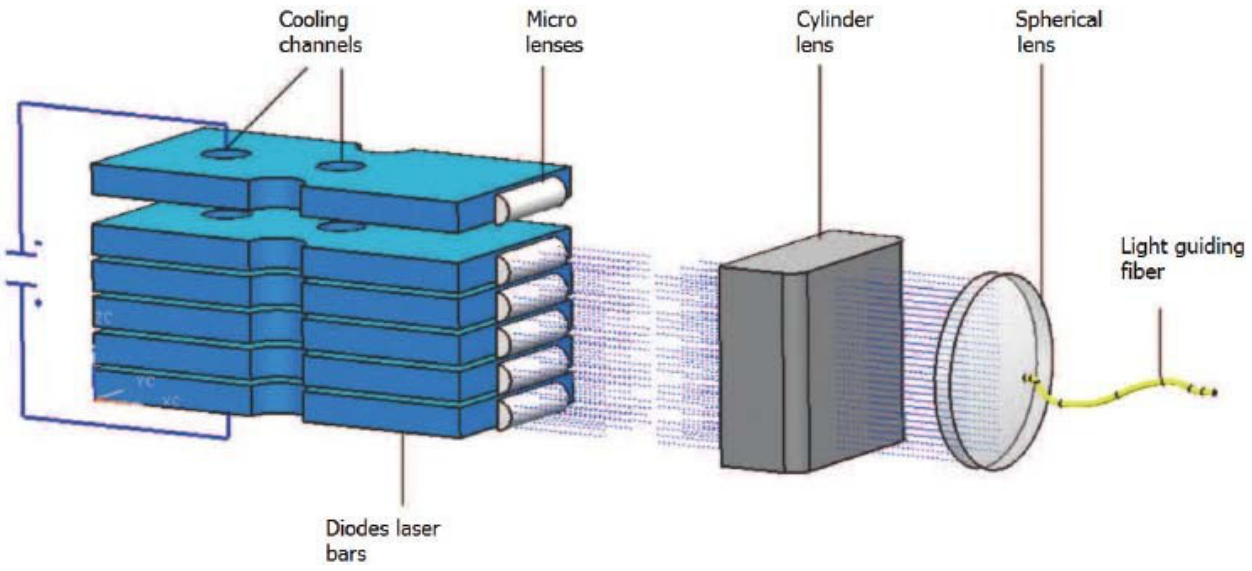


FIGURE 14.46 Schematic of a diode laser.

Beam Guiding Systems

Beam Guidance Using Deflecting Mirrors

In lasers, the beam guiding system consists of a number of deflecting mirrors. The beam path is enclosed by a gas-filled system of pathways made up of tubes and bellows.

Beam Guiding Using Optical Fibers

Beam guiding can be implemented by means of an optical fiber for Nd:YAG and diode lasers. Input coupler optics ensures that the laser light is fed into a very thin fiber (diameter = 0.10 mm). The output coupling optics on the end of the optical fiber forms the beam as appropriate for the machining process.

Laser Machining Heads

Laser machining heads are used at the end of the beam guidance system to focus the laser beam on the workpiece. This can involve spherical or parabolic mirrors or lenses. In addition, process gas and, if necessary, shielding gas are fed to the machining head.
Sophisticated sensor systems (e.g., for distance control) make the machining head an extremely important component for process control.

Motion Axes

The following kinematic arrangements are possible for positioning the machining head relative to the workpiece

TABLE 14.2 Motion Axes and Machine Concepts for 2D and 3D Machining

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Source: Trumpf.

- Moving optics with a stationary workpiece
- Stationary optics with a moving workpiece

■ Moving optics with a moving workpiece

Laser Cutting Systems

Thermal cutting with laser beams can be divided into the following three processes:

1. *Sublimation* The material in the area of the kerf is vaporized. Because no noteworthy melting takes place, the result is smoothly cut edges, and the workpiece can be processed with practically no posttreatment.

2. *Fusion* The material in the area of the kerf is transformed into a molten state and ejected by a jet of gas (e.g., nitrogen) under high pressure of up to 30 bar. Much greater cutting speeds can be achieved than with sublimation cutting.

Oxygen is used as a process gas. The oxygen assists in the cutting process, thus enabling high cutting speeds. The cut edges oxidize, however. This can possibly necessitate a postprocessing or make downstream processes, such as painting, more difficult.

Overview of Laser Cutting Systems

Given the various types of machines and laser units, laser cutting systems come in an extremely wide variety of designs, but all have the same basic components. The machine concept most often found in sheet-metal manufacturing is a flatbed laser cutting system operating with a laser with the following characteristics:

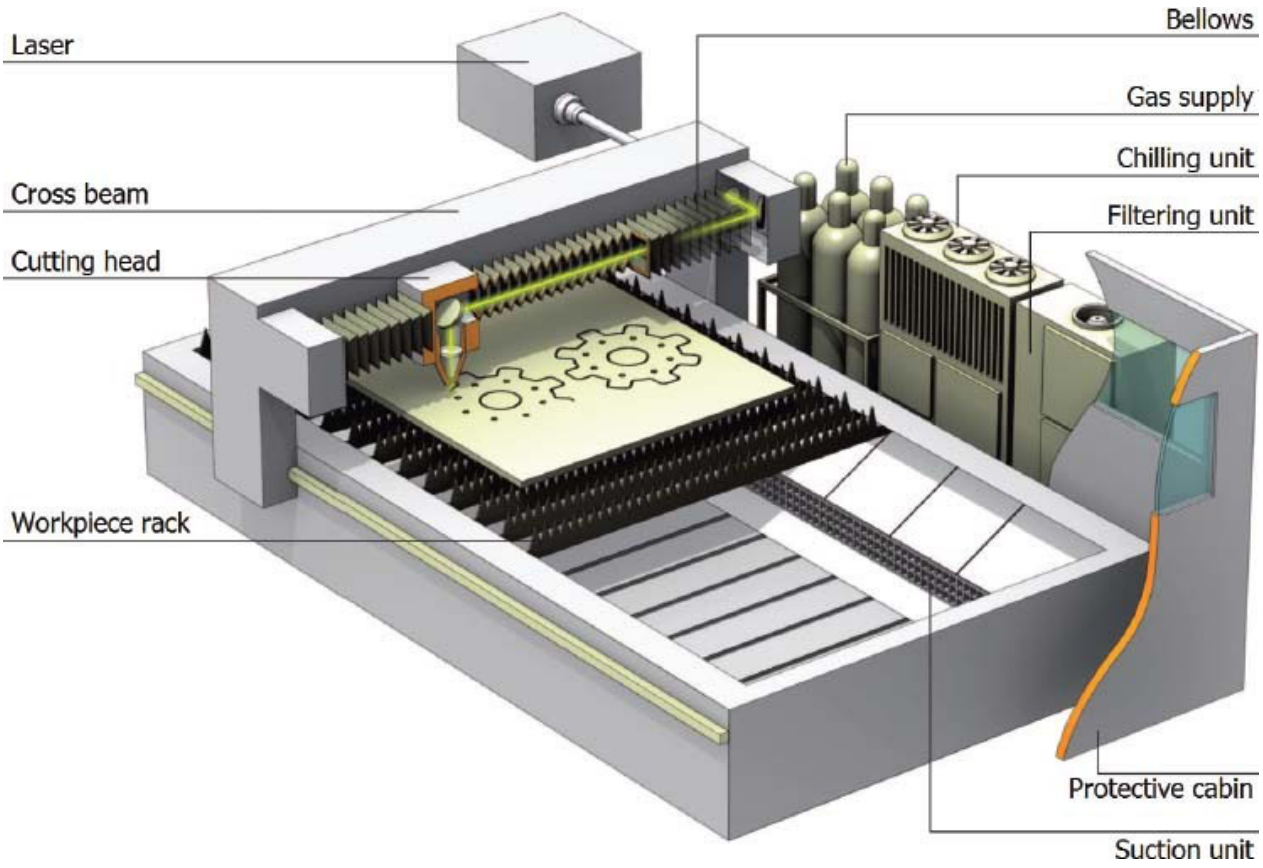

FIGURE 14.47 Essential components of a flatbed laser cutting machine. (Source: Trumpf.)

■ Basic machine with drives that carry and move all the components and the workpiece

■ Laser unit that supplies a laser beam with sufficient power and in the correct wavelength

■ Beam guiding system that directs and shields the laser beam

■ Cutting head that focuses the laser beam with the supply of cutting gas

■ Workpiece support or a fixture that holds the workpiece

■ Extraction and filtering system that removes cutting fumes and particles of slag

■ Protective booth that shields the operator from reflected radiation and metal spatters

Application Examples

Flat-Bed Laser Cutting Systems

The most frequently used system concept is the flat-bed laser cutting system. It is used to machine flat sheets of metal. With these two-dimensional (2D) parts it is sufficient to have motions in a plane and vertical motions in order to reach all the required points. Furthermore, it is possible to move the workpiece while the cutting head remains mounted in a fixed position. Systems with moving optics are still more common, however. Here the cutting head is moved over the workpiece.

3D Systems with Laser Beams

If a laser is used to cut contours in 3D workpieces, the optics must be very flexible. 3D laser systems have optics with at least five motion axes. In addition to the three spatial axes, there is a rotary axis and a swivel axis. In special cases, it is possible to move not only the optics but also the workpiece

FIGURE 14.48 3D laser cutting machine with five-axis processing optics. Trumpf.)

Tubes and Profiles

Tubes and profiles up to 9 m long can be machined using special tube-cutting systems or 3D systems. The machining optics have two to five moving axes. Additionally, in these systems, the workpiece is always moved.

Robots

The combination of robots and solid-state lasers is best known from the automotive industry. The robots operate in automatic mode in transfer lines, machining 3D body parts. They are suitable for both welding and cutting tasks. Because robots constitute a cost-effective alternative to 3D systems, their use is ever increasing. For many years, combining robots with lasers was very difficult. It was not possible to guide the laser beam via an optical fiber and was therefore carried to the cutting head via tubes and mirrors. Compact diffusion-cooled beam sources have solved this problem. These are very compact and lightweight, so they can be mounted directly on

the robot arm. Figure 14.49 shows a robot that operates with a solid-state laser.

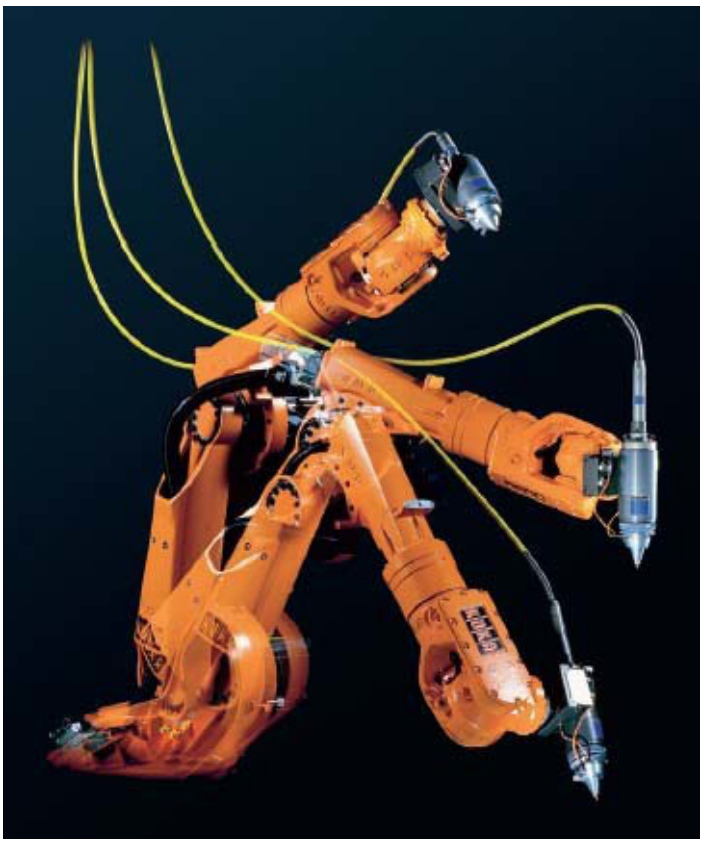

FIGURE 14.49 Alternative for 3D processing: this robot carries cutting optics with integrated distance control. Trumpf/Kuka.)

PUNCHING AND NIBBLING MACHINES

Principle of Punching

Punching is a chipless manufacturing process. It is a cutting process in which a sheet of metal or other material is cut through in a single stroke. The forming tool has two parts. The sheet is located between the upper tool, also known as the and the lower tool, also known as the *matrix*

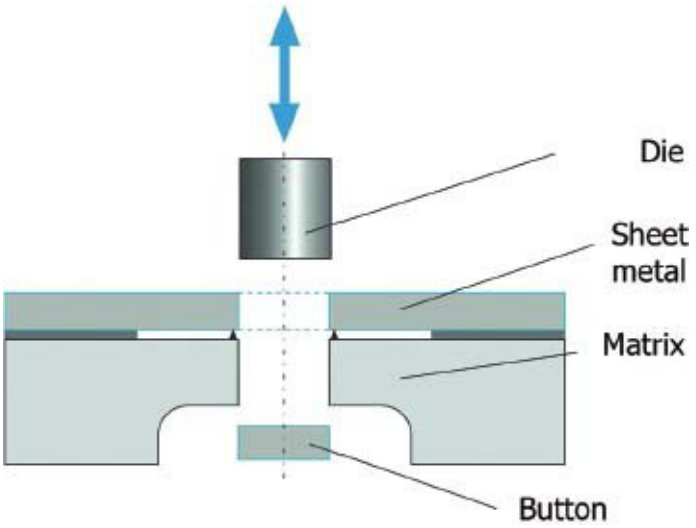

FIGURE 14.50 Schematic of a punch tool.

The punch moves downward and into the matrix. The edges of the punch and matrix move parallel to and past each other, thus cutting the sheet. Punching is therefore one of a group of processes called

Principle of Nibbling

In nibbling, punched holes are made next to each other in such a way that they overlap. In this way, apertures and contours in any desired shape can be created. The sheet is gradually shifted by a fraction of the size of the punch as soon as the punch rises up and out of the sheet. In this manner, a strip is nibbled out of the sheet at a rate of up to 1,200 strokes per minute. The tool that is used can be a small round punch, for example. Whether the tool is round, slot shaped, or square depends on which punch is best suited for creating a particular geometry.

Punching and Nibbling Machines

These machines can be used to process stock up to 12 mm thick, with a sheet size of up to 1.5 × 3 m. This is done by fastening a plate in a coordinate guide using a number of clamps and positioning it under the machining head of the tool using two axes. Punching can create holes up to about 100 mm in diameter. Form-punching tools are used when it is necessary to create a large number of small apertures. Such operations are more efficient with punching than with nibbling.

Structure of Punching Machines

A comparison of punching machines made by several manufacturers reveals different machine concepts. Each concept can be characterized based on the design of the machine frame, the punching head, and the tool holder. Figure 14.51 shows the basic structure of a punching machine.

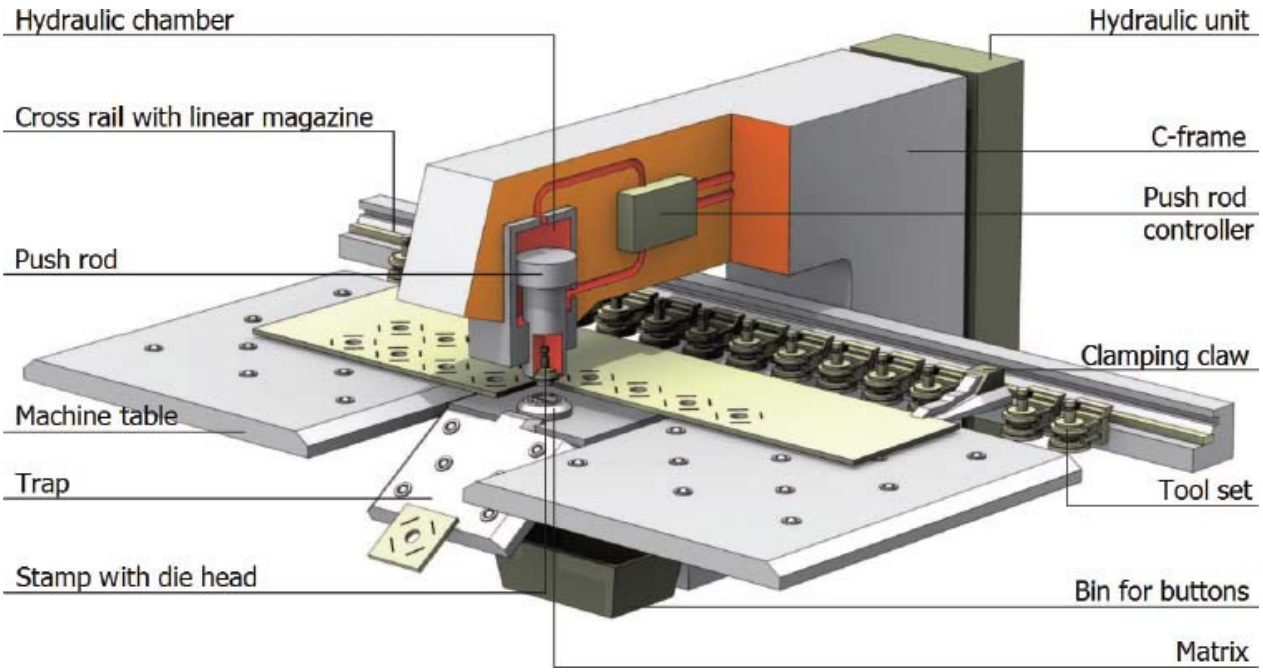

FIGURE 14.51 The essential components of a punching machine with a C-frame. Trumpf.)

The Machine Frame

The machine frame generally is constructed from steel plates that are several centimeters thick because it must be able to transmit dynamic forces, that is, acceleration forces and vibration, of several hundred kilonewtons. The frame has a C or O shape to allow easy access by the operator.

The Punching Head

The punching head is the central element of the machine. It consists of the push rod and the mechanism that moves the rod. For high-end machines, a rate of 1,200 strokes per minute is possible. The push rod is driven hydraulically or electromechanically. As with other machine tools, however, there is a trend toward fully electrical machines.

Tools

A punching tool consists of a punch, a matrix, and a stripper. Sophisticated tools and tool changers have been developed to allow machining centers to execute complicated machining operations fully automatically and in ever shorter times. These tools include, for instance:

■ Rotating tool holders so that the tools can be moved quickly to any desired angular position

■ Multitools (Up to 10 punching tools can be kept in one single holder, and this holder can be brought to any desired angular position. This reduces the machining time for parts in which small holes of different sizes have to be punched; see Figure

■ Tool magazines with tools that can be used immediately in the machine time

FIGURE 14.52 Linear magazine. Trumpf.)

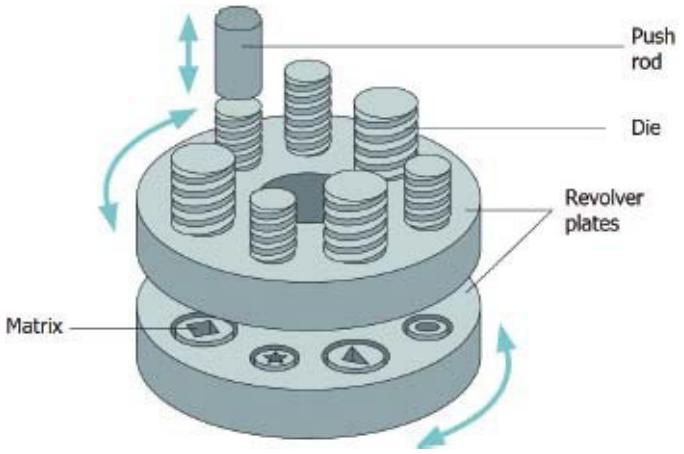

FIGURE 14.53 Schematic of a multipunch tool.

Flexible Machining Cells

Automation for single components is possible. Machine manufacturers offer additional components that can be used to turn series-production machines into flexible machining cells including:

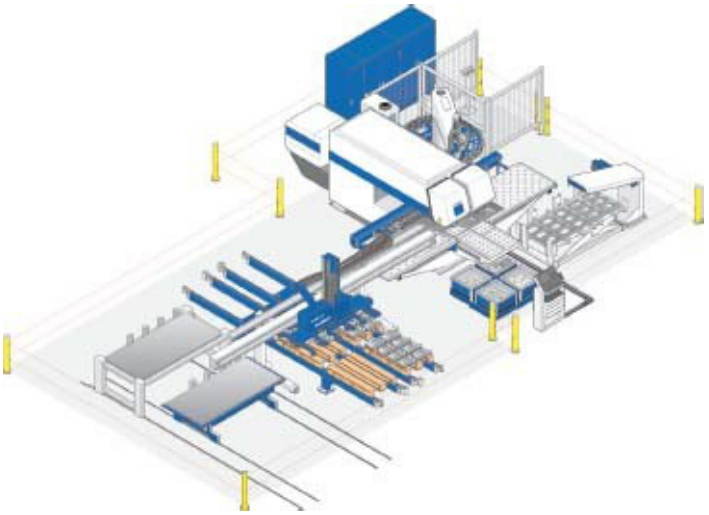

FIGURE 14.54 Flexible processing cell. Punch machine with loading and retrieving unit, parts storage bins, lattice waste retrieval device, and external tool magazine. Trumpf.)

■ Loading and unloading units with sorting function that insert the sheets and then remove the parts separately, sort them, and put them down

■ Several parts containers into which small parts or waste can be collected via a slide

■ A gripper that removes the waste lattice

■ External tool magazines with tool changers that can exchange the tool sets in the linear magazine

■ Compact or vertical storage bays to retrieve raw material and store finished parts

■ Sensors that monitor the production process

■ Programming systems that are used to generate the NC programs for all the automation components

Combined Punching and Laser Machines

Punching/laser machines are constructed according to the same principles as punching machines. However, the C- or O-shaped frame is broadened in such a way that it can hold two machining stations: the punching station and the laser machining station

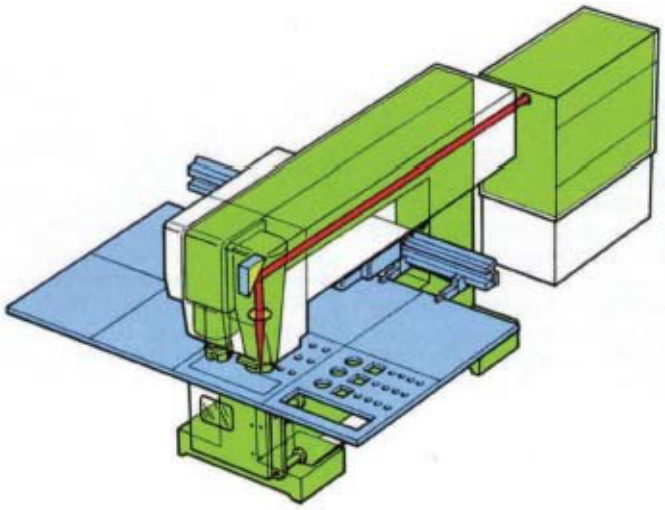

FIGURE 14.55 Combined punch/laser machine with a C-frame. Trumpf.)

Unlike laser flat-bed machines, though, here the metal sheet is moved and not the laser beam. There is an opening directly under the laser station for a suction unit to evacuate residual slag and cutting fumes. The advantages of combination machines become evident in operation: complex inside and outside contours are cut by the laser. Punching is performed when standard contours have to be machined quickly (e.g., round holes). Table 14.3 shows that the laser power has to be adapted depending on the capabilities of the punching processes and the user's requirements.

TABLE 14.3 Maximum Sheet Metal Thickness for Nibbling and Laser Cutting

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Laser Processing Machines

Laser welding is a prerequisite for compact, weight-optimized components and thus for energy-efficient vehicles. The precisely metered concentrated energy of the laser beam allows a high welding speed and minimal distortion of the welded component. As a result, individual parts can be finished cost-effectively, welded, and transported to assembly without other intermediary steps and processes. The flexibility of the laser welding process allows new designs and workpiece geometries. For instance, the joining and laser welding of cast iron materials and case-hardened steel inserts is possible on a production scale. The high process speed and the exact reproducibility render laser welding the ideal process for the mass production of precision components in motor vehicle powertrain and chassis production 14.56 through

FIGURE 14.56 Fully automated CNC laser machine for the series production of precision parts. EMAG.)

FIGURE 14.57 Two rotating pickup spindles load the individual parts, transport them to the work area, press them together, position the assembly in front of the welding optics, apply the weld, and return the completed subassembly to the transport system. EMAG.)

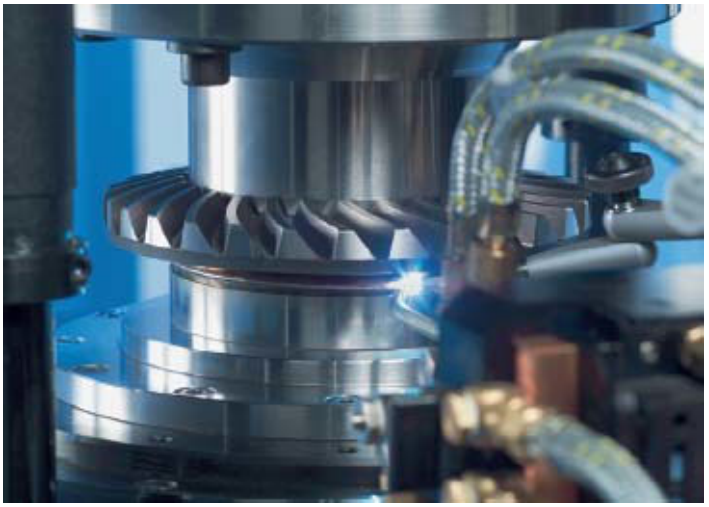


FIGURE 14.58 Laser welding of a gear with a differential gear.

TUBE-BENDING MACHINES

Bent tubes are used as structural elements or for transporting fluids in a wide range of industries, including:

- The aircraft industry for wings, engines, rudders, and brakes

- The machine-tool industry for hydraulic systems, compressed-air systems, and heat exchangers

- Shipbuilding for conduits of all kinds such as freshwater, waste-water, seawater, fuel, hydraulic fluids, and lubricant and sprinkler systems

- The automotive industry for exhaust systems, fuel-tank fill pipes, seat frames, stabilizers, front-end guards, and frame components and handlebars for bicycles and motorcycles

- Cooling systems and heating coils in appliance construction

- Sporting goods, toys, and lawn furniture

These parts require an accuracy of ±0.1° for the bending and torsion angles and ±0.1 mm for the distances between the individual bends. In order to satisfy these requirements despite the relatively large tube tolerances and the great differences in spring-

back behavior, additional compensation values have to be entered for the longitudinal position, the bending angle, and the torsional angle at each step of the program. These motions are functionally independent and therefore require only relatively simple NC systems for three to six axes. Modern CNC tube-bending machines with multiple tool levels have 12 to 15 controlled axes. Hydraulic cylinders or hydraulic swivel motors can be used as axis drives, but the preferred solution is electric servo drives 14.59 and

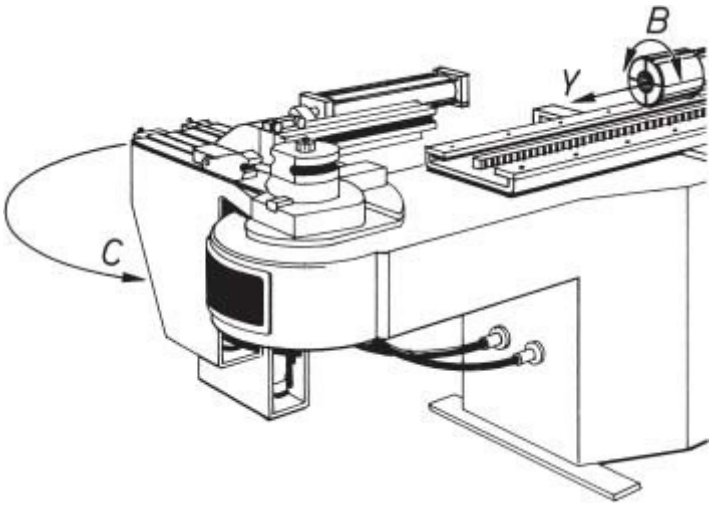


FIGURE 14.59 Schematic of a pipe-bending machine.

FIGURE 14.60 3D pipe-bending machine. Trakto-Technik.)

Control System

NC tube-bending machines meet the requirements in terms of accuracy, quick correction, and quick conversion. For fully automated production, they are also equipped with a magazine, a feeder, and weld-positioning and ejector mechanisms for the finished tube, so in these cases multimachine operation is possible.

The Fraunhofer Institute, in cooperation with Tracto-Technik GmbH, has developed a machine-integrated measuring system for determining the bending angle in tube-bending machines. Measurement of the bending angle takes place immediately after each bending process directly in the machine in less than a second. The amount of spring-back of the bent pipe depends on several material-, machine-, and process-related parameters and can be corrected with the input of appropriate values. Also, the user has the option of recording the process-relevant data and applying them on subsequent operations.

ELECTRICAL-DISCHARGE MACHINES

Electrical-discharge machining (EDM) is one of the most important methods used today to manufacture punching tools, injection molds, die-casting tools, compression molds, blow molds, and dies used in extrusion and other processes. EDM methods can be subdivided into wire and die-sinking EDM. These methods have proven especially useful in areas where parts exhibit the following characteristics:

- Complex forms
- High-strength materials
- Problematic manual machining
- No other automatic machining method possible
- Required high accuracy

The EDM process takes advantage of the physical effect that surface particles evaporate at electrothermal discharges between an anode and a cathode. It is important to prevent the development of an arc during the process because this could destroy the electrode and the workpiece. This process takes much more time than machining with a cutting tool. Nevertheless, it becomes cost-effective because ED machines can run around the clock in a fully

automatic, unsupervised mode, even when machining complex parts.

Highly qualified personnel are required to set up and operate an EDM. Thus a skilled metal worker will need several weeks of specialized training to master the peculiarities of EDM. One reason for this is that the EDM process does not allow the operator to view the area in which the process actually takes place. Contrary to traditional cutting methods, the operator is required to operate with unfamiliar, abstract electrical parameters and has to monitor the process by means of instruments.

WIRE EDM

In the wire EDM process, material is removed from the workpiece by a wire electrode with a diameter of 0.1 to 0.3 mm. This removal involves neither contact between the workpiece and electrode nor application of mechanical force. Thousands of discharges take place every second, melting and vaporizing tiny particles of material, which are then condensed in a dielectric fluid and drained. Deionized water is used as a dielectric because it serves several purposes at the same time: it creates the breakdown resistance that is necessary for the discharges to occur, and it also flushes the removed particles from the cutting zone, cools the stressed machine parts, and improves the antifriction properties in the areas of the wire guides and current-supply wires.

The electrical pulses that are required for the discharges are produced by a generator. A feed regulator ensures that the required spark gap is maintained between the wire electrode and the workpiece during relative motion. When a short-circuit occurs, that is, when the cutting wire comes into contact with the workpiece, the wire has to be retracted while maintaining the correct path until the short-circuit is eliminated. Only then can the cutting process be resumed. The form accuracy and surface quality of the cuts depend on the feed rate and feed consistency

FIGURE 14.61 Wire EDM with five CNC axes. GF Machining Solutions.)

The wire electrode is worn away by the discharges. Therefore, new wire is continuously passed through the cutting zone at a constant rate. A spool of wire weighing 6 kg is sufficient for more than 100 hours of cutting time. The drive and guidance devices for the wire electrode are very important in obtaining precise results.

Numerical control of the motion ensures close adherence to the desired cutting path. When cutting on an incline or in three dimensions at variable angles of inclination, a second motion in the upper is superimposed on the lower guidance plane. Conical cuts and continuous changes in inclination are also possible.

The material processed in wire EDM can be any type of electrically conductive or semiconductor material. This process has

the advantages that hardened steel can be cut and that an extremely high precision and surface quality can be achieved.

Die-Sinking EDM

In this method, a shaped electrode is moved toward the workpiece from above, and the electrical discharges produce a "negative" impression on the workpiece. Like cutting operations, EDM also involves the removal of large volumes of material in the roughing operation and smaller volumes in the finishing operation. To produce superfine surface quality, an additional polishing operation can be performed. The polishing step also works on the principle of electrical discharge but uses very low pulse power. The CNC system guides the electrode in an orbital (circular) motion in the plane while also providing a very slow in-feed in the

FIGURE 14.62 Die-sinking EDM with four CNC axes. GF Machining Solutions.)

In contrast to wire EDM, die-sinking ED machines are manufactured not only as console or frame machines but also in larger designs as portal-type machines. This type of construction is necessary for extremely heavy workpieces and electrodes, for example, automobile bodies and large dies.

To create shapes and contours, the CNC system guides the electrode along straight lines and circular paths (in the plane) and monitors the in-feed in the When the system short-circuits, the electrode retracts and immediately feeds in again. This process runs constantly and requires special control-loop signals to be exchanged with the generator. Smaller machines also can be equipped with automatic tool changers (i.e., electrode changers) and pallet changers for the workpieces. The CNC system is often programmed directly at the machine. In this programming, the operator has access to stored cycles and can check the data input on a graphical display.

ELECTRON-BEAM MACHINES

These machines have been used for 50 years for welding and drilling. In individual cases, they also are used to harden materials or improve them by surface remelting. The "tool" is a narrow, sharply focused beam of electrons moving at a high velocity and with high energy. In principle, the beam is generated similar to what occurs in the neck of a television picture tube, but the beam power is higher by several powers of 10, ranging between approximately 1 and 100 kW. This high power is focused on a small spot with a diameter of 0.1 to 2 mm, yielding a power density of to When this electron beam strikes the surface of a workpiece, the electrons are decelerated very suddenly by the atomic lattice of the workpiece, and their kinetic energy is converted to heat. The workpiece can be hardened, welded, or drilled depending on the type of beam control (i.e., continuous beam, pulsed operation, or deflection). The fact that the beam can be controlled with practically no delay is often the decisive advantage of this method

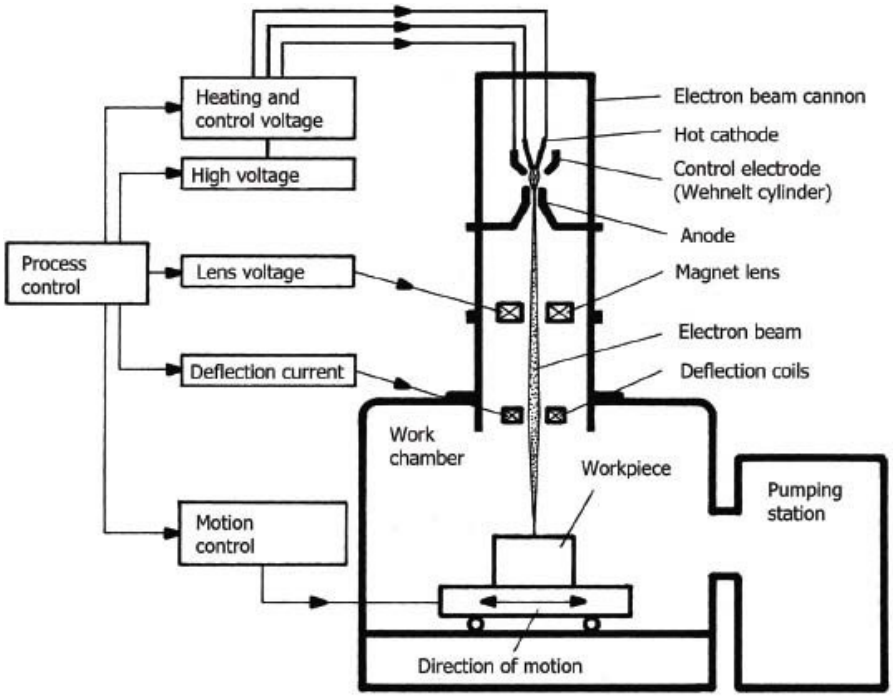


FIGURE 14.63 (a) Schematic of an electron-beam machine. (b) Illustration of an electron-beam cannon. Steigerwald.)

The beam can only be generated in a high vacuum mbar). Processing takes place only in a fine vacuum (< mbar) because air molecules cause deceleration and scattering of the electron beam, reducing the power density. Airlock systems are used to eliminate the time that otherwise would be required for evacuation.

This process is used when there is a requirement for especially low distortion and/or low heat input into the component being processed. A further advantage is the very large welding depth of 100 to 200 mm that can be achieved (more info at

In electron-beam welding in atmosphere, the vacuum chamber is replaced by a pressure-stage system, and the welding process takes place inside a radiation-protection chamber because of the danger from the hard x-rays. The evacuation time is eliminated because the beam source is kept constantly under vacuum. The beam is scattered by the air and is applied at a working distance of 10 to 20 mm from the pressure stage. This method is used mostly for the welding aluminum and steel sheet metal

FIGURE 14.64 Vertical arrangement of an electron-beam machine with and pivoting head. Steigerwald.)

The CNC system for electron-beam welding must perform the following special tasks:

■ Control of two to eight CNC axes for workpiece motion and an additional three to four CNC axes for wire feeding

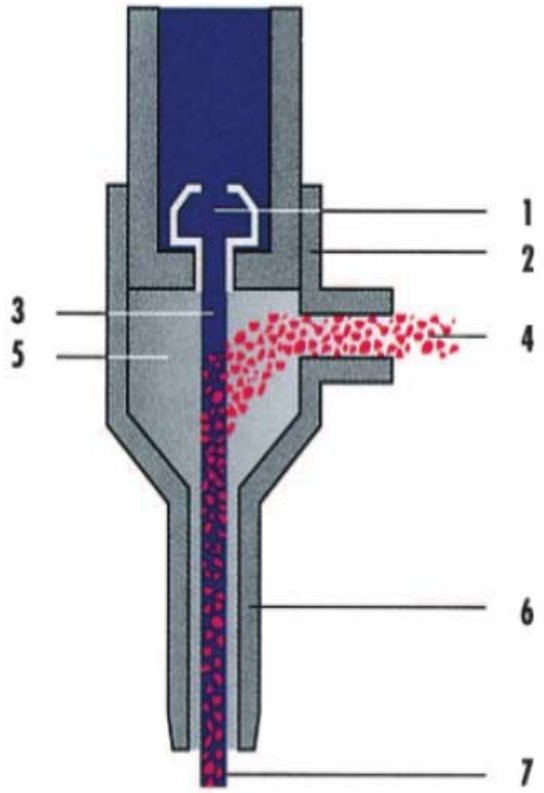
■ Control of the beam current

- Control of the lens current (focusing)
- Beam deflection in the and
- Pulsed operation, continuous beam, switching the beam on and off
- Monitoring the process
- Online seam detection during the welding process
- Image processing for automatic positioning of the workpiece
- Freely programmable axes (e.g., for vectorization)

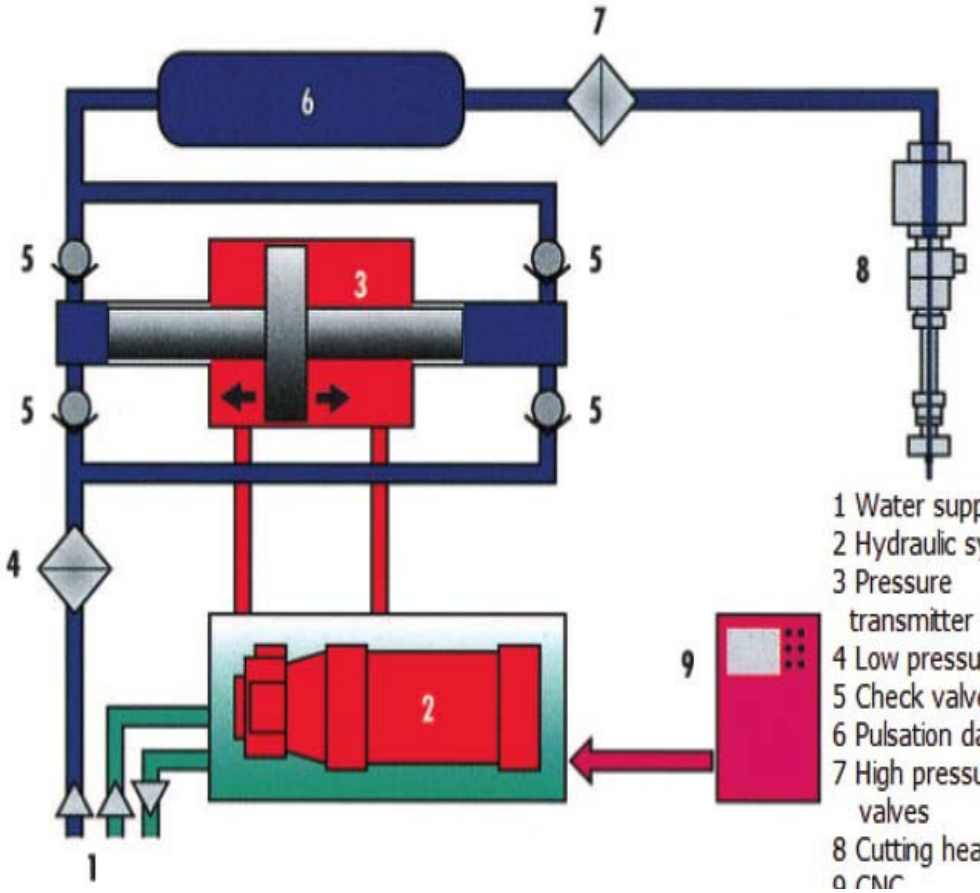
WATER-JET CUTTING MACHINES

Conventional cutting tools do not lend themselves well to cut soft or weak materials such as rubber, leather, paper, foamed plastics, or Styrofoam. They are also poorly suited for cutting polyvinyl chloride (PVC) or plastics that are reinforced with carbon or glass fibers. Water-jet cutting represents a suitable modern alternative in these cases. The principle is simple: water is forced through special nozzles under a pressure of 4,000 to 9,000 bar. The diameter of the nozzles ranges from 0.1 and 0.3 mm. The exit velocity of the water jet is 800 to 900 m/s, which is more than twice the speed of sound. When directed against the workpiece to be cut, the jet functions as a thin, invisible blade. It bores into the material and can cut in all directions with equal effectiveness. The kerf measures only 0.1 to 0.3 mm. The cutting speed can range between 1 and 500 m/min depending on the type and thickness of the workpiece material. Water consumption is about 1.5 liters/min; it can be recycled after it has passed through special filters.

If the water jet alone is not sufficient, an extremely fine abrasive powder can be added to the water. This is called *abrasive* This method can be used to cut steel up to approximately 80 mm thickness, as well as titanium, marble, and glass



1 Water nozzle
2 Abrasive head
3 Water jet
4 Abrasive
5 Mixing chamber
6 Abrasive nozzle
7 Water-abrasive jet



1 Water supply
2 Hydraulic system
3 Pressure transmitter
4 Low pressure filter
5 Check valve
6 Pulsation dampener
7 High pressure valves
8 Cutting head
9 CNC

FIGURE 14.65 Water-jet cutting machine: principle of jet nozzle; principle of pressure generation.

The advantages of water-jet cutting include:

- Ability to cut flat and 3D workpieces

- High-quality cutting surfaces (better than flame cutting when used to cut steel)

- Clean-cut edges without burrs

- Low amounts of material loss at the cut edge

- No chips, no accumulation of dust, and no deposition of dust on the workpiece material, although the abrasive does leave behind a fine, dust-like deposit

- High feed rates

- No high cutting temperatures

- No feed or cutting forces and thus no deformation of soft materials during cutting

■ No electrical charge imparted to the workpiece (Therefore, even printed circuit boards can be cut using this method without damaging sensitive components already mounted on the board; see Figure

FIGURE 14.66 Combined cost-effective production with water-jet abrasive cutting and milling. The parts are premanufactured in a nested manner, and only precise fits are reworked. Bystronic.)

Most water-jet cutting machines have the basic structure of a three-axis gantry machine with two additional swivel axes for the jet nozzle. However, it is also easy to combine the cutting nozzle with a robot to achieve optimal flexibility.

MULTITASKING MACHINES

Multitasking machines are understood as the combination of different cutting technologies, for instance, turning/milling, milling/turning or grinding, laser cutting, milling/turning/etc. in one machine tool. These combinations of cutting technologies in a multitasking, or hybrid, machine tool increase the productivity and quality of the production considerably because there is no loss in quality as a result of reclamping the workpiece in another machine. Also, workpieces with considerably greater complexity can be processed.

Milling/Turning Machining Centers

Based on the concept of a milling machine and in contrast to turning-milling centers an interesting and new machine genre was created. The starting point for the development of a milling/turning center was the analysis of part spectra and part families, characterized by high volume and different kinds of operations. A salient example of this is the production of tool systems for CNC machines

FIGURE 14.67 Milling-turning center with bar-stock supply. STAMA.)

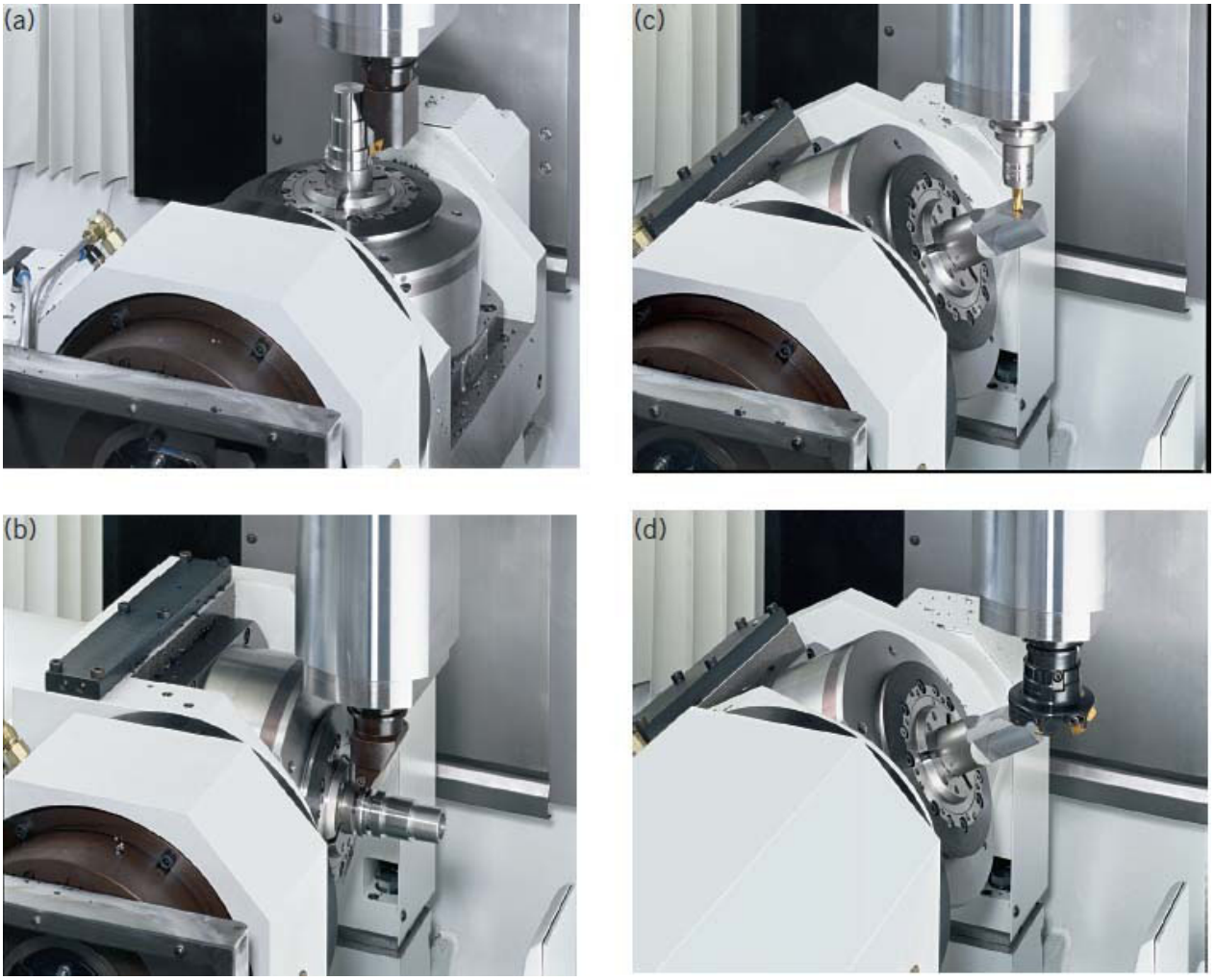


FIGURE 14.68 Modern milling/turning center allows different cutting operations with a spinning or stationary tool such as (a) vertical turning, (b) horizontal turning, (c) drilling, and (d) milling. STAMA.)

The parts have milling and turning operations performed with the main focus on milling, requiring complicated six-surface machining. There are small series that require a high degree of flexibility of the CNC program. The parts usually are up to 60 mm in diameter and 100 mm in length. These machining centers are also often called *bar-processing centers* because diverse, highly complex parts can be produced directly from bar stock. Mainly milling operations are

carried out, but turning operations will be performed equally effectively because the rotary swivel units are equipped with integrated rotary spindles.

The bar stock is removed from the magazine and fed to the main rotary pivot unit. The first five surfaces of the workpiece are processed simultaneously in five axes. To machine the sixth side, the workpiece is picked up by the second rotary pivot unit.

Turning/Milling Centers

The power of modern CNC systems and appropriately equipped lathes has made it possible to perform milling and drilling operations on a part clamped in a lathe chuck. Even grinding spindles have been used within these machines to postprocess turned parts.

For this, the turret is equipped with driven tool spindles to accommodate the required cutters, drills, taps, or grinding wheels. As required, the main spindle will be automatically coupled with an additional encoder and positioned as a such as a turntable and continuously controlled. In this way, the driven tools run reach every point on the workpiece and perform the desired milling or grinding operation. The prerequisite is a CNC machine that can perform a coordinate transformation. This function allows the programming of milling and drilling operations in Cartesian (linear) coordinates, and the CNC machine transforms the movements in the polar coordinate system (rotation of the 14.69 and

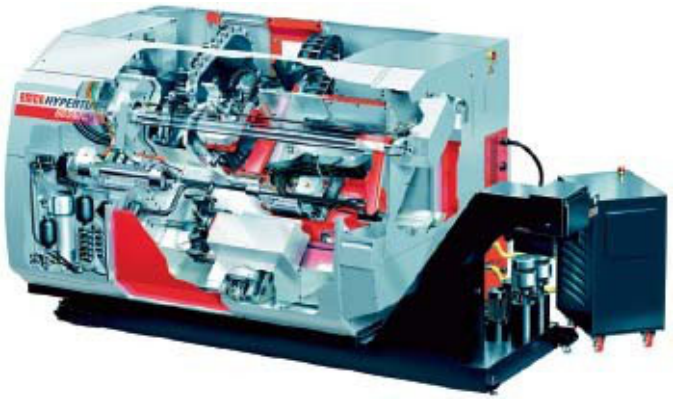


FIGURE 14.69 Lathe/milling center for single, complex milling, drilling, and gear-hobbing operations. EMCO.)

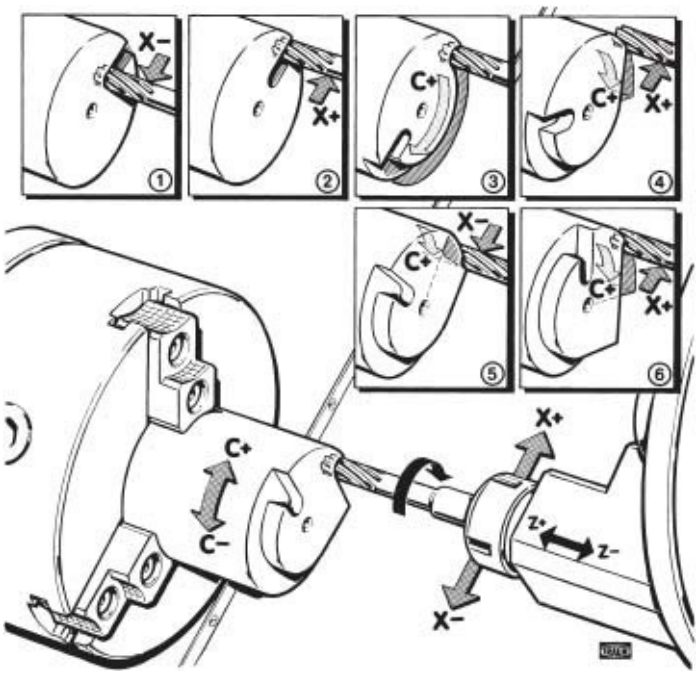


FIGURE 14.70 Turning/milling center: end-face processing with live milling tool.

Turning/milling centers are particularly suitable for the production of smaller, complicated parts made of solid material and are offered by all well-known lathe manufacturers. These machining centers are also available for large parts in different configurations. They take

advantage of performing all turning and milling on a workpiece without reclamping and with a high material removal rate

FIGURE 14.71 Parts produced on a turning/milling-center.

In line with machining centers and production cells, highly automated lathes are also referred to as *turning centers* or *lathe* The variety of possible uses for such machines is almost unlimited. They provide the user with the great advantage of being able to produce the workpieces in one machine ready for assembly in a much shorter time than would be possible with multimachine processing. In addition, the time for possibly multiple clamping and unclamping

steps and associated dimension variations is avoided. Additionally, the expense for respective clamping fixtures will be saved. In conclusion, complete machining replaces individual machines, increases quality, and reduces the processing time, altogether reducing production costs.

Milling Laser Centers

The five-axis milling machine integrates "generative" laser deposition welding with a powder nozzle and milling. This technology combination offers the user new applications and geometry options with fully automatic change between milling and laser operations. Metal parts thus can be repaired or manufactured individually, precisely, and quickly. For instance, entire complex parts with undercuts can be fabricated, or extra layers of material for mold making and machine construction can be deposited

FIGURE 14.72 Milling laser center. DMG MORI SEIKI AG.)

The metal powder is applied in layers and fused with a diode laser. This creates a high-strength weld between the metal powder and workpiece surface. The resulting metal layer can be machined after cooling. In order to also machine parts that cannot be reached by the milling cutter on a finished component due to the component geometry, it is also possible to mill the finished shape between the built-up welding. One of the strengths of the process is the successive buildup of layers of even different materials 14.73 and During the milling operations, the powder application head is parked outside the processing space in a docking station; for the laser operation, it is automatically loaded into the hollow shaft cone (HSK) tool holder of the milling spindle.

FIGURE 14.73 Laser deposition welding of a socket on a flange. DMG MORI SEIKI AG.)

FIGURE 14.74 Milling operation after laser deposition welding. DMG MORI SEIKI AG.)

Turning/Grinding Centers

The production of small chucked pieces is often associated with very large quantities. Especially components such as gear wheels, planet wheels, sprockets, cam rings, pump rings, and cams for the production of cars are needed in the millions. This machine was specially developed for the productive and high-precision production of said components. The blanks are loaded automatically with the pickup system. While processing takes place, the next blank can be placed on the revolving conveyor belt manually or automatically. This arrangement considerably reduces unproductive machine times

FIGURE 14.75 Turning/grinding center for chucked parts up to 100 mm in diameter. EMAG.)

Turning/Rotary-Hobbing Centers

The machines shown in Figures 14.76 through 14.80 are high-speed pickup turning/gear-cutting machines for cylindrical workpieces with diameters up to 230 mm and module 4. The gear-cutting machine combines turning and gear-cutting technologies in one machine. This allows the second side to be turned and the teeth to be milled in one clamping. Thus the user has the advantage of the functions of two machines, providing an extended range of machining options. Even a third level of machining is possible by means of a revolver, for instance, milling, drilling, or deburring operations with respect to the previous turning or teeth-cutting steps. Processing one part in one clamping saves time and avoids reclamping errors.

FIGURE 14.76 Lathe/grinding center loading and unloading according to the pickup principle. EMAG.)

FIGURE 14.77 Turning and grinding, a complete machining. EMAG.)

FIGURE 14.78 Turning operation on a lathe/hobbing center. EMAG-Koepfer.)

FIGURE 14.79 Gear hobbing after a turning operation. EMAG-Koepfer.)

FIGURE 14.80 Parts produced on a lathe/hobbing center.

Hybrid Cutting and Hardening

Heavily used components today are heat treated for protection against wear. The manufacturing process for this takes place in several steps on different machines. The transfer of parts from one specialized machine to another causes long production times and undue logistical effort. An answer to these issues is a hybrid machine tool that can perform all these tasks 14.81 through

FIGURE 14.81 Monforts RNC 400 LaserTurn hybrid machine tool.

FIGURE 14.82 Hybrid tool system with integrated revolver.

FIGURE 14.83 Hybrid processing of a work gear that is soft machined, laser hardened, and hard finished.

An example of a hybrid machine tool with a high degree of maturity is the RNC 400 LaserTurn from Monforts, which allows the combination of machining with subsequent surface heat treatment with laser technology. The process could be the following: turning the soft stock, laser hardening, and turning the hardened material, all in one chucking. The machine is based on the proven RNC 400 mass-produced lathe. The hydrostatic circular guide ensures a high level of stability and machine accuracy. The practical use of the machine is based on the combination of cutting and laser operations. The RNC 400 LaserTurn has a maximum of six laser tools out of 12 tools in a special tool turret. The laser tools are held in standard tool holders in the same revolver and are opposed with cutting tools. The tool system performs beam guidance through the revolver, whereas the optical components are shielded from the impact of chips and coolant. The tool change only takes as long as the revolver needs to swing. A diode laser serves as a radiation source, and a cable is led from the outside into the work chamber.

In laser hardening, selected component areas are hardened with the Martens method. All materials can be hardened that can otherwise be hardened by flame and induction. The materials can be tempered steel, cold and warm rolled steels, high-speed steel, cast iron, and rust- and acid-resistant steel; the carbon content must then be greater than 0.3%. The attainable hardness is equal to the material-specific maximum hardness. The advantage over other surface-hardening methods is the limited input of energy, which prevents thermal distortion and does not render adjacent areas needlessly brittle. Postprocessing can be reduced accordingly. There is no need for quenching because the thermal energy is absorbed by the component volume. The achievable hardening depths are in the range of 0.1 to 1.5 mm. Surface speeds are approximately in the range or 0.15 to 2 m/min depending on the required track width, hardening depth, and laser power. For example, the seat of a bearing shaft of 40 mm diameter and a width of 35 mm cures in about 6 seconds.

The example of manufacturing a worm shaft for oil presses demonstrates the economic advantage of the process. Given a period of 7 years with 16 hours of daily operation, the expensive investment will break even after only 2.5 years. The unit costs are 20% lower, and the lifecycle cost of the production line is 35% lower. As a result, the production process and logistics costs are reduced. Likewise, product quality increases due to the elimination of distortion, and possible geometry errors caused by reclamping are eliminated because the part is processed in the same setting. The hybrid tool machine is best used where short delivery times and a flexible response to customer requirements are important, for example, in short-term spare parts production and in prototype work. But even in series products, the combined technology can make sense because the processes are executed immediately one after the

other and the run time is very short. When combining cutting and laser hardening, the advantages are particularly evident when the areas that must be hardened are small.

MEASURING AND TESTING

Measurement Systems and Measuring Cycles

The introduction of NC machines on a shop floor usually also requires far-reaching changes in the area of quality control. Simple and complex workpieces have to be tested for compliance with stringent quality specifications. The focus of testing constantly alternates among these different parts. Sometimes a measuring machine is implemented for the sole purpose of determining whether a part should be accepted or rejected. In other cases, the measurement system must provide data that will be used to correct various parameters in the manufacturing process. The objective in these applications is for the measuring time to equal approximately 30% to 100% of the machining time depending on part geometry, thus allowing any necessary corrections to be carried out quickly and preventing unnecessary downtimes of expensive machines.

Coordinate measuring machines (CMMs), equipped with the necessary extra features related to this special measuring task, can fulfill the 11 most important requirements of any automatic measurement process

FIGURE 14.84 Portal-style coordinate measuring machine (CMM). Carl Zeiss.)

1. Universal measuring probes must be provided for multiple axis directions.

2. Operation must continue without interruption when measuring programs are being loaded.

3. Measuring must be executed at high speeds. This may require a positioning speed as high as 3 m/min. Fine programming must achieve a level of precision that corresponds to the resolution of the measuring system. Coordinates must be captured quickly after probing.

4. Measurements must involve a low degree of uncertainty and a high degree of accuracy.

5. There must not be an excessive number of measuring points or repetitions required to increase the accuracy of measurements.

6. It must be possible to change quickly from one type of workpiece to another.

7. The measurement data that are put out must be usable without requiring conversion to a different form. This output must be useful for purposes of fast, reliable evaluation and correction of production quality.

8. Measuring programs for new types of workpieces must be created quickly.

9. Systematic measuring errors must be avoided.

10. The machine must have a future-oriented design, including such features as higher accuracy than parts to be measured, a universal probe system, expandability for special measuring tasks, easy adaptability of software for control and data analysis of all potential requirements, and lastly, the capability of creating customer-specific computer programs.

11. Measurement records must be created and printed out automatically. These are more reliable than manually created records and eliminate the need for subsequent analysis.

Programming a CMM is usually performed by using a master workpiece on the measuring machine. After loading an appropriate program, the CMM temporarily becomes a programming workstation. The workpiece-specific program can be created by manually probing the first part. This task does not require any special programming knowledge, but it does require an understanding of geometric relationships and metrology. All positioning and measuring operations are saved so that the process can be repeated later. The probe head is the most critical element of any CMM. It determines the machine's accuracy and range of use 14.85 and

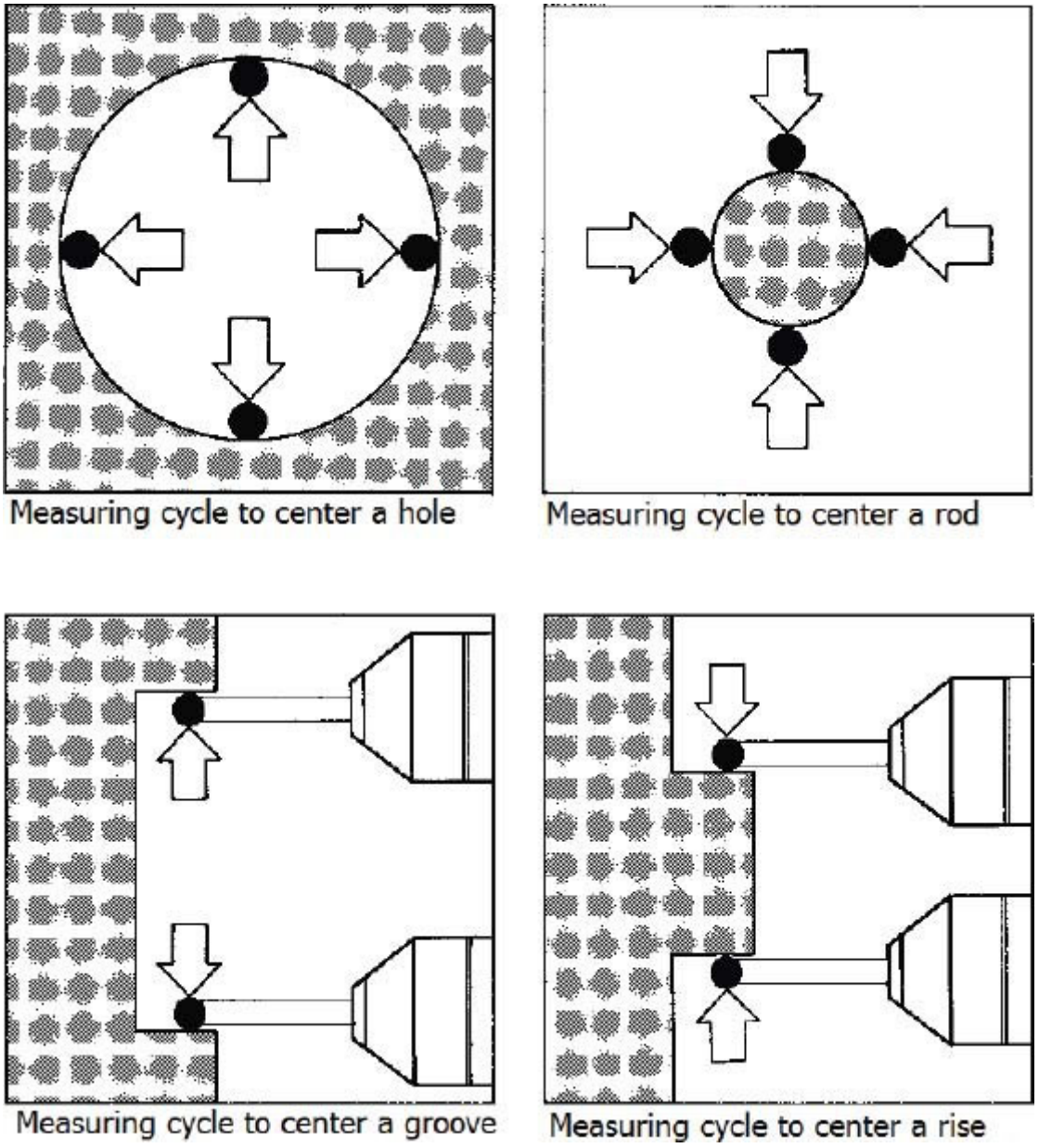


FIGURE 14.85 Examples of various measuring cycles.

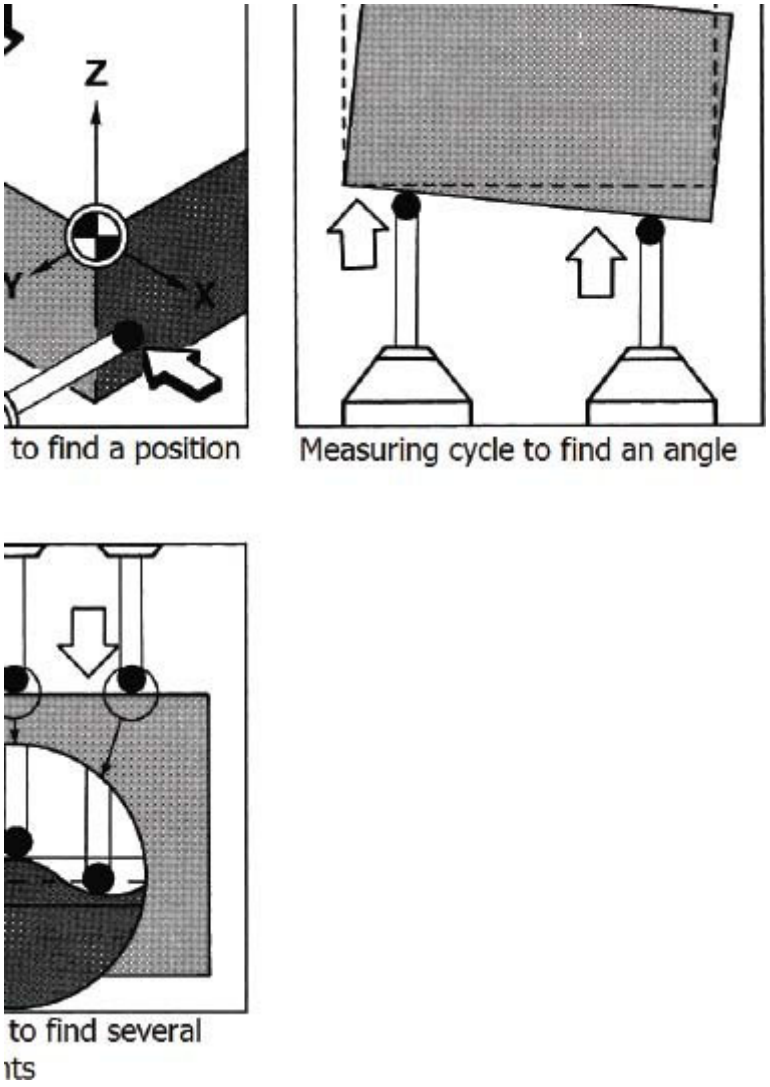


FIGURE 14.86 More examples of various measuring cycles.

When the probe contacts the workpiece, it acts as a control element, providing position feedback control for the axes in reference to its own zero point. It can also provide measurement values for the and that must be superimposed to the positional values of the CMM. In connection with special software, the computer fulfills numerous tasks in addition to processing of the machine coordinates and stylus coordinates. These tasks include:

■ Recognition of the measuring plane or measuring axis with spatial transformation of coordinates (3D alignment)

■ Distinguishing between the inside and outside contours of holes and cylinders

■ Detection of input errors such as unintended probe collision, absence of drilled holes or failure to reach a certain point on the workpiece, overtravel protection, and standstill mode for data collection

■ Storage of measurement data

■ Processing and analysis of measurement data and output of these data in the desired format

■ Subprograms for measurement of:

● Spatial elements such as cones, spheres, cylinders, and flat surfaces

● Straight sections of spatial elements such as ellipses, circles, straight lines, and intersections

● Coordinate points and relationships between them such as distance, angle, symmetry, etc.

The control of a CMM differs from that of a CNC machine tool in a few small but important details. The machining program

for a machine tool is based on the assumption that the tools and machine geometry conform to the assumed values. By contrast, measuring machines must determine:

■ The magnitude of the deviations between the target and actual values on a workpiece

■ Whether the drilled holes and surfaces are perpendicular to each other

■ Whether a particular feature, such as a drilled hole, incline, or surface, is present at all

■ Whether, when, and how a compensation value should be factored into the process for purposes of conforming to tolerances

■ Whether the production process must be stopped at once when large deviations indicate a problem in the machine tool

In order to switch the CMM between measuring and programming modes, the operating system must be interchangeable and have adequate resources. The processing speed must be sufficient to allow all the various processor operations to be executed in the shortest possible time.

Scanning

This term refers to the continuous probing of a surface. To do this, the CNC system guides the probe over the workpiece surface in a continuous, line-byline fashion. At the same time, the computer stores all the measured values at predefined time intervals or at certain distances along the measuring path. The CNC system constantly adjusts the probing axis by means of the servo drives so that the probe always remains within its measuring range. For this reason, a scanning probe must be used in place of the switching probe. The displacement of the scanning probe is constantly measured and used to correct the measured values. Given a resolution of 0.1 µm of the probe, a measurement accuracy of ±1 µm can be achieved 14.87_and

FIGURE 14.87 Scanning-probe head for measurement of dimension, form, and position. Optionally single-point or multipoint measurement.

FIGURE 14.88 The switching central probing head for quick single-point probing.

The measured values can be analyzed in measurement records or used directly by suitably equipped CNC systems for milling of a similar surface. Advancements in metrology and measuring probes will lead to increased use of optical probes that function without contacting the workpiece. These optical probes are likely to make use of laser technology. The CMM itself will be brought near the production machine so that correction values can be fed back on a short, fast path.

SUMMARY

CNC machines with the use of modern control technology are capable of automatically fabricating complex workpieces with high precision and without manual intervention. They exceed manual or mechanically operated machines in terms of flexibility, precision, repeatability, and speed. The main characteristic is the step-by-step instruction of workpiece nominal dimensions in the NC or part program and simultaneous control of the NC axes.

NC programs required for machining are almost exclusively generated by means of CAM systems or directly on the machine with SFP. Most CNC machines are equipped with sensors for automatic quality control and monitoring tool wear and tool breakage.

The PLC program, provided by the machine builder, is placed between the CNC system and the machine as an adaptive control unit. It allows for the coordinated sequence control of all additional functions, such as tool change, workpiece change, safety doors, coolant, lubrication, and other components.

The axis positions or the traverse path is measured with encoders with a resolution of 1/1,000 mm and finer. The measuring signals are monitored for perfect function. Emergency signals are issued in case of measuring errors.

Special three-phase motors or linear drives with highly dynamic digital control circuits are preferred as feed servo drives for the NC axes. These have a high torque, even at zero speed, and replace additional mechanical clamps.

Machining centers or special-purpose CNC machines can have six or more NC axes, where and *Z* are the major linear axes and and *C* are rotation axes (rotation and pivot axes) of the major axes. Additional auxiliary axes can be used in multispindle machines, in machines with parallel axes, or for positioning and controlling the tool magazine.

Additional automation components such as workpiece or pallet magazines with automatic changing devices allow CNC machines to become highly automated flexible manufacturing cells (FMCs). Several FFCs, connected with an automatic workpiece transport system are referred to as *flexible manufacturing systems* These require the use of an additional master computer for the entire system.

CNC lathes that can also perform milling operations or CNC milling machines that can also perform turning operations are referred to as *CNC multifunction or multitasking* Complete machining in one clamping improves achievable workpiece accuracies noticeably, reducing nonproductive time and improving profitability. Hybrid or multifunctional machines with up to five types of processing are already in the planning stage.

IMPORTANT POINTS TO REMEMBER

1. Machining centers are CNC machines with at least three axes, a tool magazine with automatic tool- and workpiece-changing system. Depending on the work spindle, one distinguishes between horizontal and vertical machines.

2. With an additional swivel table or pivoting tool, prismatic workpieces can be machined with five sides in any orientation in space.

3. Lathes are the most produced CNC machine tools based on production numbers. They are produced in many different designs and tool-changing options.

4. Vertical lathes with two work spindles and automatic part storage and loading are fabrication cells for complete machining of workpieces.

5. Lathe/milling centers are designed for additional drilling and milling jobs to be performed on the chucked part.

6. Grinding machines are distinguished according to the various surfaces that can be processed. The most common machines are flat, round, profile, and tool-grinding machines.

7. Because the grinding disk wears and the profile changes during operation, the tools must be redressed, usually with diamond tools. The measure of change of the tool is fed to the CNC system for correction.

8. In modern CNC gear-cutting machines, there are no gears that must be changed. The required ratio of the coupled NC axes is programmed.

9. Laser processing machines with different laser powers are used for different applications. These can be:

a. (gas) lasers

b. Nd:YAG (solid-state) lasers

10. The laser material of a Nd:YAG is a neodymium-doped crystal of yttrium-aluminum-garnet.

11. The laser machines also include machines for the generative manufacturing processes stereo lithography, beam melting, laser sintering, and others

12. Nibbling machines can also be equipped with additional laser cutting hardware, rendering them more productive and flexible.

13. When nibbling, punched overlapping holes are placed next to each other. With a stroke rate of up to 1,200 per minute, a track

is created and a form is removed from the material. Thus breakthroughs and contours of any shape can be created.

14. Spark-erosion machines take advantage of the physical effect in which electrothermal discharges occur between anode and cathode, and surface particles on the workpiece are evaporated.

15. Wire cutting uses continuous-wire electrodes with a diameter of 0.1 to 0.3 mm that remove material without touching it and without exerting mechanical force.

16. Electron-beam machines are used mainly for welding high-quality metals, such as titanium, in a vacuum chamber. The tool is a high-energy, slender, sharply focused beam of fast electrons.

17. For this purpose, beam power in a range of 1 to 100 kW is focused on a spot of 0.1 to 2 mm diameter.

18. Water-jet cutting presses water at 4,000 to 9,000 bar through a nozzle with a diameter of 0.1 to 0.3 mm. The exit velocity of the jet reaches from 800 to 900 m/s.

19. This method is particularly suitable for separating "soft" material such as rubber, leather, paper, foam, polystyrene, and PCBs because there is no electrical charge.

20. By adding an abrasive of very fine grain size, steel up to 80 mm thick, titanium, marble, and glass can be cut.

21. Multitasking machines are the combination of various processing technologies in one machine tool. This combination increases productivity and quality significantly. In addition, more complex workpieces can be processed.

22. CMMs are important for quality assurance. They are used for 3D measuring of any workpiece contours and for process monitoring of workpieces with high accuracy requirements.

23. The programming of the measuring process is predominantly carried out with the measuring machine and the sample workpiece.

24. To measure 3D surfaces, the CMM guides the probe continuously and line by line across the surface of the workpiece to be measured and stores the measured data or the difference values.

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INTRODUCTION

Additive manufacturing processes were first presented to the public in 1987 in the United States; in 1989–1990, the first machines were delivered to Europe. At that time, this generally involved stereolithography (SLA) machines. Additional process variants were developed over the next few years, including selective laser sintering (SLS), electron- and laser-beam melting, and laminated-object manufacturing (LOM). Based on the current know-how (see also Section 15.4), new processes will be developed and existing processes will be modified in the next few years because additive manufacturing has not reached its full potential when it comes to processing multiple materials.

The process sequence also can be summarized as follows (see also "Process Chain" later in this chapter): parts are built up layer upon layer through the consolidation of an amorphous or neutrally shaped feedstock material and the supply of energy. All layer manufacturing processes must meet the following requirements with regard to data processing (CAD/CAM link):

■ The starting point for the additive manufacturing of a part is a 3D solid model that depicts the workpiece data in digital form.

■ For the construction process, the 3D solid model must be broken down into individual layers, thus reducing it to two dimensions. These layer data define a process-specific CNC program.

■ The subsequent manufacturing process is performed on an NC machine that executes the information layer by layer, thus generating a part.

Comparison with conventional manufacturing processes shows the economic and technical potential of additive manufacturing. While simple bodies can be produced cost-effectively in large quantities using familiar processes such as turning, milling, or casting, for smaller quantities and more complex components, the use of layer manufacturing becomes more economical. Moreover, some highly complex components, for example, those with internal geometric features, can only be produced using additive manufacturing processes. Workpieces generated by means of additive manufacturing can be used for a very wide range of functions in various fields of application, including:

■ Concept models are employed to visualize the dimensions and general appearance of a new product being developed at the earliest possible stage. Design models are employed to depict the CAD model accurately regarding shape and dimensions. The surface quality and positions of individual elements are important.

■ Functional prototypes, which are largely identical to parts that will be mass produced later, are used to confirm one or more of the planned functions. Technical samples, which only differ from the later series parts in the manufacturing processes that are employed, are used to verify that the requirements are met.

■ Tools and molds can be used to fabricate end products in a subsequent manufacturing process, for instance, via injection molding. Fully functioning customer-specific individual or series parts can be produced that are close to the final contours. As this brief overview shows, additive manufacturing processes can be used in all phases of product development.

DEFINITION

Additive manufacturing processes are defined as all processes that are used to create 3D models, prototypes, and components additively, that is, through the joining or layering of multiple solid elements. Many other terms can be encountered in practice and in the literature; these have been combined and standardized in VDI Standard 3404, which was introduced in 2010.

For historical reasons, it is a common practice for additive manufacturing processes to have the word *rapid* added to them in order to convey that additive processes are faster for small and medium-sized quantities than the conventional alternatives. These generally require tool making. By avoiding this, additive processes are not only faster but also in most cases provide large potential cost savings. In short, this is why additive manufacturing processes are also called *rapid*

As described earlier, additive processes can be used economically anywhere in the product-creation process Rapid technologies can be subdivided into rapid prototyping, rapid tooling, and rapid manufacturing.

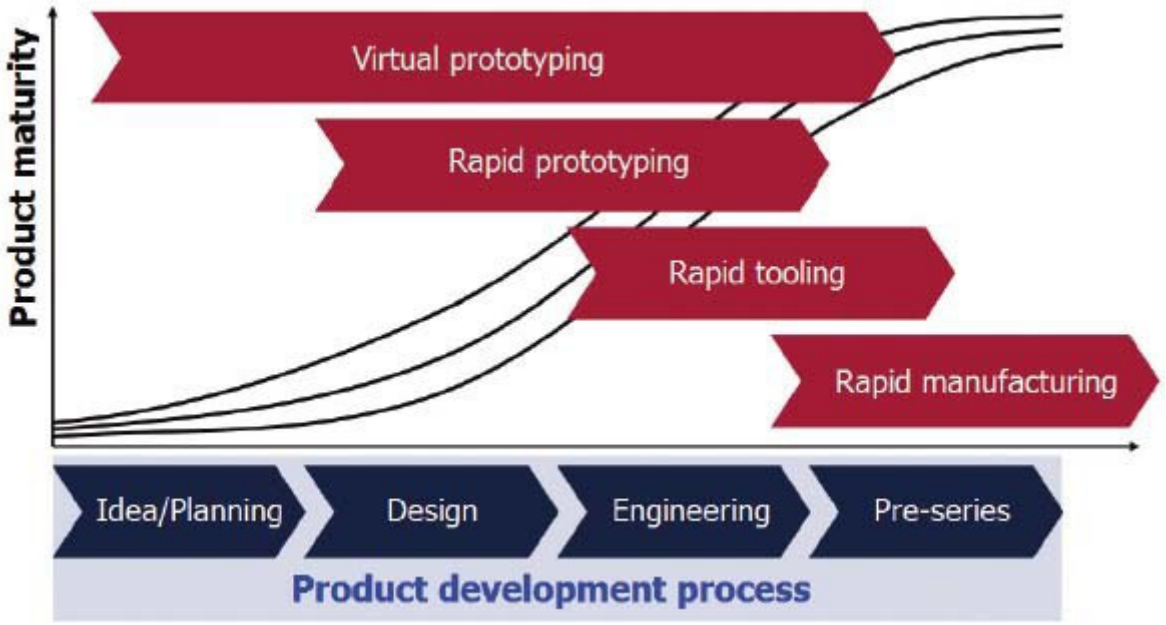

FIGURE 15.1 Rapid technologies in the product-development process.

■ *Rapid prototyping* is an application of rapid technologies for cost-effective, quick production of test parts and prototypes. These components generally have limited or special functions. Their design can be, but does not have to be, optimized for series production. With rapid prototyping, it is also not necessary to use the generally more expensive material that is used for series production. The term *rapid prototyping* thus covers only a small subset of additive applications and therefore should not be used as a synonym for the term *additive*

■ In *rapid* additive processes are used to create tools and molds, for example, casting molds, injection molds, and deep-drawing dies, for the production of prototypes, preseries parts, and series parts. For the most part, selective laser melting is employed here,

allowing not only rapid manufacture but also efficient use of the shaping options provided by rapid technologies. In order to achieve the necessary precision and/or the required surface characteristics, conventional processes such as *high speed cutting* are often implemented to rework the tools and dies created by means of the additive process. This is called *direct rapid tooling*. *Indirect rapid tooling* is the production of tools by molding master patterns created using additive processes. Processes in which CNC programming and subsequent HSC are used to create tools from solid stock within a short time are also considered to be rapid technologies, along with additive manufacturing processes. Because they involve chip removal, however, they should not be confused with additive processes.

■ *Rapid manufacturing* is the additive manufacturing of end products for single-part or series production. The parts are manufactured in the genuine material based on the design data and have all the characteristics of the final product. Besides the ability to produce parts rapidly, building up parts using additive processes allows the creation of certain product design characteristics, for example, cooling channels that are close to the surface or curved boreholes, which are difficult or impossible to create using conventional production methods.

This means that with rapid technologies it is possible to expand and master the various options for the manufacture of new design elements and to move on directly to the manufacture of end products for single-part or series production. Additive manufacturing cuts the time required for product design and development through the use of rapid technologies; thus prototypes, tools, and final parts are manufactured. The use of

additive manufacturing processes also eases the logical interlinking with data processing. Not only can the manufacturing time be described as rapid compared with conventional processes, but the direct CAD/CAM link also simplifies and speeds up production planning, for example, for generating and converting the manufacturing data.

For metals, the rapid technologies with the greatest potential for the future are beam melting, also known as *laser* selective laser melting (SLM), LaserCUSING, electron-beam melting (EBM), direct metal laser sintering (DMLS; Figure and direct metal deposition (DMD). These methods are suitable both for prototype production and for repairing or modifying tools and molds. DMD makes it possible to process spatial surfaces by fusing powdered metal layer upon layer with a laser beam. The amount of induced heat in the workpiece is minimal. The two process variants described earlier have the following characteristics:

FIGURE 15.2 Metal pentagonal dodecahedron with complex internal structure produced through beam melting.

■ Powdered metal is the feedstock material.

■ Complete melting of the powdered metal is accomplished by the laser.

■ Mixing and application of various powdered metals to base materials of a different type are possible.

■ Fully automatic production is possible; no manual interference is needed.

■ Parts can be directly generated from the 3D cad data.

■ Manufacturing is close to the final contours, with minimal rework of the functional surfaces needed.

PROCESS CHAIN

The generation of models and the process chain follow similar principles for all process principles in additive manufacturing as illustrated in Figure The process for generating additive components can be subdivided into the following areas.

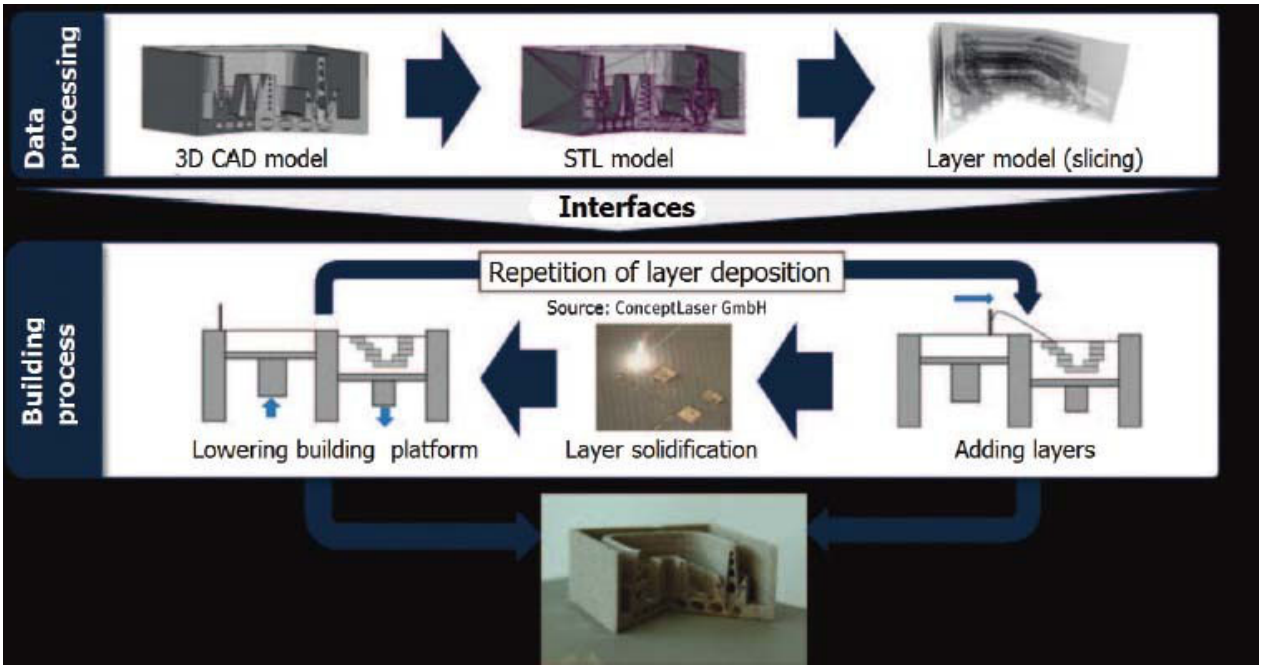

FIGURE 15.3 Data processing and manufacturing process of 3D model to the finished part.

Preparations for the Construction Process

A complete, dimensionally accurate solid 3D model is the basis and prerequisite for all additive manufacturing processes. The CAD program used is based on the available options for data export. Formats used with rapid technologies include Stereo Lithography (STL), Initial Graphics Exchange Specification (IGES), and Standard

for the Exchange of Product Model Data (STEP). The format most often used is STL, which is based on the approximation of the geometry using triangulation. This format is also supported by all the commonly used CAD programs. The triangulation process used here involves approximation of the outer geometric surface by means of triangles. These triangles are defined via the position of their three vertices and the associated normal vector pointing away from the solid of the part. The aggregate of the triangles and normal vectors embodies all the surface information. Nevertheless, the geometry of the parts always should be verified after triangulation. As a rule, all software programs for data preparation provide repair functions for use in the event of triangulation errors.

The STL data set for the part is the input information for the slice process. This breaks the part down into individual layers. The thickness of the layers depends on the process being used and the required surface quality. This means that with slicing, the geometry information for the construction process is generated for each layer. Where curvatures, sculptured surfaces, and blunt angles appear, the layer-by-layer construction means that a “stepped” effect is created. This leads to lower surface quality. The greater the layer thickness, the greater is the stepped effect. On the other hand, increasing the layer thickness reduces the construction time and thus also the cost of the part. It is necessary to find a compromise for each individual construction process.

The last step in the preparation for the construction process is to place the part virtually in the machine space using the system software. At the same time, the information for the individual layers is send to the CNC system. Lastly, the operator defines system-specific parameters, such as the travel speed or the temperature of the workspace.

The Construction Process

As a general principle, all additive processes are performed in three process steps:

1. The material is applied.

2. The layer is consolidated.

3. The platform is lowered to allow application of the next layer.

On the other hand, application of the material and the joining process vary depending on the specific system and manufacturing technology. Moreover, the basic states of the materials may vary and can include powdered, liquid, and solid materials. The feedstock material is consolidated via the application of an energy source or a chemical activator. After the first layer from the preparation for the construction process has been consolidated, the platform is lowered by the amount of the thickness of one layer, and a new layer of feedstock material is applied. In order to create as even a base layer as possible, this is generally performed using a broad application mechanism, such as a roller or a blade. This is followed by consolidation of the new layer in accordance with the data specified in the preparation for the construction process. At the same time, the layer is joined to the underlying layer. In additive processes, this method leads to anisotropic properties in the material because the joining of the feedstock material in the (or horizontal) plane generally is stronger than in the (vertical).

Postprocessing

In most cases, the parts produced in additive processes have to be reworked because of the relatively low surface qualities. The reason for this is the stepped effect inherent to the process and the limited dimensional accuracy of additive manufacturing technologies. For this reason, fixed points should be provided during the design phase as reference points for subsequent rework. Thus it is possible to set up an auxiliary coordinate system as a basis for finishing operations using a CNC machine. The design engineer should select these fixed points so that that they can be produced accurately using the additive process. Furthermore, the anisotropic properties in the material can be reduced or eliminated by means of thermal posttreatment processes.

CLASSIFICATION OF ADDITIVE MANUFACTURING PROCESSES

The additive manufacturing processes in use today can be classified based on two aspects: the feedstock material and the shaping method.

Classification Based on the Starting Material

As shown in Figure three types of starting materials are used today:

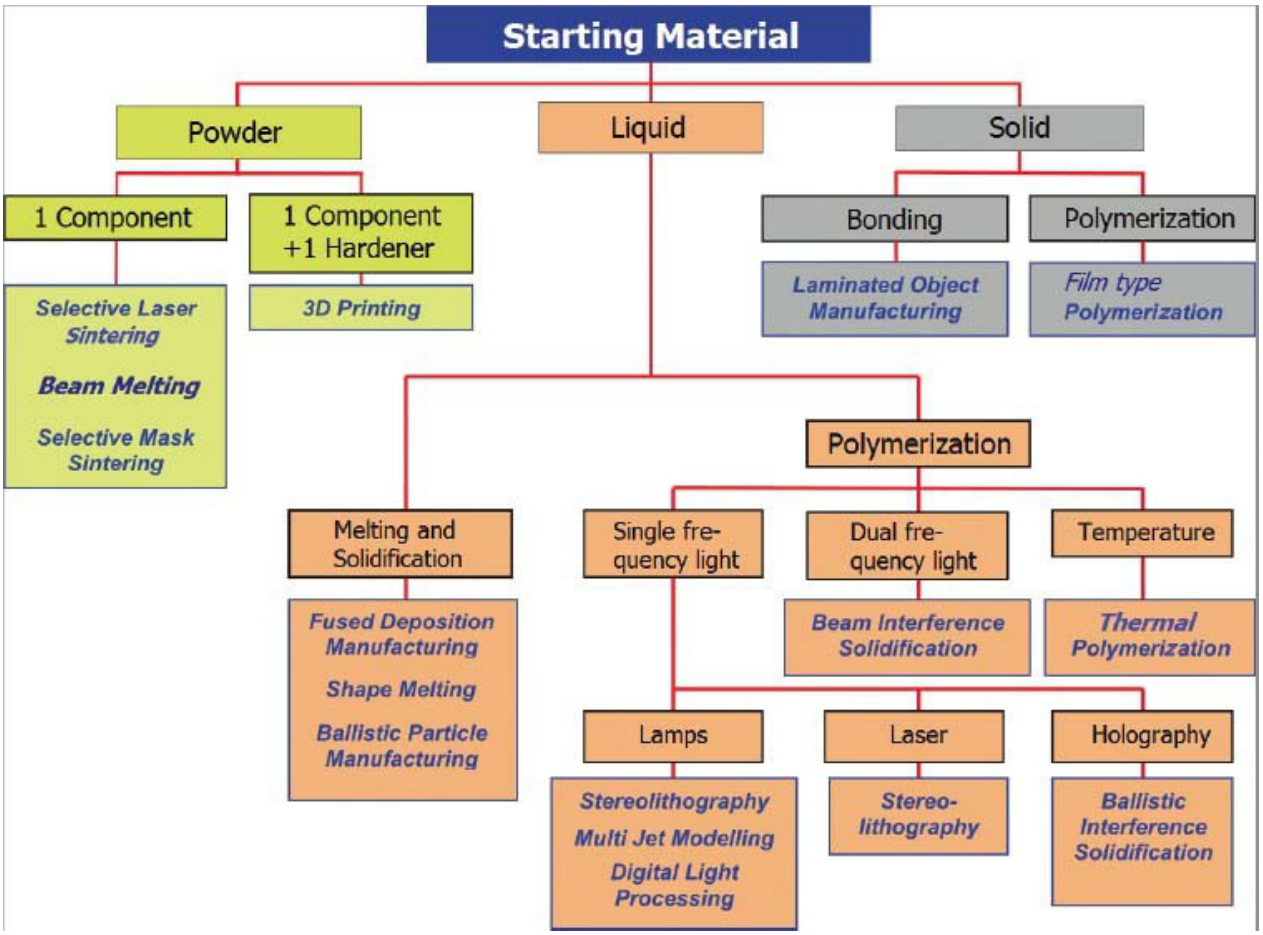

FIGURE 15.4 Classification of the currently used materials for additive fabrication according to the state and base material.

- Powdered granulates

- Liquid synthetic resins
- Solid feedstock materials

In processes where powdered or granulated material is used, sintering or bonding processes are employed. Here a targeted laser beam is used to melt and consolidate material that is "applied" or fed onto each other in thin layers. In 3D printing, the consolidation is performed via the targeted introduction of binding agents, for example, water in plaster. In the case of liquid materials, a targeted laser beam or ultraviolet (UV) light is used to consolidate, or polymerize, synthetic resins and join the new layer with the underlying existing layers. This process also includes the use of solid materials (plastics) to build up the existing model layer upon layer by means of melting followed by rapid cooling. The semiliquid plastic is sprayed on the previous layer and so on.

When it comes to solid materials with a neutral form, this generally involves layers of film or paper that are bonded on top of each other layer upon layer and then cut out to the exact contours using a laser or cutting blade. Both conventional bonding processes and partial polymerization (bonding via heating) are used.

Classification Based on the Shaping Method

A distinction is made here between processes that can be used to create 3D forms directly and processes that generate the final shape layer by layer. Figure 15.5 provides an overview of the various processes. All the processes used today function in two dimensions,

that is, with individual layers. Models are built up layer upon layer, thus creating a third dimension. This also applies to processes that generally would be able to work in three dimensions directly, for example, fused deposition manufacturing. The reason for this is that the 3D software required for this is significantly more complex and therefore not available at this time.

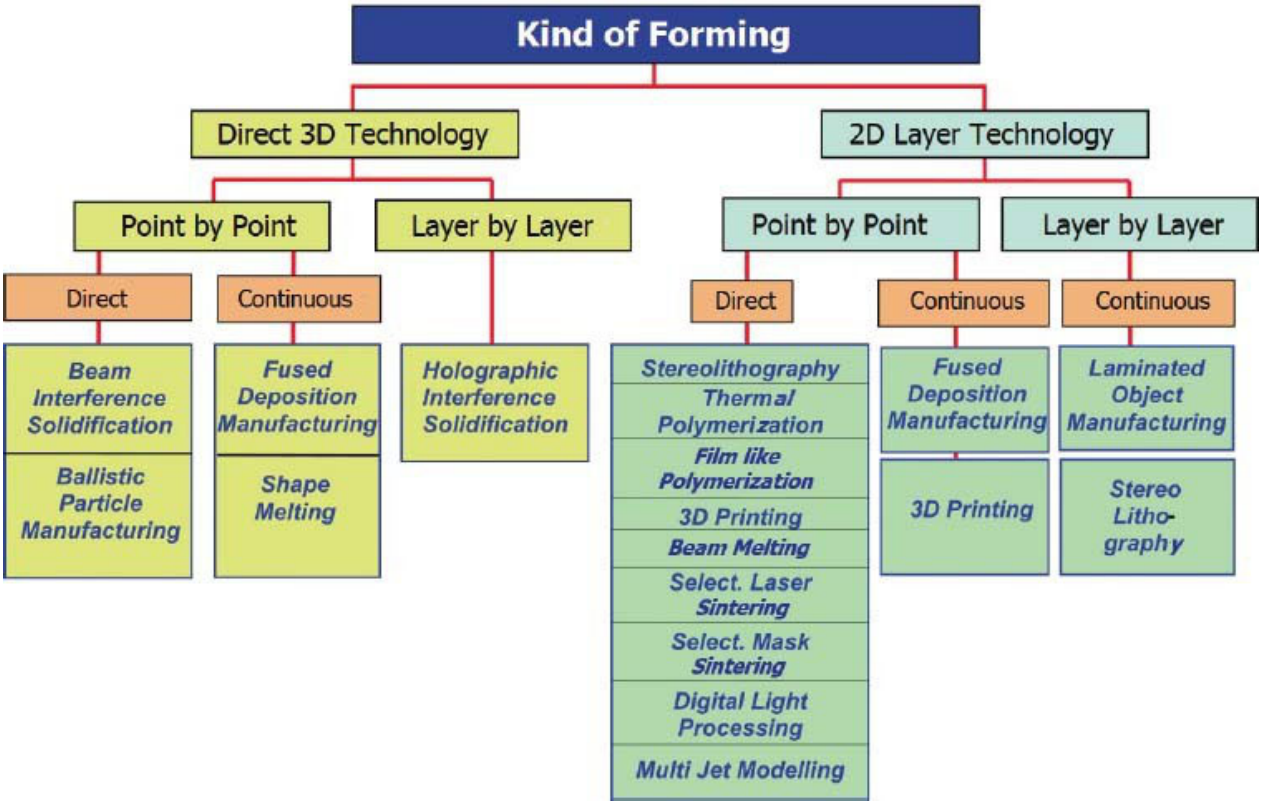

FIGURE 15.5 Classification of modern additive fabrication processes according to form generation.

INTRODUCTION TO THE PRINCIPAL LAYER MANUFACTURING PROCESSES

Beam Melting

Process Description

In additive manufacturing processes that use beam melting, the stock material is in the form of a powder. At the beginning of the process, a layer of powder is applied to the platform using an application mechanism, for example, a sharp blade. Next, this loose substrate is fused and thus consolidated into a solid body using an electron or laser beam depending on the process method. The part is created layer upon layer by lowering the platform, each time applying a new layer and thus creating the component volume

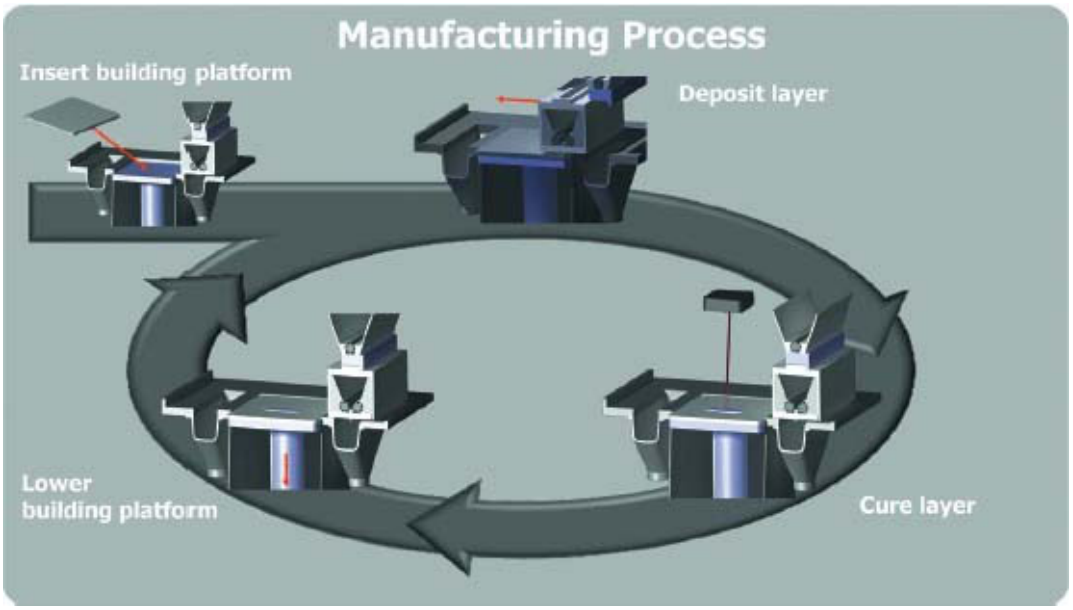

FIGURE 15.6 Process of direct and indirect beam melting.

The effects that appear when the powdered stock is fused locally are characterized by complete transformation of the powder into the molten state, which is what differentiates this process from sintering processes. Instead of a two-stage sintering process (see Section 15.5.2), a single-stage beam melting process now has become the established practice in industrial applications. Various terms are used to describe this process. Whereas EOS GmbH uses the *direct metal laser sintering* other companies prefer the terms *LaserCUSING* (Concept Laser) and *selective laser melting* The process, however, is the same for all manufacturers: The stock is always a single-component powdered metal that is completely fused during the building process. In this way, it is possible to create a nearly pore-free component whose material properties are similar to those of a component created from the same material using conventional processes (e.g., casting). Unlike with the *indirect metal laser sintering* process (see Section 15.5.2), no thermal postprocessing is necessary. At present, the powdered kinds of stock that are available include various tool and stainless steels, aluminum and nickel alloys, pure titanium, various titanium alloys, and gold. The range of materials is constantly being expanded as a result of numerous research and development projects.

The single-stage process can be used to produce usable components for various applications, in particular when it comes to prototype engineering and small-scale series production. Especially in medical technology and the tool and die industry, these technologies are regarded as important, cost-effective manufacturing alternatives for creating geometrically complex components and functional elements. Cooling channels, for example, can be created very close to their theoretical form. These processes are also becoming more and more important in the aerospace and automotive industries.

It should be noted, however, that the laser-based melting processes described earlier have the disadvantage of a limited traversing speed. There are two main reasons for this:

■ The mechanical mirror optics used to redirect the laser limit the power of the beam because of the limited thermal load capacity of the mirror system.

■ The mass moments of inertia in the mirror optics limit the traversing speed of the laser beam because increased deflection speeds have an adverse effect on the accuracy of travel.

These disadvantages can be eliminated with the EBM process, allowing an increased process speed

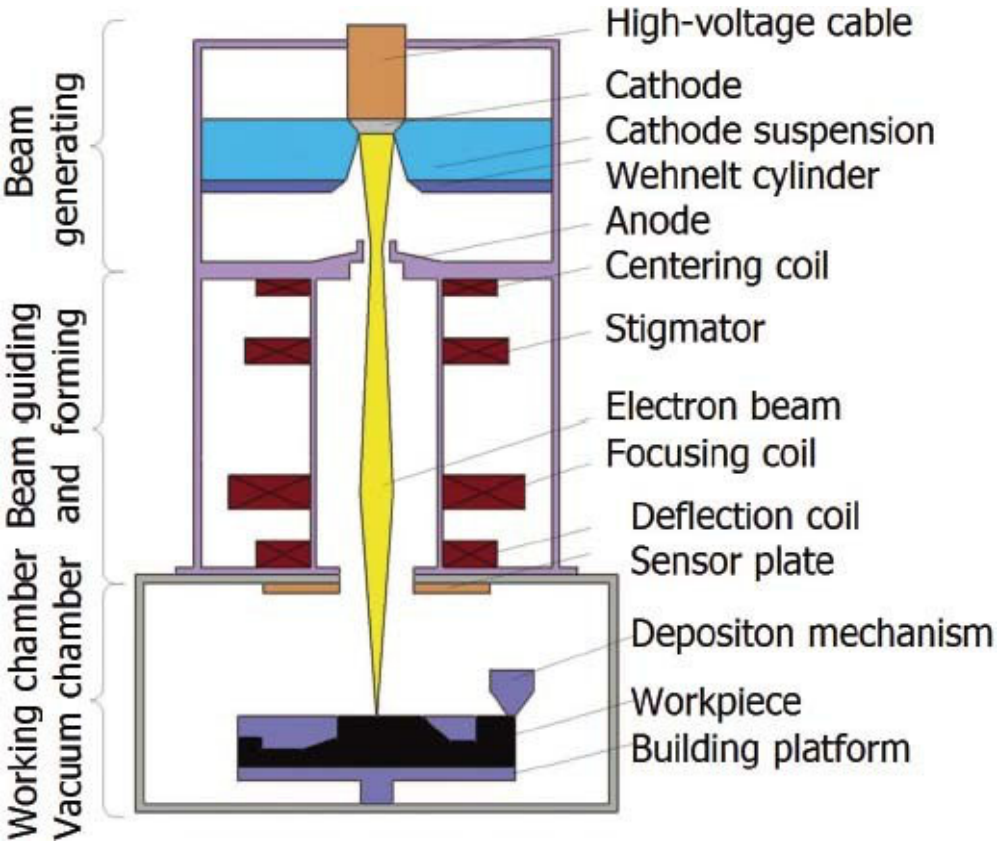

FIGURE 15.7 Schematics of an EBM installation.

In this type of processing, the beam is generated by an electron-beam cannon, which can be used to apply the beam current, that is, the power of the electron beam, in a targeted manner. By means of electromagnetic lenses, the electron beam is shaped to form a circular cross section, focused and deflected in the plane. The workspace is in a vacuum chamber, thus preventing the scattering of the electron beam. The powder reservoirs, the application mechanism, and the platform are located there as well.

The higher deflection speeds and power density of electron beams allow higher process speeds. The high deflection speed also offers a number of options for improved process control, such as quasi-parallel exposure and freely configurable beam shaping to control and optimize heat input to the part. Thanks to these advantages, the EBM process is currently being subjected to further research and development with the goal of establishing it as an industrial application on a larger scale.

Advantages of Beam Melting

- Many geometric shapes are possible.
- Thin wall thicknesses can be realized.
- Usable functional components can be made.
- Internal cooling channels that are close to the contours can be integrated.

■ Materials difficult or impossible to process using conventional methods to their thermal and mechanical properties can be used.

■ Multimaterial processing and the implementation of graded material properties are possible.

Disadvantages of Beam Melting

■ Supporting structures are necessary where overhang occurs.

■ A platform has to be used that must be cut off during postprocessing.

■ Layer construction of the part results in a stepped effect.

■ High production costs arise for parts with long processing times.

■ Internal stresses occur in part due to high temperature gradients during cooling.

■ Rough surfaces are present in some cases, possibly requiring rework of functional surfaces.

■ There is a limited work area and thus limited part sizes (presently 300 × 350 × 300 mm maximum).

■ A shield-gas atmosphere or vacuum is necessary for electron-beam melting.

Laser Sintering

Process Description

Sintering is defined as a consolidation process for crystalline, granular, or powdered materials through coalescence of the crystallites by means of the application of heat The powder is placed on a bed and is heated up to several hundred degrees Celsius, depending on the material. This process can be used for both metals and plastics.

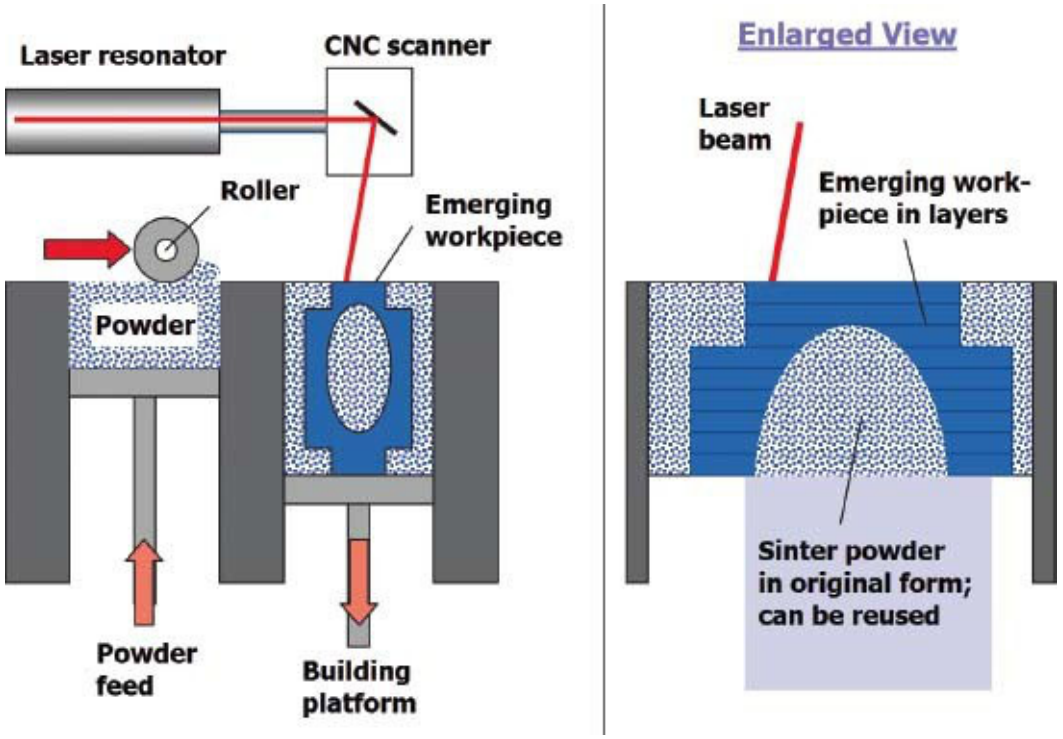

FIGURE 15.8 Schematic of laser sintering.

For metals, the process involves two steps. *IMLS* is used to fuse a plastic binder contained in the powdered metal surrounding the metal particles. This initially produces an incomplete body with low strength. In order to turn it into an adequate metal part, a subsequent heat-treatment process is required in which the plastic binder is expelled and so-called sintering necks are formed between the metal particles. At the same time, bronze is infiltrated into the

part, thus creating a stable structure consisting of about 60% steel and 40% bronze.

Laser sintering is also known as *selective laser sintering* This process is based on the powder-bed principle and can be used to produce prototypes and functional components from plastics in just a few hours The materials used most often in this case are polyamide and polystyrene. In contrast to beam melting processes in which the material is fused solely by means of the beam, with LS the stock is first heated to a temperature just under the melting point via a large-area heat radiator. Next, it is fused locally using a low-power laser (up to ~30 W). The laser beam is guided by the scanner optics. After the iterative production of the individual layers of the part, the support structure is slowly cooled down to room temperature. The time required for this cooling process is approximately the same as the time required to build up the part. If the cooling is too rapid, the temperature gradients will be too steep, thus resulting in excessive distortion in the part. The cooling process is followed by unpacking and cleaning. The sintered part can be extricated and the adhering powder can be removed with compressed air. The next step is postprocessing. Any material that has not been fused can be reused. A mixture of old and new powder in a ratio of 1: 1 can be used for best results.

FIGURE 15.9 Gripper made with additive manufacturing process. Festo Pneumatic.)

Advantages of Laser Sintering

■ Short process time compared with beam melting processes

■ Complex, functionally integrated parts

■ Wide range of materials

■ No support structure needed

Disadvantages of Laser Sintering

■ Shrinkage and distortion of large components owing to the thermal construction process

■ Porous surface

■ Aging due to the effects of UV light

3D Printing

Process Description

3D printing is an additive process in which a liquid binder is applied to a bed of powder in a targeted manner by means of a print head or nozzle. The part is created one layer at a time by successively lowering the platform and then applying a thin layer of powder. By selecting an appropriate combination of powder and binder, it is possible to work with a wide range of materials, including plastics, ceramics, sand (for casting molds), and metals. Because the print head is much less expensive than a laser system, the costs of this process are much lower relative to LS. The mechanical properties of plastic parts can be improved when, after the models are constructed, they are treated using infiltration agents such as epoxy resin or wax. When processing powdered metal, the material is fused by means of a binder substance and consolidated to form an intermediate state. Next, it is heat treated in a similar manner to IMLS and infiltrated with bronze.

Advantages of 3D Printing

■ High construction speeds are possible.

■ Many different materials can be used.

■ Large work areas are possible.

■ A considerable number of system manufacturers are available

- Colored parts can be created.

- This is an economical process.

FIGURE 15.10 3D printer. (Source: voxeljet.)

Disadvantages of 3D Printing

- Low surface quality

- Mediocre mechanical properties because of low density 15.11 and

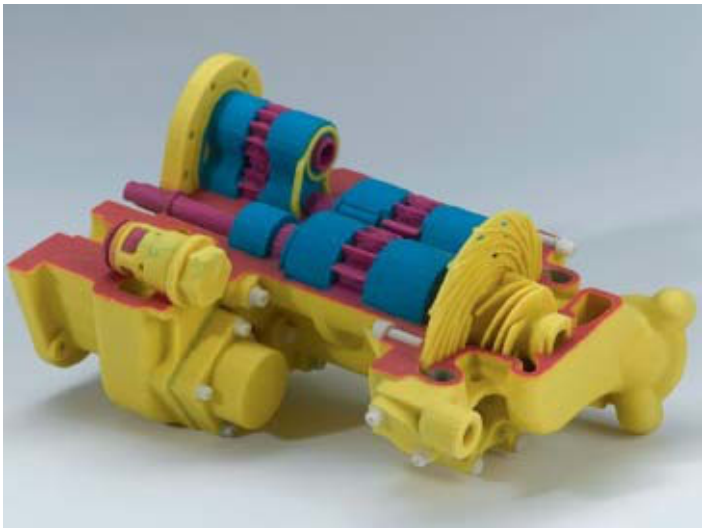

FIGURE 15.11 Model of a transmission made with a 3D printer.

FIGURE 15.12 Machine model with mobile modules, made with a 3D printer. Roschiwal + Partner.)

Fused Deposition Modeling

Process Description

In extrusion processes, a liquid or softened material is applied to a platform via one or more nozzles. The subsequent cooling process provides strength to the part. *Fused deposition modeling* also known as *fused layer modeling* is the most relevant process that makes use of only one material. A subcategory of this process is multijet, respectively poly-jet modeling, which can be used to create parts with graded properties. Here the nozzle generally has two degrees of freedom (in the and whereas the entire platform can be moved in the In this way, 3D parts can be manufactured. The adhesive bond between the extruded beads is formed during the cooling process. The bead structure results in a relatively low surface quality, as shown in Figures 15.13 and

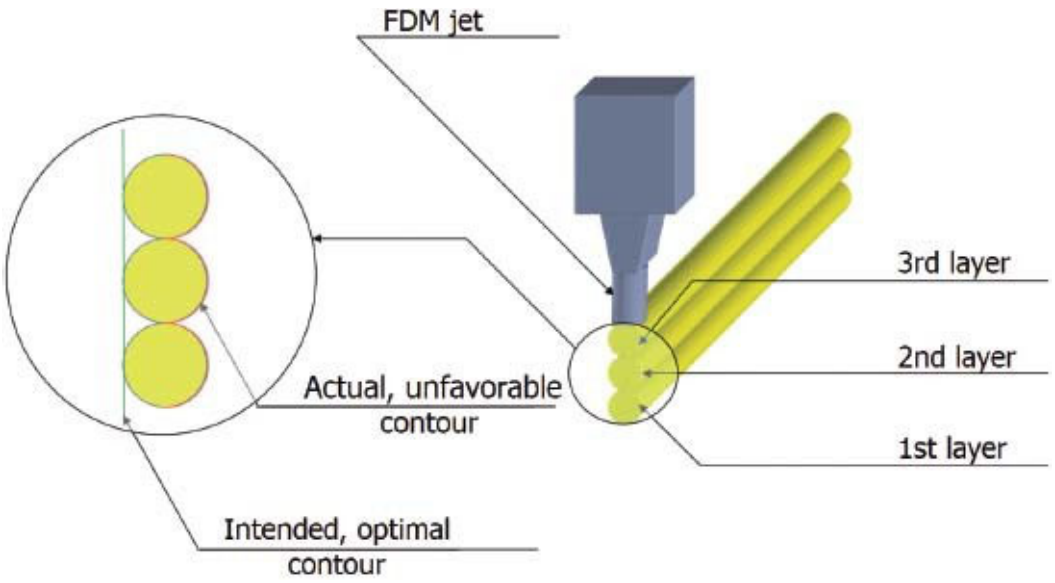

FIGURE 15.13 Component quality made with FDM.

FIGURE 15.14 Various components made with FDM.

Advantages of FDM

- Good mechanical properties
- Compact design
- Can be used as an office system
- Acrylonitrile butadiene styrene (ABS) can be processed.
- Multimaterial parts possible with multiple-nozzle systems
- Large number of system manufacturers
- Build-it-yourself systems are available.

Disadvantages of FDM

■ Low surface quality

■ Overhangs are hard to implement because no supporting material is present.

■ Considerable effort is required to remove the support.

Stereolithography

Process Description

Stereolithography is the oldest of the additive manufacturing technologies In this process, plastic parts are created by means of selective 3D polymerization of a photosensitive resin. Polymerization generally is performed using a UV laser in which the critical energy required to cure the part is reached only at the focal point of the laser beam. By lowering the platform, a new layer of liquid resin can be deposited on top of the already cured layer. By means of successive lowering and curing, a 3D part can thus be created.

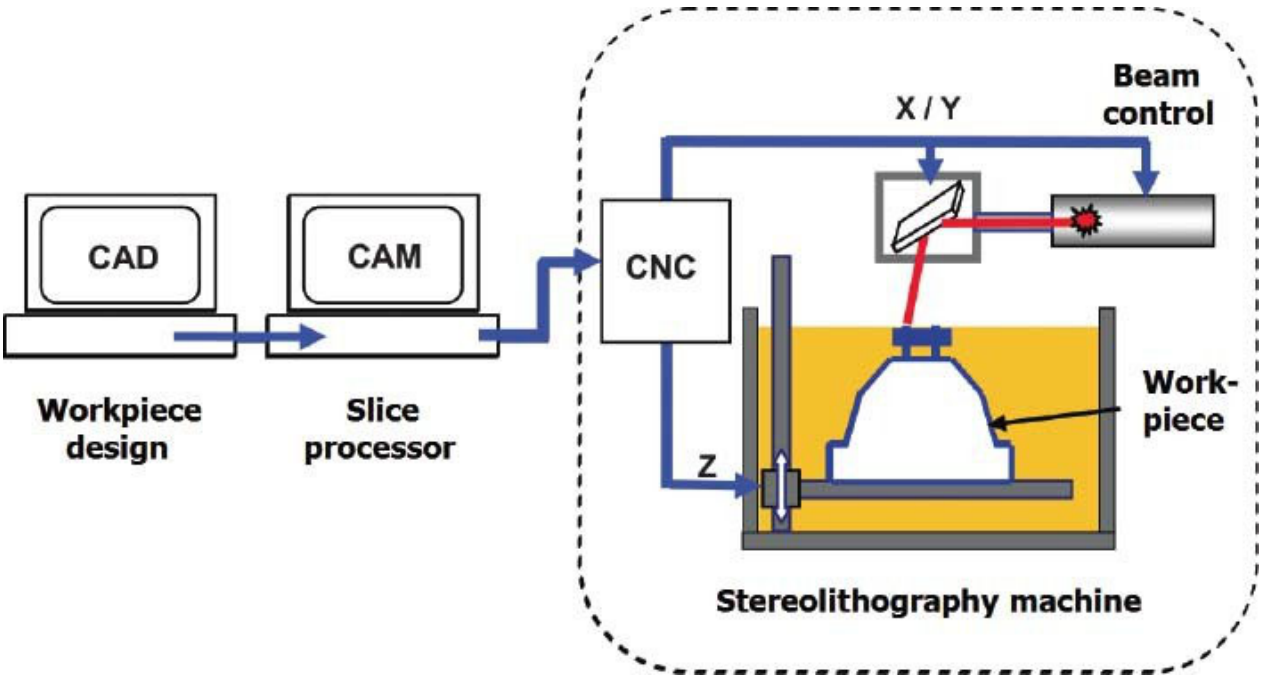

FIGURE 15.15 Principle of generative manufacturing systems. The workpiece data created by means of CAD are broken down into many uniformly thick layers in a slice process, and—depending on the process—the workpiece is built up in layers. In STL, the workpiece is formed on a platform from bottom to top Layer by layer is stacked and bonded together by exposure to a UV laser beam and solidification of the liquid monomer.

Polymerization is defined here as a chain reaction in which unsaturated molecules are bonded to form macromolecules. This can be broken down into four steps:

- Chain initiation, or the primary reaction
- Chain propagation
- Chain termination
- Chain transfer (branching of a molecule chain)

The materials used in SL have to respond to UV radiation and reach chain termination very quickly so that the resin is cured only in the illuminated areas. In order to give the parts their final strength, the construction process itself is often followed by a curing process in a UV enclosure. STL parts are used mostly as concept or functional models during the product-development process. Another area of application is the fabrication of product masters for vacuum and precision casting.

The STL technology is constantly being advanced by the market leader 3D-Systems and used by all well-known rapid prototyping service providers. STL technology is standard for high-end prototypes and product masters for vacuum casting.

STL technology is far superior to 3D printing technology for many forms because it uses only approximately 3%– 5% of the component weight for support purpose. Because with 3D printing the object must always be vertically oriented and must be 100% supported, the support structure can take as much as 10 or 20 times the component weight. Also, there is no need to collect waste in a separate container as it is with 3D printing, where at least 200 g of material needs to be flushed from the print head and nozzles at the start of the process. This is a significant expense given a material cost of around $240 per kilogram of resin.

The current standard in STL is a laser focus of only 0.017 mm and a possible layer thickness of 0.01 mm. This allows parts to be produced in the micro range. Compared with 3D printing, the material diversity is much greater.

An advancement of STL is micro-stereolithography. This technology can produce geometries with very high complexity and also fine detail. Here the resin is not cured point by point with a laser, but the complete layer surface is cured with the use of a digital light-processing (DLP) chip.

Advantages of STL

- Easy to produce complex, thin-walled structures

■ Practically no thermal stress, thanks to the low laser power (generally <1 W)

■ High-precision parts can be produced.

Contested Disadvantages of STL

■ Aging of the material is only a problem at a very low volume and after standstill of the device for an extended period of time. In this case, there is no replenishment with fresh material, and premature aging can set in. At continuous use, the machine has a basic supply, and new material is constantly added. Large devices have containers holding up to 480 kg of material; spoilage would be intolerable.

■ The UV part of sunlight does not pose a problem as long as the windows of the facility are covered with a UV filter. Direct exposure to sunlight of the material must be avoided.

■ Changing of the resin in large installations is a problem and should not be performed. One filling of material runs about $100,000, plus $58,000 for the container. A change of resin might be called for in case of low usage. Smaller installations see several replenishments each week. This is typically a minor task and lasts between 30 and 45 minutes.

■ The advancement of STL systems led to completely new types of systems: they are very small and delicate, process up to 20 different materials, and the material change takes about 60 seconds. The advantage of these new systems is that although they have a construction platform, they have no dedicated material container and

operate with minimal amounts of resin. Therefore, there is no risk of aging of the resin.

■ Support structures are indispensable for this technology and not a disadvantage. Using the software "Materialize E-Stage," a column generator, the columns are quickly and automatically generated after positioning the parts

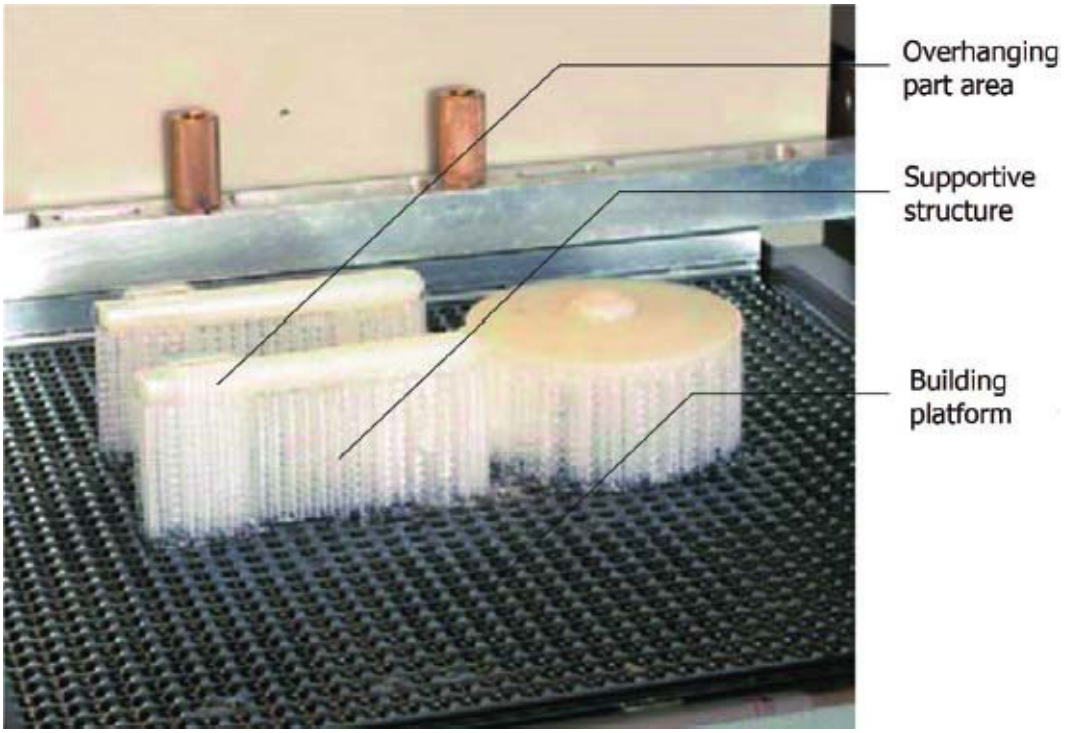

FIGURE 15.16 Part with support structure generated with stereolithography.

Actual Disadvantages of STL

■ Very high expenses for the required maintenance contracts

■ Very high purchase price since there is no competition to the 3D systems brand

■ The company 3D Systems protects its supply containers with chip coding. Therefore, off-brand material available on the market can only be used in older systems

■ Operation requires climate control.

Other Processes

Mask Sintering

Mask sintering is very similar to SLS. Here, too, energy is applied to a powdered material in order to fuse it. But unlike laser sintering, MS does not involve a single laser beam that is deflected by means of a scanner but rather illumination of a layer over a large area via a mask. The mask is printed for each layer in such a way that the energy emitted by a UV source is reflected onto the powder in the areas that are to be consolidated. The mask consists of a mirror and is printed with ceramic powder for each layer. Illuminating a complete layer over a large area greatly reduces the construction time per layer

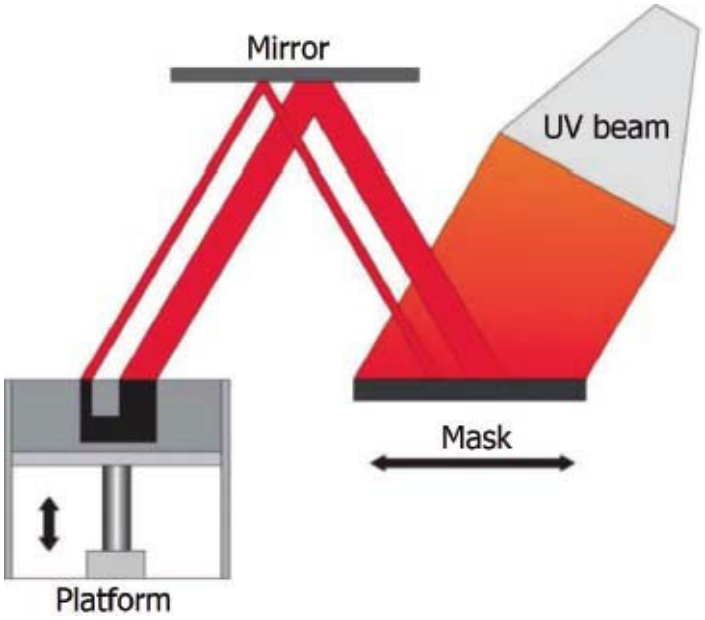

FIGURE 15.17 Principle of mask sintering.

Digital Light Processing

Digital light processing uses a similar process sequence to that of SLT, but through the use of a special chip it is possible to illuminate and consolidate an entire layer at a time. The DLP projector is controlled by converting the construction data into a bitmap format and projecting them onto the construction plane as a mask via the mirror unit. As in conventional SLT, working with a fluid necessitates support structures. This process is especially used in the additive manufacturing of microcomponents.

Laminated-Object Manufacturing

In *laminated-object manufacturing* also called *laminated-layer manufacturing* the material is in the form of sheets, for example, plastic film or sheets of paper. These sheets are bonded to each other layer on layer and then cut along the component contours. Both laser systems and conventional cutting tools such as rollers are used for this. The completed block is removed from the system, and the sections that are not part of the component are removed. It is also possible to work with metallic materials. High surface quality can be achieved because of the minimal thickness of each individual layer.

Laser Cladding

Laser also known as *laser deposition* uses a laser beam to create a localized weld pool on the surface of a metallic workpiece. The metallic material, generally in the form of a powder or wire, is applied to this weld pool by means of a feeder unit. By moving the

weld pool over the surface of the material, it is possible to create a bead-shaped line. To protect the fused material from oxidation, the process generally takes place in a shield-gas environment. By superimposing a number of individual layers, 3D solid structures can be built up. Components built up using this additive process have a comparable density to that of components created from the same material using conventional processes and a relatively rough material structure, very similar to that of a casting. Furthermore, only a low surface quality can be obtained using this process.

ADVANTAGES OF ADDITIVE MANUFACTURING

At the beginning of 3D printing in the mid-1980s, the objective was to create physical products that could possibly be assembled. Today, this is called *rapid prototyping* Later, better machines and a variety of new materials were developed so that 3D printed parts, carefully planned and manufactured, could also be used industrially.

Additive manufacturing has become increasingly relevant and holds the promise of "printing" metals on an industrial scale. The most important reasons for the use of AM compared with milling and drilling are as follows.

Faster and "On Demand" Fabrication

Spare parts often must be kept for decades. With AM production, one particular part can be manufactured overnight; there is no cost of warehousing.

Price

If the volume is low, the expense of molds, tools, and time can be saved. Examples are prototypes, equipment, and implants.

Weight

Weight is a significant cost factor in the aerospace industry; significant amounts of fuel can be saved over the lifetime of an aircraft with lightweight construction Weight reduction is also ever more important in mechanical engineering—with ever-shorter cycle times and thus higher accelerations of machine components. AM also makes it possible to hide conventional conditions, such as minimum wall thickness, draft angles, and so on.

FIGURE 15.18 Airbus door hinge: conventional manufacturing; made with AM—50% weight reduction!

Improved Features

A design no longer has to comply with previous production methods. Instead, the new product can be purely functional, for example, the hydraulic block as in Figure

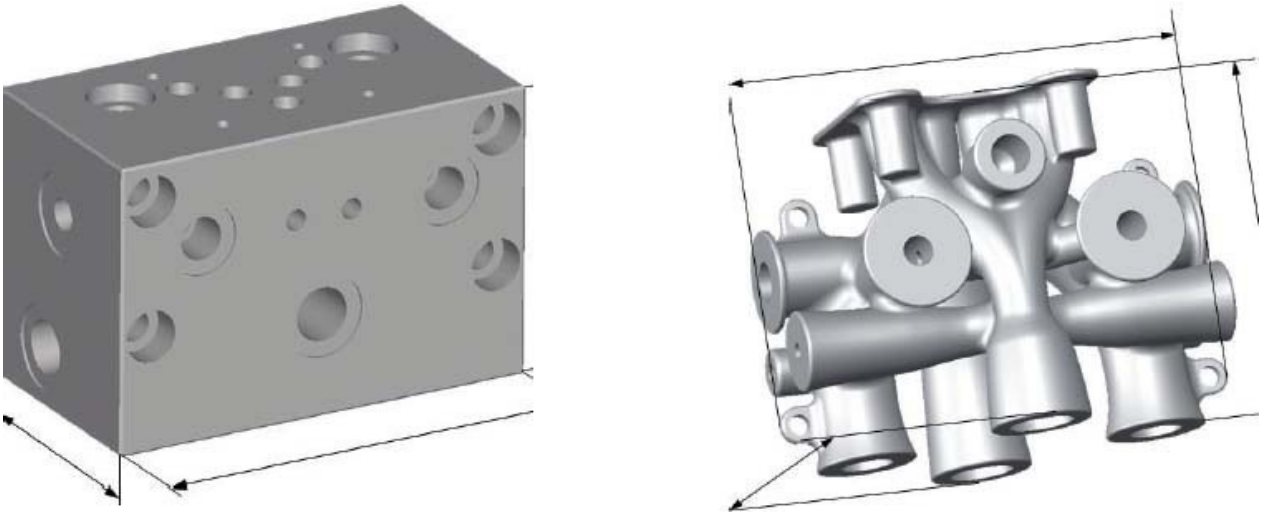

FIGURE 15.19 Hydraulic block valve, conventionally manufactured cuboid, for cost reasons with as few holes as possible. Same valve

manufactured with AM. Result: weight savings of 80%; more important: the holes no longer have to be straight and cylindrical but can conform to the optimal flow, resulting in a 50% reduction of pressure loss during actual operation.

Cycle Times

Cooling holes in injection molds no longer have to be straight but can be closely oriented on the article geometry. This has two advantages: less distortion during cooling and significantly shorter cycle times.

Number of Parts

Traditionally, parts cannot take any shape and can generally consist of only one material. With AM methods, several parts can be fabricated together, and several materials can be combined (see example in Figure There is no need to weld and assemble; flexible hoses are connected with fixed flanges.

FIGURE 15.20 Comparison: AM fabrication; traditionally fabricated with milling and drilling operations.

Repairs

Another important application is the product repair called Especially with complex products made of high-quality materials (e.g., turbine blades), the part is more economical to repair than to replace with a new part. In such an additive repair, the defective product is scanned, compared with the target geometry, and the material difference is built up. Depending on the required precision, the added/repaired feature is milled to finished contour and postprocessed.

There is a number of other methods, the most widely known is *laser metal deposition* Here, metal powder is applied onto existing parts and heated at the point of impact by a laser so that it melts and merges with the existing substrate. The great advantage is the relatively high build-up speed and excellent material quality. The use of several nozzles allows the mixing of different materials—with a fixed or gradual transition

FIGURE 15.21 Steel and bronze in one component. DMG Mori.)

Hybrid Machines

AM-fabricated parts for industrial use typically must be machined at the functional and connection surfaces, and the support geometry, if applicable, must be removed—usually via a cutting operation These operations today are not yet integrated in the automatic process flow and are performed manually, but there is a strong trend for future automation. A modern approach is the development of a machine that can apply material with a laser and remove the excess material via milling and grinding; this is called *hybrid*

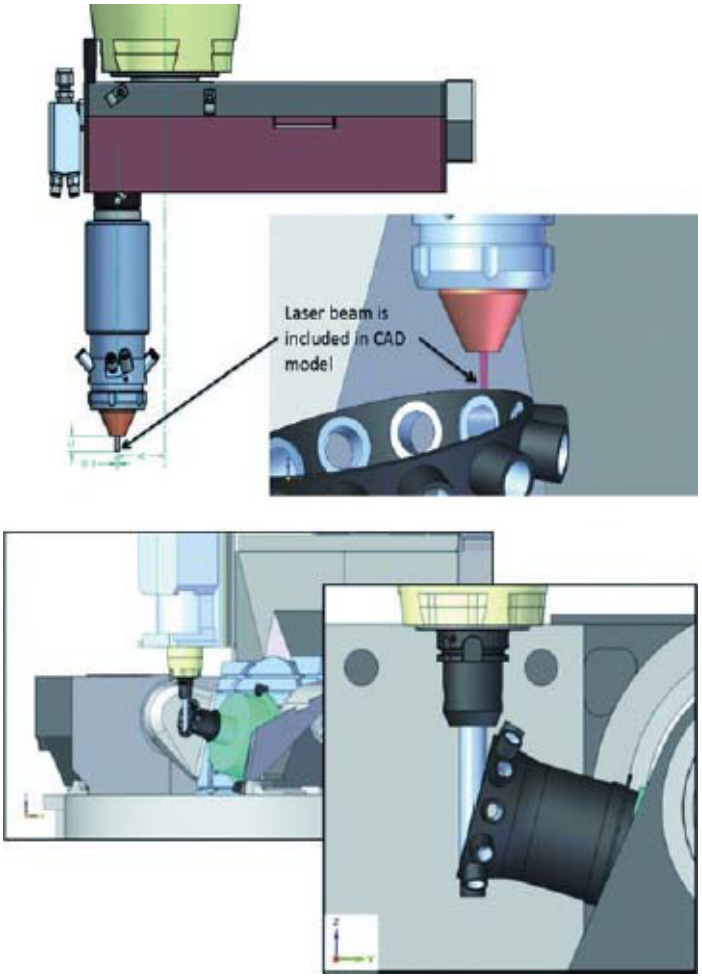

FIGURE 15.22 3D model: material deposition (AM) and removal (per milling) on the same machine. DMG-Mori.)

SUMMARY

Generative manufacturing processes can be used for the production of prototypes, molds, and end products. In all cases, the component to be produced must be available as a 3D CAD model. Production may be done, depending on the intended use, with very different layering processes. In addition to the procedures described herein, there are other (but only marginally different) processes. Current developments in AM processes in industry and research are very complex. The focus is on the acceleration of the manufacturing process, for instance, by the application of higher laser powers and thus larger buildup rates. In addition, after AM process reworking operations must be performed in order to provide for sufficient quality of the components. Thus both the process robustness and the assurance of component quality are subjects of research and development activities. The constant expansion of the workable material portfolio means that generative manufacturing processes will continuously open up new fields of applications.

IMPORTANT POINTS TO REMEMBER

1. Additive or generative manufacturing processes create physical objects out of amorphous or form-neutral materials layer by layer directly from 3D CAD data.

2. Rapid technologies are composed of generative and cutting processes and have the objective of producing components or tools quickly.

3. Three requirements in terms of data processing must be met for additive manufacturing processes to be successful:

a. The data model of the part to be produced must exist on a 3D CAD system.

b. In process preparation, the volume or surface model is parsed into individual, ready-to-process layers.

c. A process-specific NC program has to be created.

4. Generatively fabricated components, depending on the process used, can be very different in their consistency, accuracy, and surface quality.

5. Many different modern generative processes are used in industries, and the product-development process plays an important role.

6. Modern generative processes can be classified in two respects:

a. According to the condition of the starting material: powdered, liquid, or solid

b. According to the type of shaping: direct 3D shaping or by stacking up 2D individual layers

7. Present commercial processes work in two dimensions.

8. The five most important procedures currently are

a. Beam melting of functioning metallic components and prototypes

b. Laser sintering of powdered plastics and one- or two-component metals

c. 3D printing, where the powdered starting material is solidified by the targeted introduction of a binder liquid

d. Fused deposition modeling, where thermoplastic material is heated and deposited by a nozzle in bead-shaped strands

e. Stereolithography, the layer-wise polymerization of liquid resin

9. Rapid prototyping means the quick production of preliminary objects or models that only have limited functions of the later components.

10. Rapid tooling means the production of tools and molds for prototype production or the production of mass-production parts.

11. Rapid manufacturing means the manufacturing processes that produce directly usable, functional components or end products.

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DEFINITION

The term *chained* or *flexible manufacturing systems* refers to a group of CNC machine tools that are connected by a common workpiece-transport system and a central control system. Various dissimilar (complementary) or similar (alternative) CNC machine tools perform all the necessary machining operations on workpieces from a group of related parts. The workpieces pass through the manufacturing process automatically. In other words, the sequence of machining operations is not interrupted by manual intervention, changeovers, or reclamping tasks. These systems thus make it possible to continue working through break times. At the end of a shift, operation can be tapered off with reduced help or no personnel at all.

In highly automated installations, production planning systems take over the production in real time, including material inventory for blanks and finished parts, clamping devices, and tool management. Assembly areas likewise can be integrated.

The use of CNC machine tools makes it easy to continually adapt to changes in the design and machining operations as these changes are introduced into the system. FMSs do not require minimum lot sizes but also can process single parts and small lots without stopping for changeovers. This requires suitable CNC programs, tools, and clamping devices. It is not necessary to combine lots to achieve larger quantities. This means that the amount of capital tied up in raw materials can be kept low, thus reducing inventory costs.

FMSs are not limited to the machining of prismatic workpieces. They also can be used for turning, sheet-metal machining 16.1 and and other production methods. Different methods, depending on the chosen processes and types of materials, open up completely new manufacturing and processing options such as additive manufacturing.

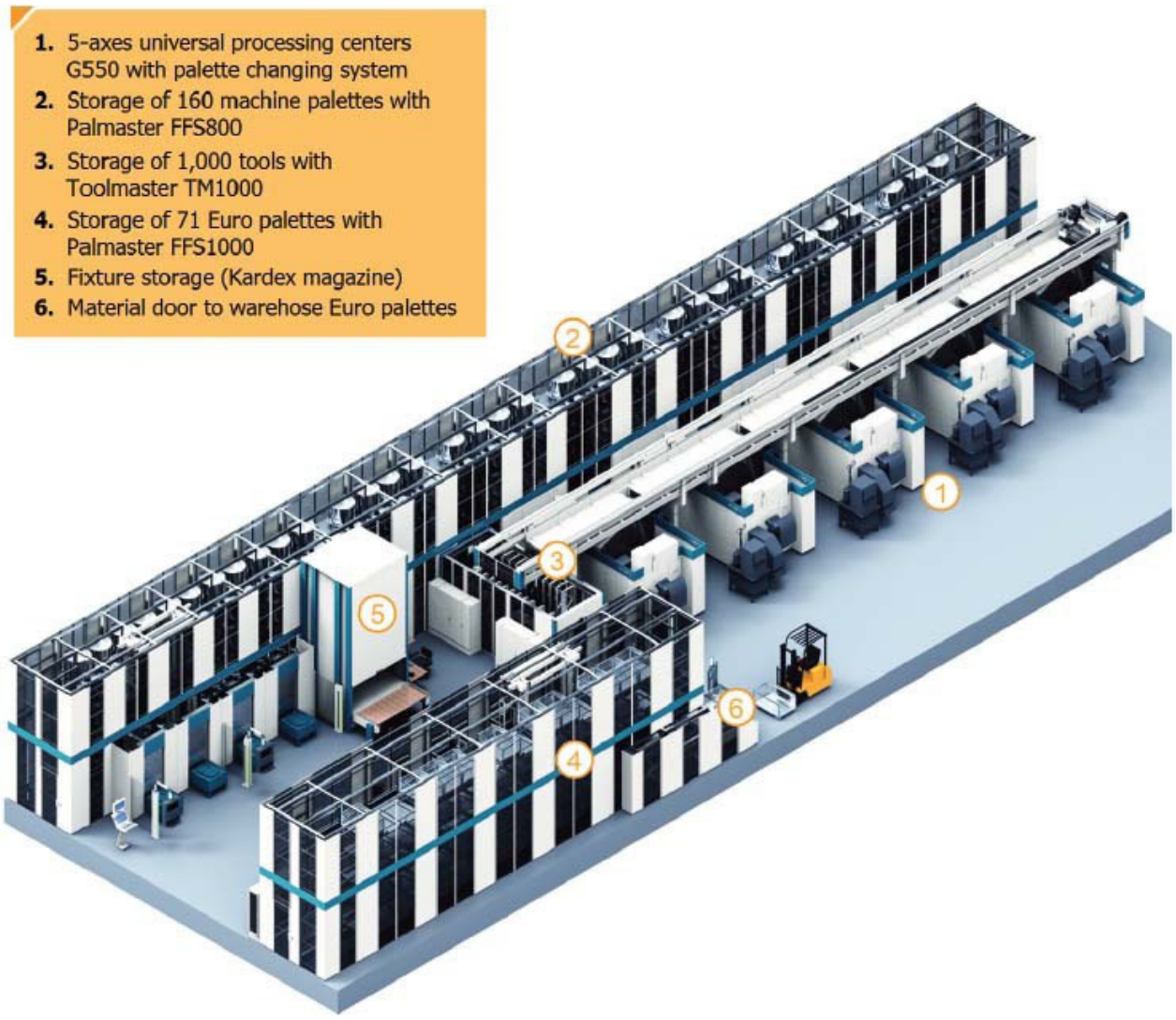

FIGURE 16.1 Flexible manufacturing system (FMS). (Source: Grob.)

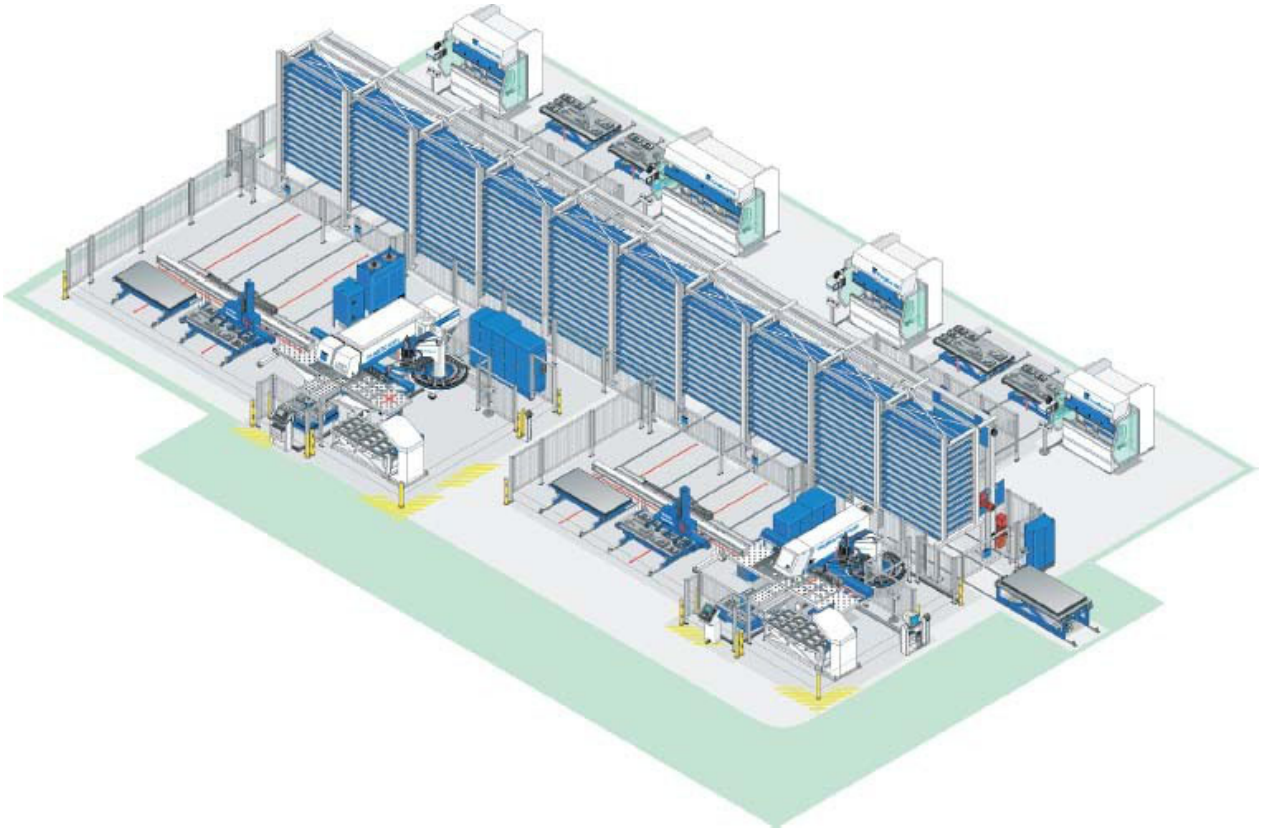

FIGURE 16.2 Flexible system for machining sheet-metal parts consisting of two TRUMATIC 6,000-liter punching/laser-cutting machines, each with an external tool magazine; TRUMATOOL automatic loading and unloading system; TRUMALIFT SheetMaster; TRUMASORT sorting systems for finished workpieces; TRUMAGRIP residual skeleton-removal system; a centralized storage system; and a TRUMABEND bending machine with linked transport vehicles; more info at TRUMPF.)

Aside from the various machine tools, this approach also requires a variety of transport systems. Individual or multiple prismatic workpieces are usually clamped and then transported on pallets. Turned parts are grouped in suitable bins holding relatively large quantities. Machining centers use pallet changers, but in turning applications, these are replaced by automatic handling devices, for example, robots or gantries. The handling device removes one part at

a time from the bin or feeder mechanism and carries it to the chuck. A double gripper exchanges the machined workpiece for an unmachined part and deposits the machined part in a finished part bin.

The general objective of using FMSs:

- Producing a variety of workpieces
- Applying a variety of machining methods
- Doing so in any desired sequence
- In lots of various sizes
- In a fully automatic manner, without manual intervention
- In a profitable manner

Figure 16.1 shows a variant of a flexible manufacturing system with a tool storage magazine. In the full expansion stage, the FMS can automate both tool and workpiece flow. The robot can exchange tools in the disk magazines of several individual machines. For workpiece flow, a magazine handling device for pallet handling has been installed. It contains three prep stations, a high-rack warehouse with 90 pallet storage places, and the processing machines.

Ever-increasing productivity requirements and high cost pressures, as in the automotive and consumer goods industries, have led to concatenating CNC machines so that all required machining of the

respective workpieces is fully automatic and can be performed without manual intervention.

FLEXIBLE MANUFACTURING CELLS

This term refers to a stand-alone CNC machine, usually a machining center, turning center, or other CNC machine, that is equipped with extra automation devices for unmanned operation of a limited duration. This requires the following features:

■ An adequate supply of parts in the form of loaded pallets or single-part storage, for single-shift operation, for example (This can be bar stock dispensers or pallet changers.)

■ Automatic loading of the machine from the workpiece magazine and the return of each machined part to its appropriate storage location

■ An expanded tool magazine so that frequent changes in workpiece types do not constantly require tool change

■ Automatic tool changing with monitoring devices to check for breakage and wear, as well as automatic retrieval of replacement tools

■ Dimensional monitoring of the machined workpieces, for example, by means of measuring probes and corresponding analysis software, making it possible to automatically apply compensation values or automatically shut down the machine when tolerances are exceeded (breakage monitoring)

■ Automatic shutdown of the machine after processing the entire supply of parts or when an error message is issued

Flexible manufacturing cells can be randomly connected to one another. Productivity and flexibility of the machines can be improved accordingly with automatic workpiece transport equipment, such as loading portals, robots, trolleys, and so on. Prerequisite for this is the coding of the workpieces or the workpiece pallets and the tools used. An upstream production control computer monitors the entire system and coordinates the entire process, also known as a *manufacturing execution system* This allows machining centers to be extended to FMCs and FMSs

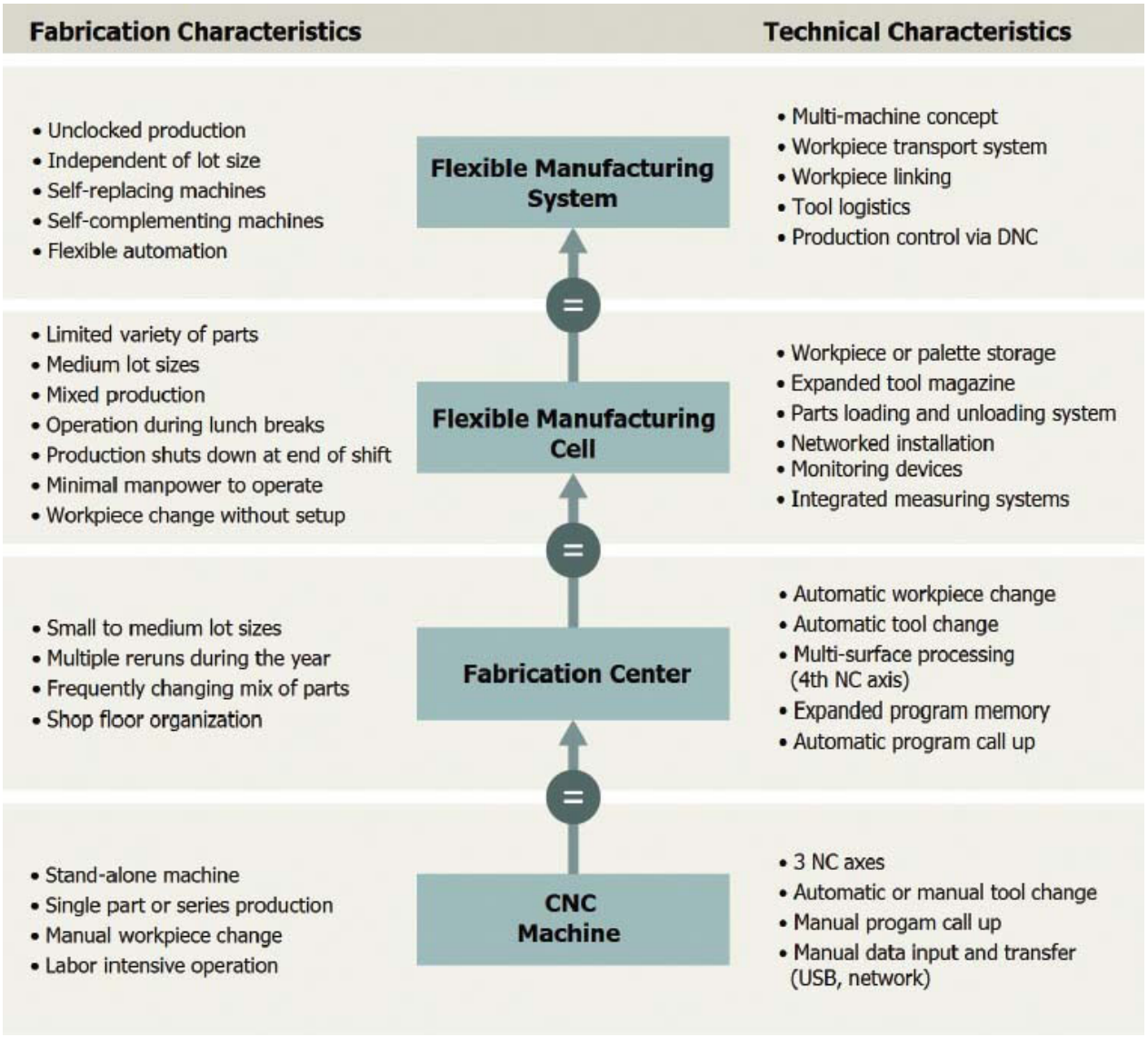

FIGURE 16.3 Expansion stages of a flexible CNC-based manufacturing system.

FLEXIBLE MANUFACTURING SYSTEMS

There are basically two types of linking of machine tools:

- Transfer lines
- Flexible production lines

Regardless of which system is used, the objective is to maintain production of large quantities without interruption resulting from break times, setup times, shift changes, and so on with reduced or even without personnel.

Transfer Lines

From the 1950s until the 1990s, transfer lines were used almost exclusively in series production. Depending on the processing volume of the workpiece to be produced, a number of transfer machines arranged in line were used for the complete processing. These machines carried out the cutting or noncutting operations, such as washing, leak testing, assembly, and others. In a manufacturing plant for a crankcase of a combustion engine block, for instance, 15 or more transfer machines were consecutively arranged depending on the production volume. Every machine performed only a limited number of the total number of processing steps, and the crankcase was moved to the next machine.

Production lines consisting of transfer machines are typically set up for a particular part, and this part is produced there for the span

of its life. The entire system is designed for minor design changes of a product or its priority in the manufacturing sequence; this applies to clamping devices, special tools, and individual stations of the transfer line. If, within the life span of the transfer line, another part must be produced, it entails extensive conversions and long downtimes of up to several months, as well as high investment costs.

Although transfer lines provide high productivity, a flexible change in production is only possible in a limited way. A system-related disadvantage is that as a result of the rigid chaining in a production line, the failure of a subsystem due to malfunctioning usually leads to a standstill of the entire system because the integrated transfer stations can only replace or supplement each other in a limited way.

Flexible Production Lines

Because of globalization and the associated changes in consumer behavior, the demands made on the flexibility of industrial production have increased since the beginning of the 1990s. The limited flexibility of transfer lines has increasingly led to changes in flexible production lines, consisting of chained single- or multispindle flexible machining cells. Transfer lines are alive and well to serve the market of very large-volume production. In the automotive industry, this applies to the production of drive-train components, such as cylinder heads, cylinder crankcases, and gearboxes. However, increasingly shorter product cycles favor the tendency toward highly flexible production lines. The coordination of the material flow within the line is performed by the gantry robot These are an efficient way of automating production processes. Accessibility to the machine is maintained by loading from above, for instance, via hatches. This is particularly important for setup processes and monitoring activities.

FIGURE 16.4 Flexible production line in engine production. Heller Company.)

The flexible production line consists of CNC machines that are connected via a loading portal, also called a *portal* The loading portal provides an automated material flow: picking up the blanks at the beginning of the line, loading the machines from above, picking up the finished parts, and evacuating them at the end of the line.

In modern mass production, flexible production lines are planned with placeholders in the first stage so that initially only a specific workpiece can be manufactured. By adding more machines, the product variety can be expanded in a second expansion stage. This allows local and global companies to flexibly adapt their production to demand. In the modern automobile industry, three- and four-cylinder engines are fabricated on the same line.

The ever-increasing demands on highly flexible production require the least possible effort for the necessary optimizations or modifications. In order to be able to efficiently implement changes to linked machines, modern flexible lines should be planned with minimal wiring. A high degree of cross-linking of machines and stations with one another has the advantage that all control systems in a network are centrally accessible. Changes can be made more easily without having to make a direct connection to the machine. An important prerequisite is the degree of diagnosis of such a flexible production line, which is further enhanced by intelligent, network-capable components. As a result of this arrangement, networking concepts must already be clearly defined when planning the installation

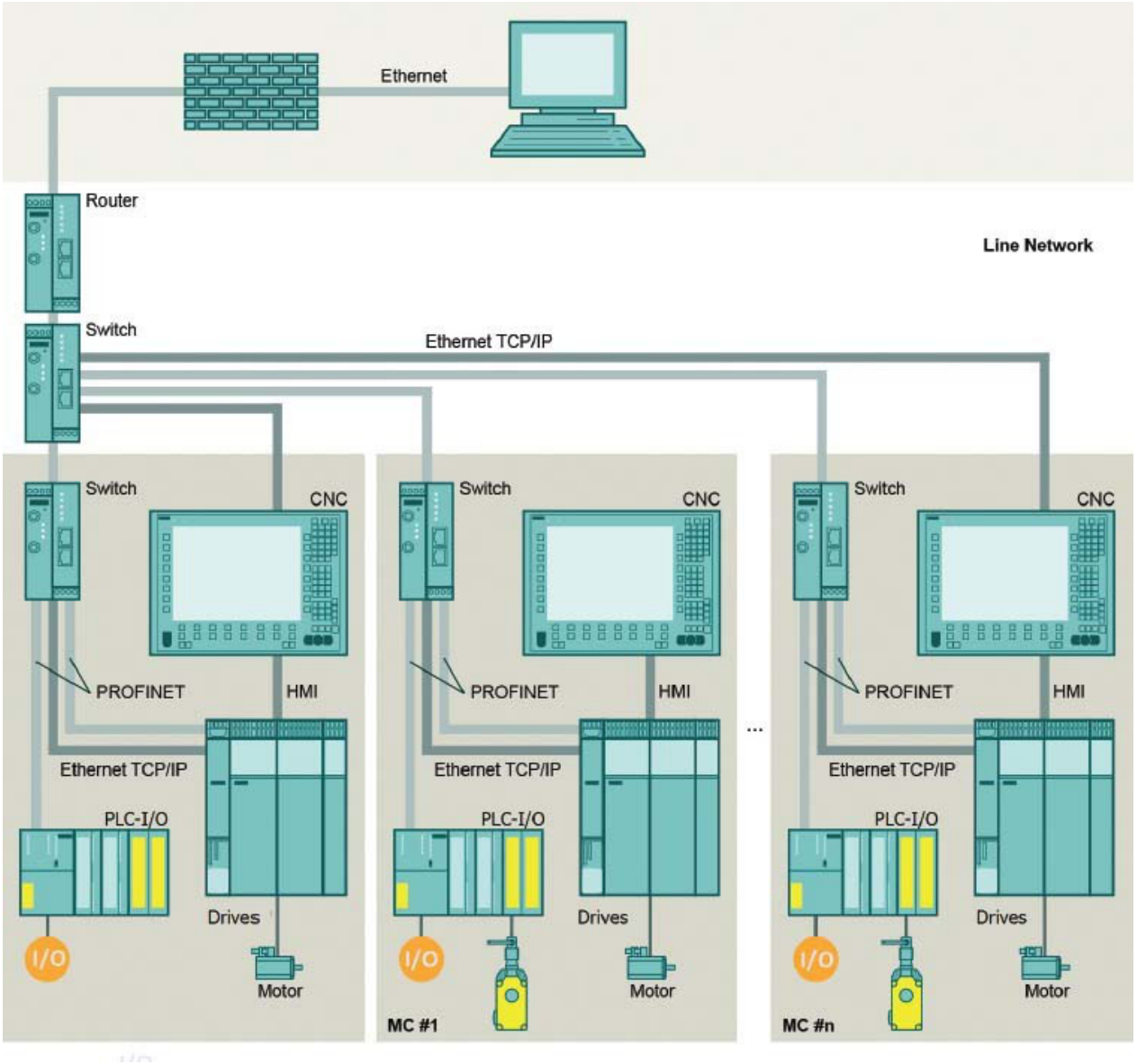

FIGURE 16.5 Networking architecture of a flexible production line.

The figure shows a CNC gantry robot and two CNC machining centers (MC #1 and MC located at the beginning and end of the flexible assembly line. The CNC control of the gantry robot coordinates not only the material flow of the workpieces but also the hub of networking between the production level and the production control level. Flexible production lines are becoming increasingly more productive and also more cost-effective for high-volume production as a result of new technical possibilities.

Modern control architecture of a networked system (see Figure includes, depending on the requirements, different levels of automation components. For instance, a low-cost expansion stage contains a LINUX-based control system without an industrial PC. If additional monitoring and software applications are needed, a Windows-based human-machine interface (HMI) must be chosen. Considering the HMI, a PC-based design makes sense because of the amount of data that have to be processed given that visual quality-management mechanisms are used.

Practice has proven that a control unit of a portal robot of a linked system can be purely programmable logic controller (PLC) based. However, if more variable adjustment options are required, dedicated CNC computers have the advantage that operator interface and diagnosis do not differ from the CNC systems of the processing machines within a production line or in the entire production facility.

The higher flexibility of chained equipment represents the following challenges for machine suppliers and end users:

■ Strict separation of production and information technology (IT) networks

■ Rules for Internet Protocol (IP) addressing of the entire installation in production

■ IT security with clearly defined access rights

■ In the event of danger, exchange of safety signals between the machines

■ Control of the system in case of communication failure

The production network, also called the *plant* and the factory, or IT, network must be physically separated. This is not only because both networks are operated by different organizational units but also because the purpose and availability of connected network components can be very different. The effectiveness of production and the linked automation components is measured by a predefined output. Linked components in the IT world, for safety reasons above everything else, always should be kept up to date. If the same IT rules of the location were to be applied to the production environment, the permanent update routines could interfere with the production process, and the achievement of the daily or weekly goals would be affected. Yet this does not mean that production poses a security risk. Other mechanisms should come to bear here, such as clear access rules, firewalls, and routers with appropriate restrictions, in order to ensure a trouble-free production process. Experts recommend defining clear rules for IP addressing and access control already in the planning phase and reconciling these with suppliers.

All machines that should be visible in the factory network should be directly integrated into the factory network. This is always necessary if the productivity of the machines or the linked system is to be monitored on the basis of operating data. Only if all relevant productivity data are recorded can the staff react accordingly on the basis of the evaluations.

Modern installations, however, not only deal with production data that can be exchanged from “below” to “above” and vice versa, but there is also the possibility of horizontal communication, meaning the exchange of standard and safety signals of the central processing unit (CPU) controllers with each other. By diligent planning, the wiring effort can be reduced even further so that subsequent changes through parameterization can be more easily implemented. Given this high degree of networking, certain scenarios should be run through so that in case of an emergency, such as a communication failure, the system can be brought back into operation quickly.

TECHNICAL CHARACTERISTICS OF FMSs

To satisfy the stringent demands of automation, FMSs must possess the following technical characteristics for the machining of prismatic parts:

■ Multiple CNC machines must be suitable for use in FMSs, usually FMCs, the size and quantity of which are appropriate for the quantity and range of parts being machined.

■ A sufficient supply of raw material or blanks must be ensured so that the system can operate with minimum of personnel or without human operators for a limited time or as long as possible.

■ An automatic workpiece handling system must manage and transport the parts from the time the unmachined parts are clamped until the machined parts are unclamped.

■ A direct numerical control (DNC) system is necessary for automatic management and preparation of the CNC programs and the correction values for tools and fixtures.

■ Automatic tool management must collect and keep all tool data and correction values and must resupply spent tools.

■ Automatic chip removal is needed for each machine.

■ Automatic cleaning of workpiece, clamping device, and pallet is necessary in the processing machines or in separate cleaning stations, followed by drying with compressed air.

■ They must have host computers, measuring stations, central monitoring, manufacturing/production data acquisition, and error diagnosis systems as needed and specified

■ Parts must be machined with high process reliability.

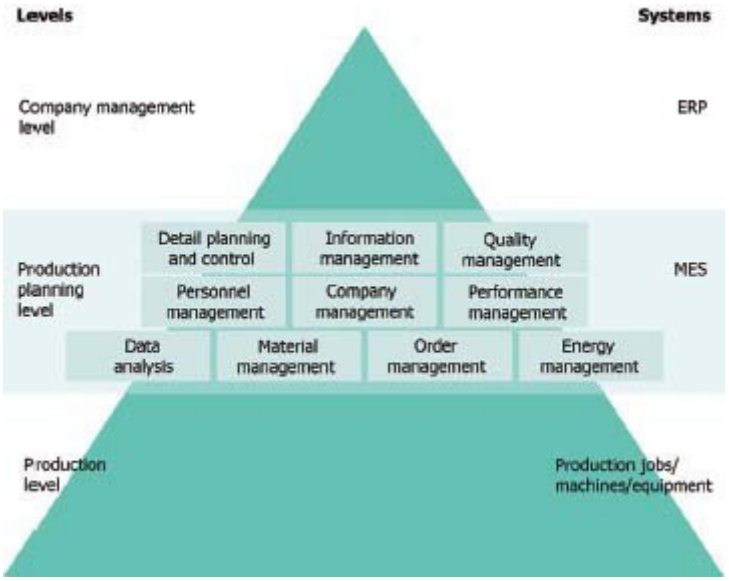

FIGURE 16.6 MES pyramid illustrates the basic MES concept. VDI.)

Despite their great technical sophistication, currently installed FMSs have limitations, particularly in regard to:

■ Size, weight, shape, and material of the workpieces that can be machined

■ Type of machining operation to be performed (three, four, or five surfaces, inclined surfaces, drilled holes, and technologies)

■ System output, that is, number of products per hour

■ Type and quantity of the available special tools

■ Accuracy requirements of the machined workpieces

Eight MES tasks are defined whose interaction allows the described comprehensive support of the manufacturing/production process. However, the concrete character of an MES does not have to include all eight tasks, but its scope of operation has to be adapted to the requirements of the user.

APPLICATION CRITERIA FOR FMSs

FMSs have especially proven their worth in situations involving products that can only be manufactured in small to medium-sized quantities at production startup and in the subsequent manufacturing of replacement parts This is illustrated with two examples.

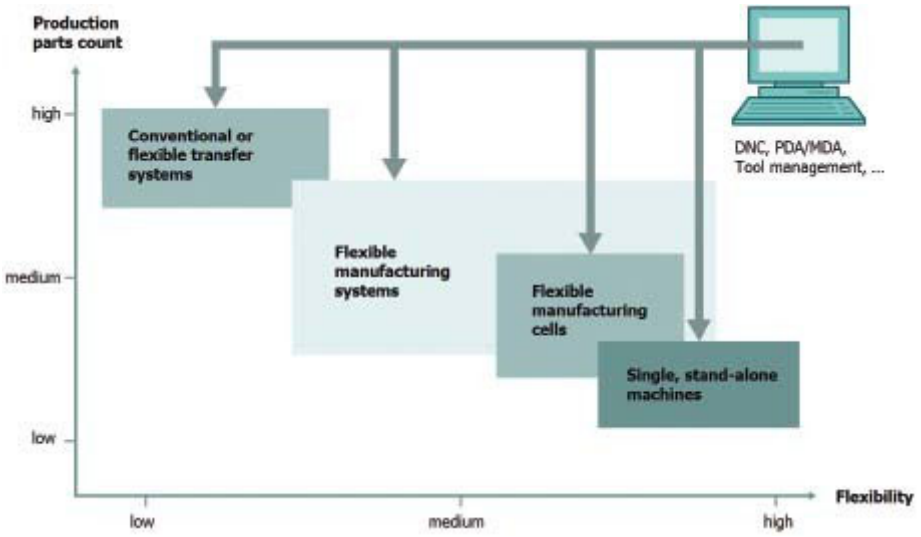

FIGURE 16.7 Criteria for using flexible manufacturing subject to volume requirements and degree of flexibility.

Example 1

A plant is manufacturing pneumatic cylinders with four different diameters. The customer can choose the length in millimeter increments, ranging between minimum and maximum values. From the very start, it has proven too costly to maintain an inventory of all possible designs. It was necessary to develop a system that would allow production to fill orders within 24 hours of receipt so

that the product could be shipped on the following day. An ideal solution to this problem was found: the cylinder body, piston rod, and tension adjustment screws are now combined, manufactured, tested, and picked on an order-by-order basis. The pistons, covers, and nuts are provided as standard series parts at the assembly stations. Because of its success, this production principle has also been applied to other products.

Example 2

Another plant had to prepare a series production process for a new product that was still in development. Relatively large production quantities were expected immediately after the product was introduced on the market, but many variations of the product would be required. It also was known that the part model would change considerably during the period of approximately 18 months that it would take for the machines to be delivered. Manufacturing on single-purpose machines or transfer lines was ruled out from the beginning because it would have been necessary to constantly adapt the machines to the changing specifications and machining methods. The solution was an FMS consisting of multiple standard machining centers. This allowed design modifications and variations to be accommodated without difficulty. Transfer lines and rotary index machines were installed to produce the required quantities, which increased rapidly after the introductory phase. The FMS continued to be used to its full capacity for a number of years to produce special designs in small quantities.

This use of flexible manufacturing systems, ranging between single machines and transfer lines, is clearly illustrated in Figure

This range has widened considerably after years of positive experiences with the FMSs.

The planning of an FMS begins with an analysis of the parts that are expected to be produced based on their sizes, weights, material composition, required quantities, lot sizes, and range of variations. This analysis will determine the necessary machining methods, the number of tools required, and the machining times. The type, number, and size of the required machine tools can be found on this basis. The clamping method, the sequence of machining operations, and the number of CNC axes that will need to be controlled are determined at the same time.

Each FMS should be custom tailored for the user while making best possible use of standard components. Not just the parts currently being planned for production but also the user's future projections and production strategies should be taken into consideration.

The integration of existing CNC machines into an FMS is possible, but in the interest of a standardized, uncomplicated approach, it should not be treated as an absolute requirement. On the other hand, conventional, manually operated, or mechanically programmed machines cannot be integrated into an FMS. This is prevented by these machines' lack of pallet-changing devices and the rigid method of programming that does not allow automatic modifications. Under certain conditions, however, it may be practical to use special single-purpose CNC machines, such as drill-head changers, face-milling machines, or special machining units. Therefore, FMSs are not new machines but a combination

of components that are already available: machining systems, automation systems, and information systems.

MANUFACTURING PRINCIPLES

Various basic options exist for machining groups of related parts on CNC machines. These are:

■ *Complementary machining operations performed consecutively on multiple machines in multiple setups* This requires a certain amount of space between the machines for the purpose of intermediate storage of the semifinished parts. It also entails repeated clamping and unclamping of the parts, which impairs accuracy. There is also the risk that the breakdown of a single machine could bring the entire production operation to a halt.

■ *Complementary machining operations, cycle-driven and performed consecutively on multiple CNC machines in a single setup* This is a possible solution when many tools are required. This solution also eliminates the need for pallet park stations or workpiece storage locations between the machines. Complementary machining + *B* + *C* + requires that the CNC programs be broken down into multiple individual programs with standard machining times in order to prevent idle time on individual machines. If one machine breaks down, however, there is the same risk as depicted in Figure

■ *Final machining in a single setup on one or two machines* This can involve complementary machining + or complete machining This makes it possible to achieve greater accuracy and reduce idle time. Without automatic workpiece transport, workpiece storage

locations would be required at each machine. This is the typical area of application of stand-alone CNC machines— usually machining centers, double cells, or turning cells. Unnecessary downtime can be prevented by providing automatic workpiece changers at each machine.

■ *Finish machining in an FMS with automatic workpiece transport* This is suitable for the simultaneous production of multiple, possibly dissimilar workpieces in any desired lot size. It is important for the appropriate CNC program, tools, and clamping devices to be present each time the workpiece is changed. The supply of workpieces is prepared for processing and then provided at multiple shared-pallet park stations for easy access. This approach is suitable for either complementary machining on two or more machines + or complete machining Most modern FMSs are based on the principle represented in Figure

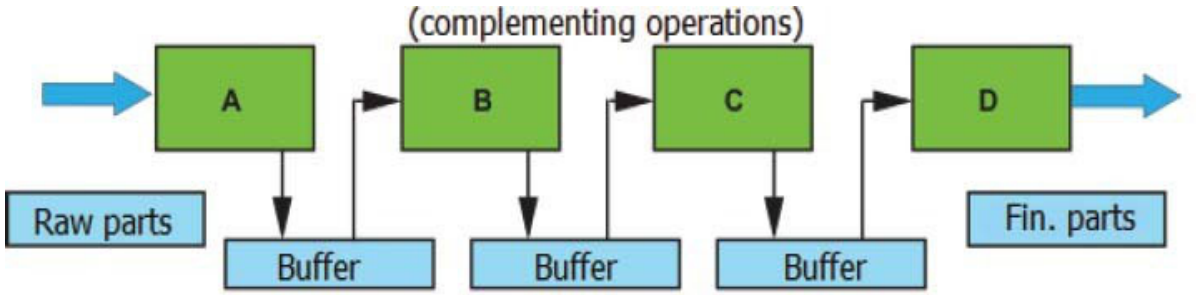

Figure 16.8a: Complementing processing on NC machines and conventional machines

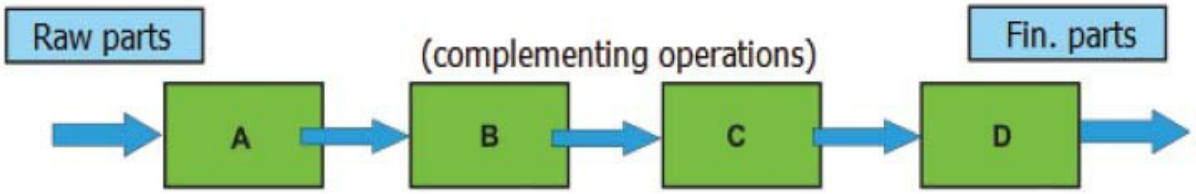

Figure 16.8b: Processing on a flexible manufacturing system with "complementing machines"

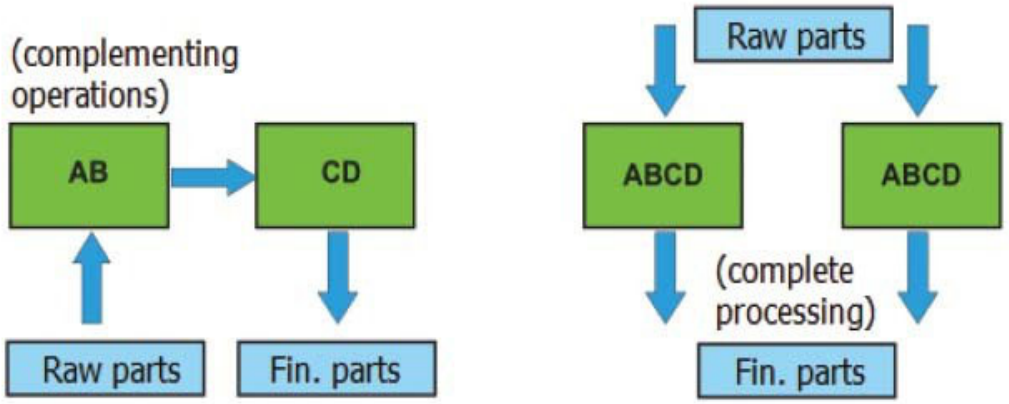

Figure 16.8c: Manufacturing on fabrication systems without automatic workpiece transport.

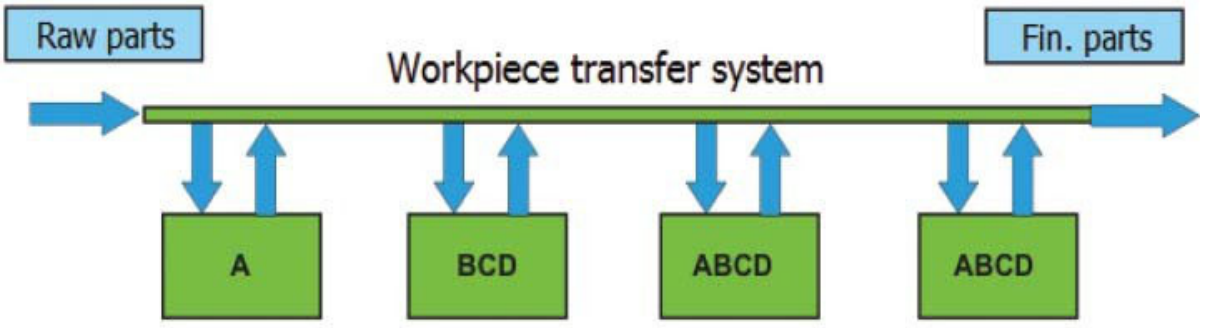

Figure 16.8d: Manufacturing on fabrication systems with complementing machines and different process principles, depending on the workpiece group, and automatic

workpiece transport.

FIGURE 16.8 Manufacturing principles of chained and nonchained machines: and *D* depict the various operations performed on workpieces, such as milling, drilling, reaming, and tapping.

MACHINE SELECTION AND LAYOUT

Machine tools are selected based on the size of the workpiece and the machining operations that must be performed. The FMS can consist of either universal machines (e.g., machining centers or FMCs), single-purpose machines (e.g., multiple-spindle drill-head changers or milling units), or special machines depending on the selected manufacturing principle (see Figure Sometimes it is also necessary to combine machines from different manufacturers. A prerequisite for this is that all machines are able to use the same tool holders, pallet changers, and table heights. The prerequisite is that all the machines are equipped with a CNC system that is suitable for use in FMSs.

An experienced manufacturer should be given the task of planning and designing the overall system. This manufacturer will also assign the orders to the subcontractors and ensure that standard interfaces are used. This keeps the responsibility for the proper long-term functioning of the overall system in experienced hands.

The general contractor also should be responsible for planning the cleaning stations, measurement systems, and reversible clamping devices that will be integrated into the system, the transport system (including the pallets), the setup stations, and the clamping devices. An FMS task force drawn from within the buyer's own company should work together very closely with the individual manufacturers. This task force should detect planning

errors in a timely fashion and use a high-performance simulation system to carry out a very close examination of the operating sequence that eventually will be used. The procurement of a suitable CNC programming system and the programming of the parts to be manufactured also can begin at this time. The FMS should be able to start production immediately after it has been installed.

Based on the experience gathered so far, it seems advisable to use standardized machines and CNC systems to the greatest possible extent and to avoid ordering any custom solutions from manufacturers. As more and more dissimilar machine types are integrated into the system, it becomes increasingly difficult to continue production when one machine breaks down. As a rule, the machines that are still functioning properly should be able to take over the work of the machine that is down without great difficulty so that production can continue, even if output may suffer somewhat. The principle of the self-replacing machine is best suited for this scenario.

As far as the required degree of flexibility is concerned, no machine should be designed to be used exclusively for one particular workpiece. Each machine in the FMS must offer universal or flexible applicability, requiring only a change in tools and CNC programs. This is the only easy way to adapt manufacturing operations to changing market demands and design modifications. Any special-purpose machines in an FMS must not be allowed to become a bottleneck that could be difficult to bypass. This will also allow the system to be expanded more easily and affordably later on.

WORKPIECE TRANSPORT SYSTEMS

The planning of an FMS usually begins with a basic determination of the most suitable workpiece transport system. Once the number and types of machines to be installed in the FMS are determined, the machines' layout and connection to the transport system are planned in detail. In many cases, the amount of available floor space is already given and is usually too small to allow much freedom to experiment with different layouts. The workpiece transport system will be based on the available space.

The automatic conveying of workpieces from the clamping station to the machines and back again represents an important component of an FMS. This is usually accomplished with machines. The clamping devices, which are fastened to the pallets, hold the workpieces precisely; standardized pallets transport the parts, as well as inserting and removing them at the predetermined positions. The number of pallets in an FMS is limited by the number of pallet-transport locations and part stations plus the number of machining stations. The use of multistory double-sided shelves and appropriate handling and retrieving systems allows the storage of all components needed for the fabrication. These storage systems have a small footprint, and stored items can be retrieved on short notice.

The clamping and unclamping of the parts in the fixtures are usually performed manually. Relatively small parts can be clamped in multiple fixtures in order to reduce the overall machining time. This method also can be used to combine the first and second setups of the parts in a single fixture, should this prove to be advantageous.

Hydraulic clamping fixtures are used a lot, for example, to standardize the clamping operations and keep them consistent.

Setup and loading stations are basic components of an FMS. Ergonomic solutions take into account the needs of operators and make their work easier. This also requires good accessibility to the pallets/devices/workpieces, for instance, by automatic lowering, tilting, and turning. Accident-prone platforms and ladders must be avoided.

A coding device on the pallet or the fixture allows the recognition and identification of the workpiece that is currently clamped on a particular pallet or fixture. This device is "read" electronically before processing begins on the machine, and the code is compared with the CNC program that has been prepared for the machine. The "go" for machining is contingent on the results of this comparison. This device generally can be omitted because transport control can reliably assume the tasks of management, error-free conveying, and identification at the machines.

From both technical and economic standpoints, the transport system represents an essential part of the overall system. It is therefore very important to devote sufficient attention to planning the sequence of functions so that unnecessary corrections, costs, and travel can be avoided.

Transport systems have to meet high requirements, some of which are as follows:

■ High speeds must be available. Rail systems should reach 240 m/min and more.

■ Control of several transport trolleys is necessary.

■ Quick docking and changing of pallets are mandatory.

■ Manual intervention must be available in the event of malfunctions.

■ Efficient, reliable, and secure transport of the pallets to the individual stations is a must.

■ Compliance with safety requirements is required, for example, as in collisions, unexpected obstacles, power outage, and control errors.

■ Operation must occur with lowest possible costs for hardware, software, assembly, maintenance, control, and functional safety.

■ For permanent assurance of the machining accuracy of the workpieces, the pallet guide and indexing must not be subject to wear due to the transport and through the changing hardware.

■ No wait time of the machines is allowed because of missing pallets. This can be tested before production commences by a simulation system.

■ Setup and clamping stations must be designed in such a way that changing the clamping devices and workpieces can be carried out quickly and easily.

■ The transport system should be easily expandable to integrate additional machines.

■ Maintenance and repairs must be performed with short downtimes.

■ If possible, the tools for the tool changer should also be able to be transported to and from the machines in order to save an additional tool transport system.

Selection of the Transport System

Various transport systems are available. The proper selection depends on the workpiece dimensions and weights as well as the machine layout.

Linear rail-guided transport systems are used most commonly These systems save space and offer high-speed travel. Each of the vehicles can be equipped with one or two pallet locations, as desired. They also make it possible to arrange the machines on either one side or both sides of the track. The track can be extended easily for the purpose of expanding the system at a later time.

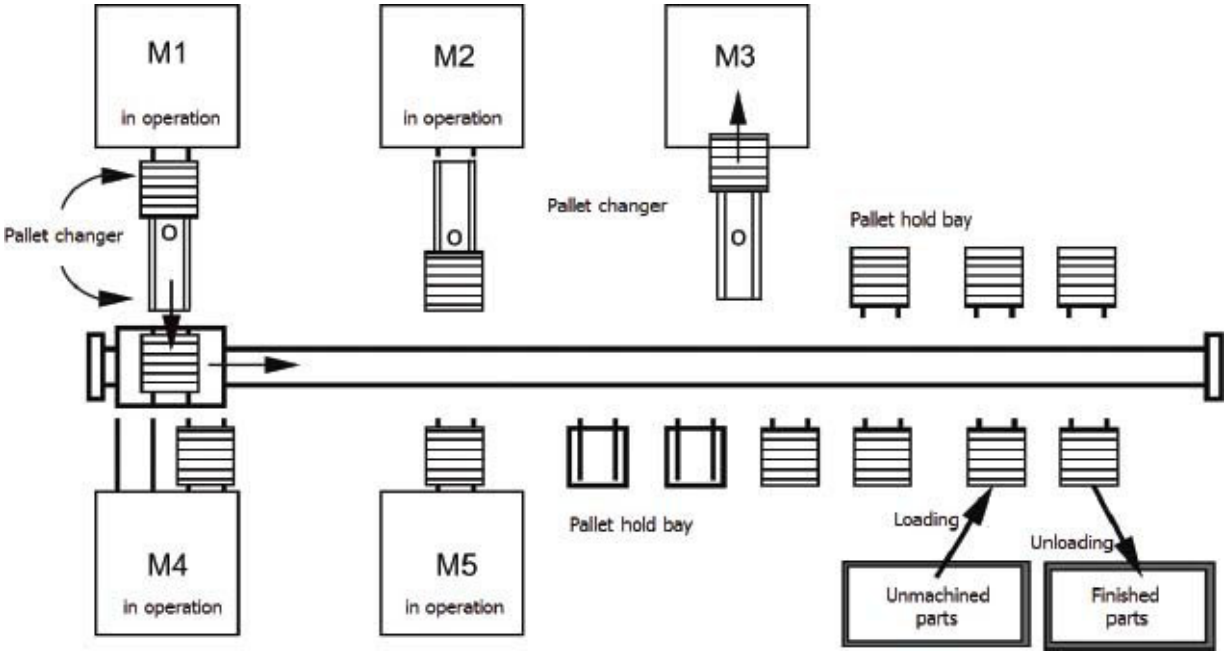

FIGURE 16.9 Linear rail-guided transport system with parallel arrangement of machines on both sides of the conveyor track. *Characteristics:* The vehicles feature one transport location. A vehicle can be equipped with two transport locations, as needed, or a second vehicle can be added, and the transport control can be modified accordingly. The prepared pallets are parked at storage locations and picked up by the vehicle as needed. Machines 1 to 3 are equipped with pallet changers. Machine 4 has one fixed loading station and one fixed unloading station. Machine 5 is equipped with only one changing station. This gives rise to various strategies for executing the changes.

Pallet circulating systems known from automatic assembly technology using double-belt conveyor systems are suitable for smaller workpieces of medium weight. Here the transport pallets carry parts that are clamped on fixtures and pass them over to the machine. The pallets are waiting outside the machines and take back the machined workpieces for further transport. For multimachine processing, the workpieces must come back to their original carrier

pallet if the part-specific code specifies that other workstations must process the part. Larger pallets require more elaborate transfer stations.

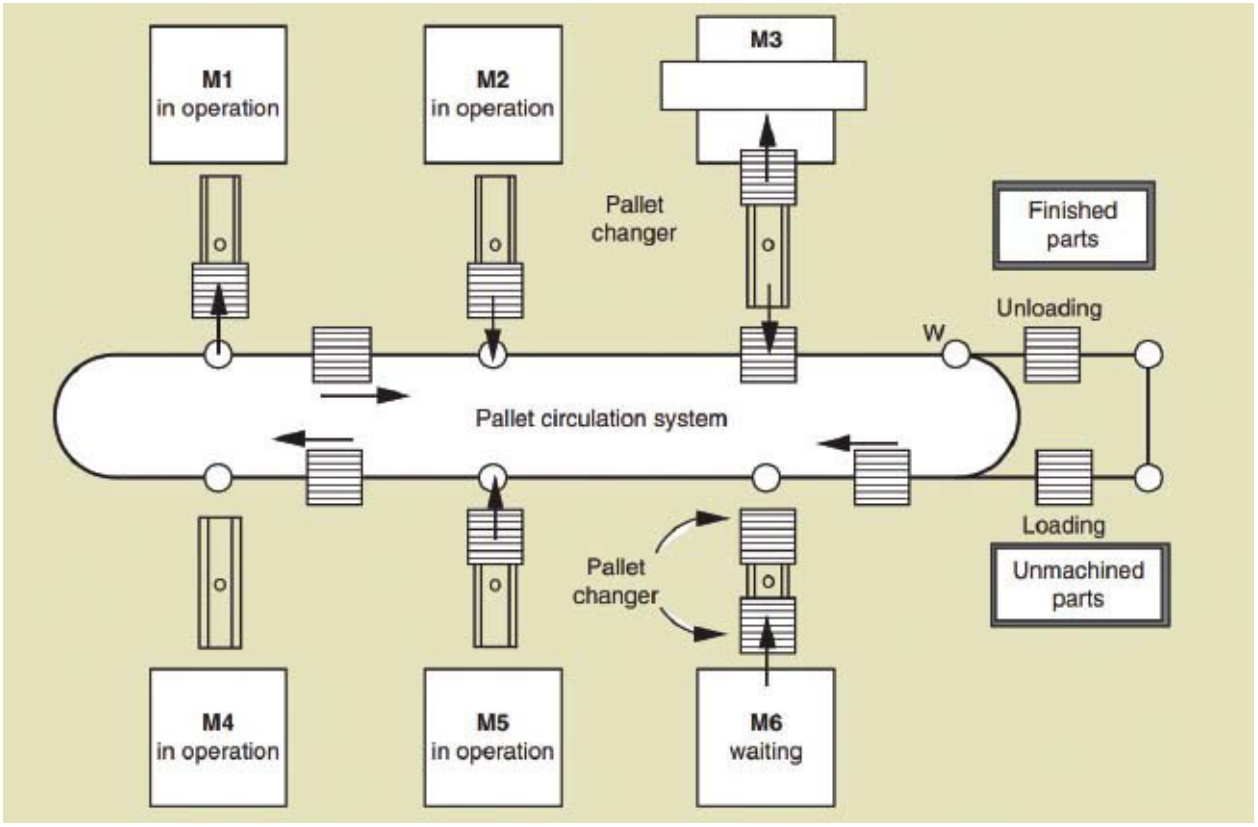

FIGURE 16.10 Pallet circulation system with parallel arrangement of machines on both sides of the conveyor track. *Characteristics:* No additional pallet storage locations are provided. The unmachined workpieces circulate in the transport system until the loading location of a pallet changer is free. The pallet changers at the machines also serve as loading and unloading buffers, holding one pallet that is ready for machining and one pallet that has already been machined, respectively. After exiting the machines, the machined pallets are automatically brought to the cleaning station and then to the loading and unloading stations on switch

Also available are mass-produced roller-conveyor systems where the pallets are transported on powered roller tracks by means of friction. However, they are not widely used. Multiple track segments can be assembled to give the overall track the desired form. The conveyor height and track width can be adjusted as needed. The load-carrying capacity can be as high as 750 kg/m, and conveyor speeds can be selected from a range of about 1 to 12 m/min. The drive system consists of a geared electric motor. The function of roller conveyors using roller chains is similar. In this case, roller chains move the pallets. Switches or pivoting devices provide for the change of direction in curves. However, under-floor drag-chain conveyors are now obsolete owing to the excessive cost of installing and repairing them and their great susceptibility to breakdown.

Driverless carts, also known as *automated guided vehicles* of various sizes have proven their use in applications involving relatively large pallets or heavy workpieces Operating with radio control, these vehicles follow a wire embedded in the floor. Track switches and queue stations also can be built into the system. Modern AGVs are controlled by GPS systems or optical beacons. They use existing infrastructure and can reach almost any location in the work area. Existing machines can remain in place on their expensive foundations; relatively remote material and tool storage facilities also can be integrated into the material flow. For reasons of safety, the speed of these vehicles is considerably slower than the speeds attained in linear rail-guided transport systems. So it is quite common to have several vehicles underway at the same time.

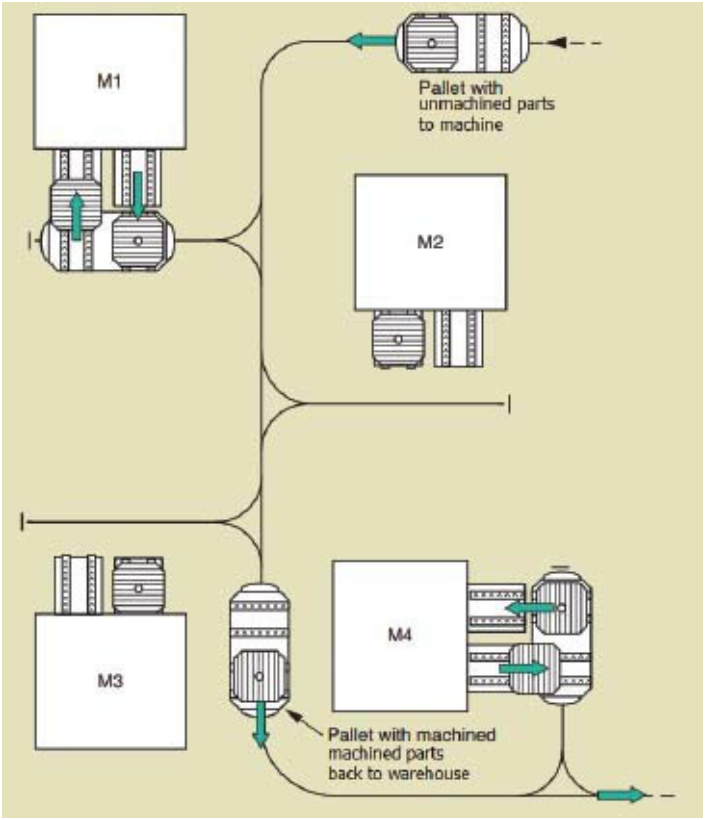

FIGURE 16.11 Surface transport systems with AGVs use the existing traffic routes. The cars are radio-controlled by a wire in the ground. *Indicator:* The machines can be distributed anywhere in the available space. The cars travel in "one-way traffic" from the stock room to the machines and back. There they are unloaded and loaded with new workpieces. The driving speed is limited for safety reasons.

Concerning lathe cells, parts are usually supplied and retrieved to and from the chuck with the help of parts-handling units, gantry-type robots, or floor-mounted robots. Another alternative is the use of machines that feature a vertical design and do not require separate handling units.

Sequence of Linear Transport Systems

The core of an FMS is a transport system that functions intelligently, thus providing transport control. In contrast to systems involving

circulating pallets, FMSs with linear rail-guided systems and those equipped with carts require central control. The selected transport strategy must be adapted to the conditions that currently exist in the system. In other words, the logistics change accordingly as the task at hand changes from startup to normal operation to changeover and finally to operation under reduced loads, as production tapers off. Below are the functions in the regular operation of an FMS

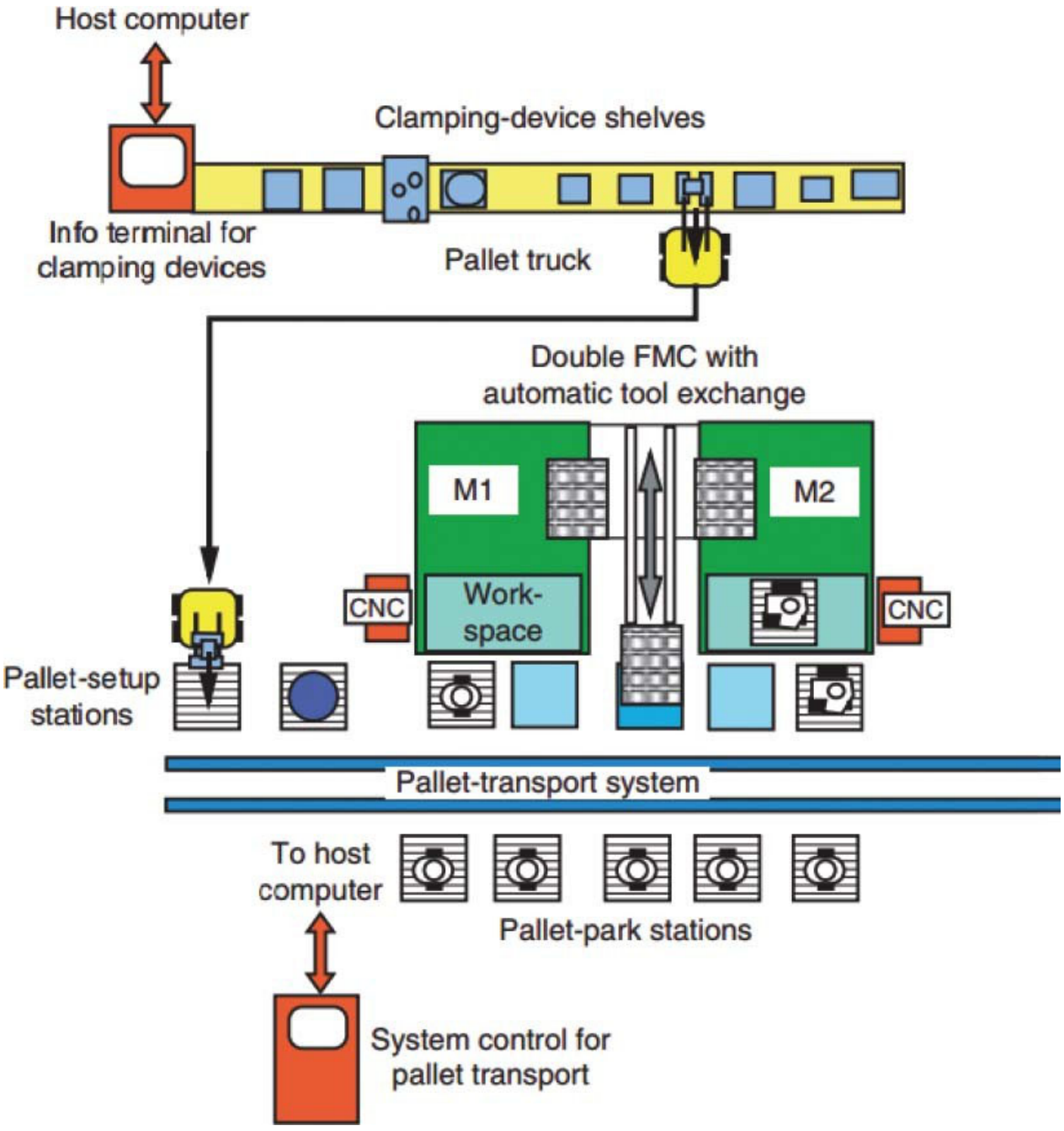

FIGURE 16.12 Typical system layout of an FMS. *Characteristics:* The machines are placed on one side of the transport system, thus providing good access for maintenance and repair work. The pallet parking spaces are located on the other side of the rail track; thus short distances are realized at optimal occupancy. The flexible double cell is supplied with tool-replacement cassettes. A gantry robot takes care of the tool handling for the two machines (M1 and M2).

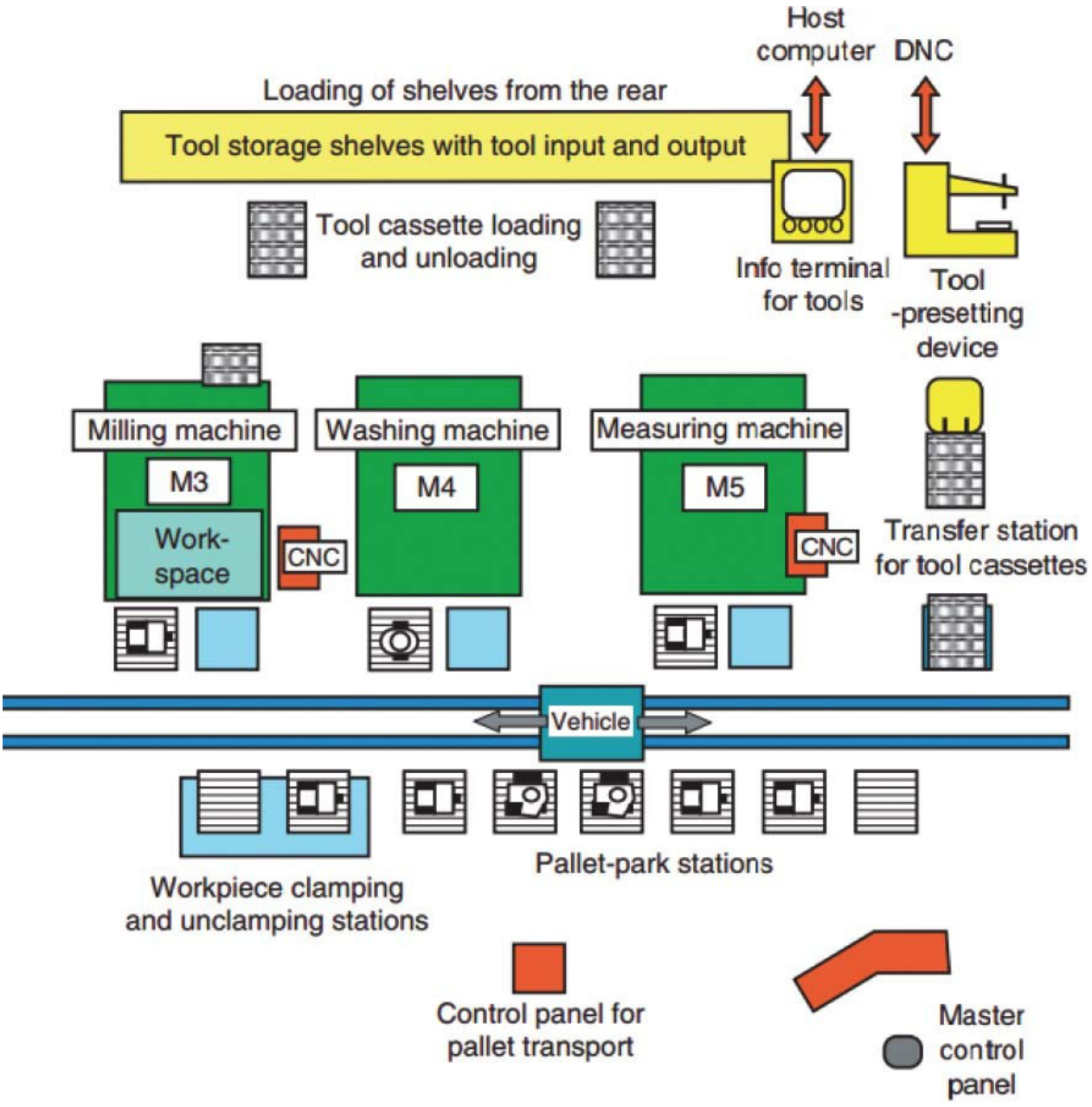

FIGURE 16.12 The pallet parking spaces are located on the other side of the rail track; thus short distances are realized at optimal occupancy. The flexible double cell is supplied with tool-replacement cassettes. A gantry robot takes care of the tool handling for the two machines (M1 and M2).

Several different workpieces are ready to be picked up from the pallet park stations. The machines are working, and the transport vehicle is positioned to wait for its next task. One machine operator is stationed at each of the two clamping stations. This operator will remove the machined workpieces from the clamping devices and then perform the clamping of new, unmachined parts.

All machines include two pallet transfer stations. The station on the left is intended to receive the unmachined workpiece as it arrives. The one on the right holds the machined workpiece that is ready to be picked up. Alternatively, revolving pallet changers are used. Each machine in the FMS can be programmed with the CNC program for the machining of all the workpieces in the system and is also equipped with the tools necessary for machining them. A cleaning station (M4) and the measurement system (M5) are also integrated into the system.

The automatic sequence is performed according to the following strategy: machine 2 has finished the machining operation and has parked the pallet at the changing station on the right. Next, it picks up the pallet to the left for processing.

Two messages are issued to transport control:

■ Bring a new pallet.

■ Pick up the finished pallet.

The transport control system works as follows:

■ It “knows” which workpiece has to be conveyed to M2 (this information was entered and stored before machining began).

■ It “knows” where this workpiece can be found (the transport control has already parked this pallet and saved the station number).

■ The transport vehicle first travels to the appropriate park station, where it docks and receives the pallet.

■ The vehicle travels to M2 and transfers the pallet to the unoccupied changing station on the left.

■ The vehicle then takes the machined pallet from the changing station on the right and transports it to the cleaning station. Here all workpieces must be cleaned and dried. If M4 is not accessible, the vehicle parks the clean pallet on an available spot.

■ At M4, the vehicle picks up a clean pallet from the changing station on the right (if one is available) and transports it to the measuring machine. If a measured workpiece is present at the “out” spot, it will be transported to an open clamping station. There it will be manually unclamped and deposited with the finished parts, provided that the measuring machine has issued a “Good Part” message.

■ After a blank has been clamped, the operator presses a “Pick up” button or key.

■ As soon as the vehicle is free, it will pick up the pallet and park it at an unoccupied storage location.

These operations are repeated continuously in a seemingly chaotic sequence. Each motion is recorded in a table within the control system. The table is preserved in the event of a power failure, allowing a trouble-free restart after power has been restored. Pallets that have been parked temporarily are automatically fetched by the vehicle as soon as the loading station at the destination machine is free. All of this applies for normal, trouble-free operation. In reality, the transport control system is constantly receiving new signals from the individual stations, indicating that workpieces should be picked up from them or delivered to them. These orders are stored, prioritized, and executed according to a predetermined strategy and the programmed priority. Without a doubt, the first priority is the operation of the machines. In other words, new workpieces must be delivered to the machines, and their unloading stations must be emptied. If a finished workpiece is ready to be picked up at an unloading station and the vehicle is free, then this particular order can be executed even if there is currently no workpiece to bring to the loading station.

The commands for tool change and pallet changeover mean additional logistical tasks. These are as follows: the pallets that require changeover must be removed from circulation; pallets with replacement tools must be brought to the changing stations that are

provided for this purpose and then picked up from these stations again; and so on.

When a single machine or the entire system is unloaded, the logistics change again: workpieces are picked up from the machines but no longer are new parts supplied. However, the cleaning and measuring machines must continue to operate. As the operation of the system is winding down and unmachined parts are no longer available for a given machine, the machine is shut down. For example, the machine may time-out after failing to find a pallet at the loading station for a set period of time. Once all the workpieces have been machined, cleaned, and measured, the entire system will power down.

From this account, it becomes evident that when working with relatively large systems, it is absolutely essential to perform simulations at an early stage. This will prevent unpleasant surprises and costly modifications later on. Next, strategies are modified, conveyor speeds are raised to the limit, and other remedial measures are identified. Vehicles with two storage locations reduce idle time because they allow two pallets to be exchanged simultaneously in a single docking and positioning operation. Another alternative is to employ a second vehicle and then coordinate the travel commands issued to the two vehicles so that collisions are avoided.

CNC SYSTEMS SUITABLE FOR FLEXIBLE MANUFACTURING

High-performance CNC systems are an essential requirement for the trouble-free operation of an FMS. In order to allow automatic and sometimes unmanned operation, CNC systems that are suitable for use in FMSs must have several special functions, such as the following:

■ A large data-storage capacity, allowing temporary independence from the DNC computer, is necessary. A large amount of storage capacity is also required for tool compensation values, zero-point compensation values, compensation for differences in clamping adjustments, and tool data management.

■ Powerful management of the stored data is required so that the entire set of data can be updated, displayed, checked, and corrected at any time. It should be possible to perform these actions at the CNC machine from a central controller or central host.

■ If multiple CNC programs are stored in the CNC system, each program must be capable of being retrieved individually by an external command and started automatically when operation is ready to begin.

■ Uninterrupted operation requires tool management within the CNC system for replacement tools and twin tools, including tool life monitoring and automatic assignment of the respective compensation values.

■ There must be a provision for assigning various compensation values to each tool depending on the program. This will make it possible to use the tolerance range that is specified for a given machining operation.

■ There must be provisions for inspecting the machined workpieces by means of measuring probes and the special measuring programs that are stored in the CNC system. After processing the measurement, a “Good Part” or “Bad Part” signal must be issued.

■ A powerful data interface is necessary that connects to the DNC system and allows bidirectional data transfer between the DNC computer and the CNC system.

■ Pallet or workpiece management functions must be included in the transport control system so that processing priorities (i.e., the sequence of pallet retrieval) can be defined. A status display must be provided to indicate the general status of all workpieces, such as machined/unmachined/machining interrupted and so on.

■ Automatic manufacturing and production data acquisition (MDA/PDA) within the CNC system involves the recording of all problems that occur during the unmanned shift, reporting of interrupted machining operations, and the constant provision of information regarding the statistic utilization rate of the machine.

■ Provisions must be possible for activating the reduced feed rates for nighttime operation with reduced output.

■ When individual components of the FMS break down, emergency strategies must be in place so that operations can be maintained with the system components that remain intact.

■ In case of a malfunction, a text message and email must be sent out automatically to a defined group.

■ Ethernet interfaces in FMS systems today are needed not only to exchange data between the machines but also as an interface for the acquisition of process and production data. This wealth of data, also known as *big* is increasingly being used in cloud-based systems. Analysis of the data is used to increase productivity, energy efficiency, and other measures to optimize production.

HOST COMPUTERS IN FMSs

The task of the host computer is higher-level control and monitoring of the individual components in an FMS. Today, an industrial desktop PC or laptop with a standard operating system and additional software for the specific host-computer functions is an adequate solution. In the case of large quantities, the material flow in the FMS is controlled via a central host computer, which is networked with the individual production cells. In large-batch production, the host computer processes are distributed over several servers, which are managed by a separate IT department.

FMS process-control functions can include the following tasks:

- Visualization of the overall system
- Control of the background processes
- Updating of the databases
- Error messages and DNC functions

Other functions include tool management with a link to tool presetting and integration with the production planning system (PPS). Data networking takes place via field bus systems and the input-output (I/O) level of the PC networks by means of Ethernet and transmission protocols via TCP/IP.

In principle, it is possible to design an FMS to work without a host computer. This essentially applies to automatic manufacturing processes, that is, pallet delivery, machining, and pallet parking. This can be accomplished using automatic workpiece transport control. All other organizational tasks connected with the FMS then have to be scheduled, monitored, and executed promptly by manual means so that waiting times are not caused by missing parts, tools, clamping devices, or other potential sources of problems. This essentially defines the important coordination tasks that are transferred to a higher-level host computer. These are determined by the system's layout and degree of automation. They may contain the following functions

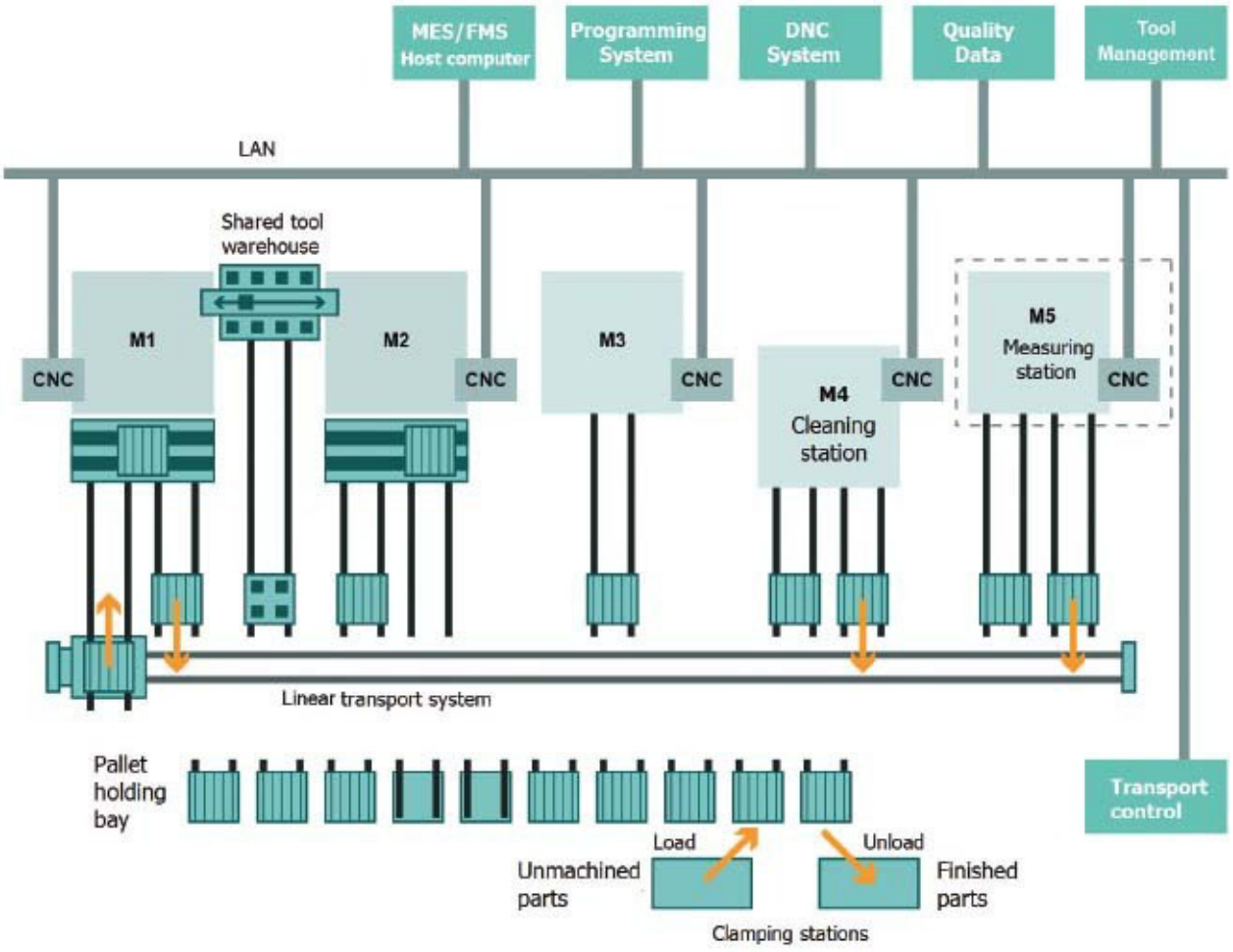

FIGURE 16.13 Principle layout of data management of a linear transport system.

■ Receipt of production orders, including production quantities and deadlines, from the PPS and following up by means of feedback messages

■ Machine assignments in normal operation, taking into account the current tooling, that is, when jobs change, which machines would require the fewest tool changes

■ Machine assignments for rush orders but without complete removal of the currently running orders from production

■ Preparation of pallets for changeovers to different clamping devices (e.g., quantity, deadlines) and preparation of clamping devices

■ Provision of raw material or blanks given that the PPS has already determined that enough blanks are available

■ Retrieval of the necessary tools, such as custom, special, and serie-stools, including tool data and their availability at the machines

■ Issuing of a tool difference list as output to the tool-setting shop, indicating the tool changes that must be made for each machine

■ Instructions to the DNC computer to make the appropriate CNC programs ready for retrieval

■ Messages to the transport control system regarding the assignment of workpieces to the individual machines, identification

codes, and so on

■ Preparation of the associated measuring programs for a measurement system built into the system or for the machine's internal inspection function

■ Information provided to shop personnel regarding changes in production and the necessary preparations, status messages, and alternative strategies to be adopted in the event of machine breakdowns, deadlines, and production quantities

■ Visualization of the operating sequence on the host computer with advanced warning of foreseeable problems

At this point, fully automatic production of the new part can start. When a machine breaks down, the host computer adopts a prepared failure strategy to divert the part to another machine, provided that it is technically feasible and compatible with the PPS. The decision then must be made by the personnel.

Another task is the central monitoring of the system and its status via an analysis of manufacturing and production data. For this, the following feedback messages are relevant:

■ Machine ready for operation/running/waiting/malfunctioning

■ Machine being repaired/time-related information/reason

■ Machining enabled/suspended

- Pallet missing/in transit/ready/being machined
- Number of parts produced per lot
- Scrapped parts report: reason/machine/time
- Transport system ready for operation/malfunctioning

These and other types of data provide the information needed for informative status reports and valuable statistics from which tendencies and weaknesses also can be clearly derived.

ECONOMIC ADVANTAGES OF FMSs

FMSs offer certain economic advantages over alternative methods of manufacturing as a result of several system properties including:

TABLE 16.1 Reduction in Usage without Automation and Time Savings Owing to Flexible Automation (Theoretical Numerical Values)

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Values)
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Note: The use of production on Saturdays would bring an additional 14% time gain.

1. More complete utilization of the production installations with respect to both time and technology (This is accomplished by

means of greater automation, continuing operation through break times and weekends, tapering off operations in the second or third shifts, and low or no staffing.)

2. Increased productivity through fast, uninterrupted retrofitting to other production jobs

3. Reduced need for production space owing to elimination of intermediate storage areas and working surfaces at the machines, for example, use of high-stack storage

4. The ability to modify the CNC programs and thus adapt to geometric modifications of the workpieces and technological changes in the machining process

5. Fast response to market changes by means of flexible priority changes in production

6. Subsequent ability to expand and adapt to new tasks or greater production quantities

Individual, unchained CNC machines and flexible manufacturing cells are used primarily to produce small or medium-sized quantities of parts. However, lots of any size can be produced more profitably by chaining multiple CNC machines. This is accomplished primarily by avoiding machine waiting times and using the extra time that has become available through the use of an improved, forward-looking organization.

There is no generally accepted scale for evaluating the degree of flexibility. In other words, it is impossible to measure flexibility in absolute terms. It is only possible to compare the relevant production data for the same job with previous or alternative production concepts. Such production data include the following:

- Reduction of cycle times of parts
- Reduction of the inventory of semifinished parts
- Reduction of the inventory of finished parts by gearing production to specific orders
- Reduction of changeover costs, expressed as the time required to change over to a new part
- The number of possible changeovers per hour without machine downtime
- The ratio of productive time to changeover time
- The scope of parts to be produced by the FMS
- Higher utilization of the machines as a result of additional automation measures

After gaining initial experience in operating a new FMS, it is often possible to further optimize the system on the basis of employee

suggestions. Among these are optimized NC program sequences to minimize wait times or tool changes.

PROBLEMS AND RISKS IN THE DESIGN OF FMSs

The number of options provided by FMSs— and the problems encountered in implementing these systems—are undoubtedly too many to be described completely in this text. Overall planning must take into account the fact that the resulting FMS will have to produce parts flexibly and at costs that are in line with market conditions. The degree of system automation exerts a considerable influence here. Too much automation raises the investment costs very quickly, as can be seen in the example of a lathe In such cases, it is worth considering whether two machines with a lesser degree of automation would be more profitable. This requires several more or less expensive expansion stages. It must be analyzed in each case whether the additional cost is profitable or whether two less automated machines would be more economical. The percentages are only guidelines and contain hardware and software costs.

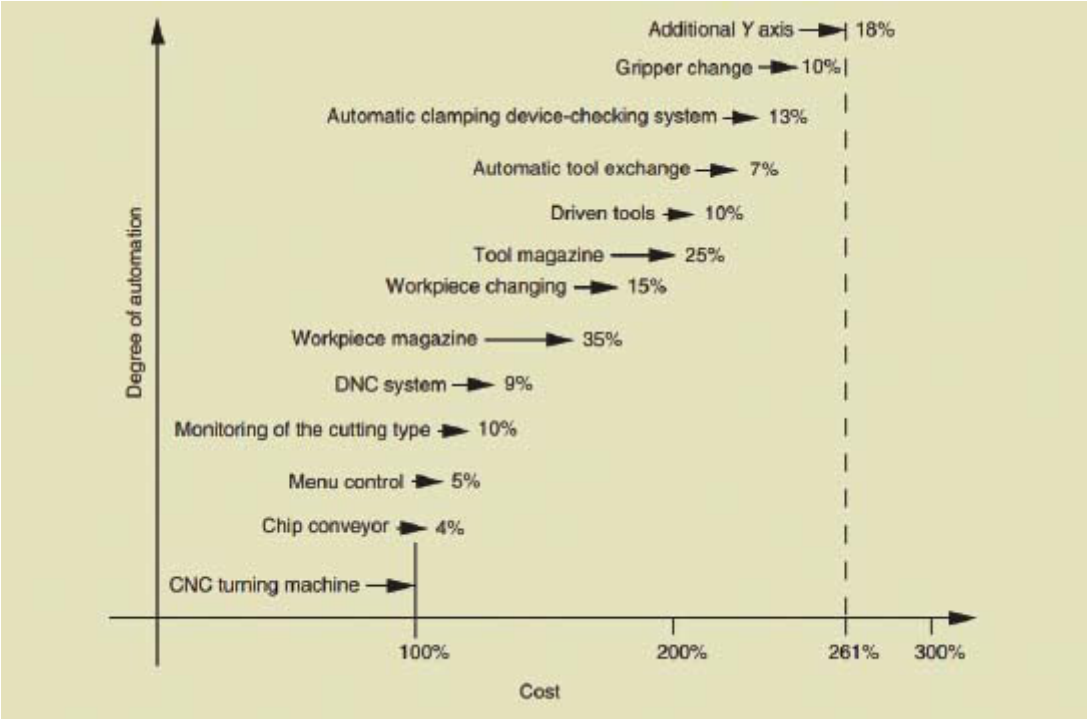

FIGURE 16.14 Additional costs for the expansion of a CNC lathe to an FMC.

Experience has shown that the maximum number of tools that can be stored on the machines is an important cost factor. To avoid having to equip all machines with expensive oversized tool magazines, the machining of parts should first be planned with the use of standard tools. If the number of tools remains excessive despite this approach, the best solution may be a central tool magazine for automatic tool exchange. When machining is performed on materials that reduce tool life to a few minutes, a constant supply of replacements must be ensured.

Temporary emergency operation of an FMS is also very difficult to implement. If the system is designed to use a host computer, its extensive set of coordinating tasks cannot simply be assigned to other systems, and the personnel certainly will not be sufficiently prepared to perform manual control of the missing functions.

The risks also include the great investment costs of a FMS. This results in a great financial burden in the form of fixed costs and depreciation, which have a negative effect on the operating result when capacity is not used to the fullest possible extent. In order to prevent this, substantial expenditures must be made as early as the planning phase. The productivity of an FMS must be calculated in such a way that the increased hourly cost of

operating the machines pays off in higher output, thus keeping unit costs down. Some of the arguments in favor of FMSs involve benefits that are difficult to prove from a commercial standpoint, for example, reduction of work-in-progress (WIP) and regular inventory. Other arguments are based on market-related benefits. It is important not to assign too much value to these arguments. All too often, FMSs have been saddled with manufacturing tasks for which they were not designed originally. Needless to say, some systems have been able to prove their flexibility in this manner. Over time, however, cost-effectiveness rules.

Because planners are guided by the requirements of each given situation, it is not uncommon for them to wind up with an entirely different type of system. For example, flexible rotary index machines can be used most profitably to produce relatively small workpieces in medium to large lot sizes

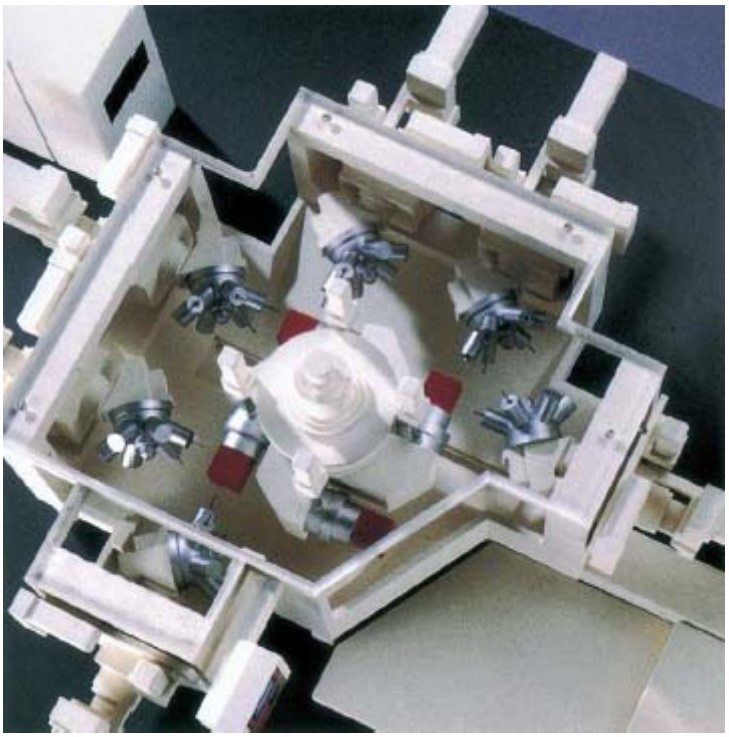

FIGURE 16.15 Special case of a flexible rotary index machine.

The figure shows a modular multistation machining center with optionally two to seven machining units for medium and large lot sizes. Four workpieces are held in the center of the machine in rotating clamping devices, which are indexed four times by 90 degrees, allowing the workpieces to be machined on five sides without reclamping. Two to four workpieces can be machined simultaneously with the spindles of the turret heads. Each turret head features either six or eight tool spindles. Because all the spindles turn together with the turret head, tool changing does not require a "Spindle stop" command. This makes it possible to change tools in approximately 1 second. Workpieces are changed (manually) during the machining time. The roller guides, motors, drives, recirculating ball screws, position-measuring systems, and so on are located outside the workspace. Because of the costs involved in programming and changeover, this machine is not suitable for small lot sizes or single-piece production.

FLEXIBILITY AND COMPLEXITY

Flexibility in manufacturing means being able to adapt to changing situations without difficulty. In terms of an FMS, this means that the overall system is tailored as precisely as possible to the range of products that must be manufactured and that the system must allow production changeovers without difficulty and with minimal time expenditure. Although, in principle, any part can be produced using an FMS, the range of related parts that will be produced should already be narrowed down during the planning phase. It is also necessary to confirm that the four most important preconditions can be met:

1. A sufficiently large group of related parts with an appropriate degree of similarity and sufficient quantities to allow the machines to operate at capacity

2. A number of machines that is as standardized and interchangeable as possible that can perform all the necessary machining operations without manual intervention or rework

3. A suitable workpiece transport system with automatic pallet changing and/or parts changing at the machines

4. Suitable clamping device, where the clamping of smaller parts using multiple fixtures is also possible

The FMS shown in Figure 16.16 consists of one or more machine tools that are coupled with a pallet container system. A user-friendly FMS is characterized by the ability to quickly adjust the production of products with short lifecycles. Changes thus can be made promptly. Scheduling and monitoring of the FMS can be done by the pallet container system. This reduces downtimes to a minimum.

FIGURE 16.16 FMS with pallet container system. Heller Company.)

The FMS shown in Figure 16.17 consists of three machine tools that are loaded by a robot. This combination can be used if the parts are too large for manual loading or need to be specially positioned in the machine.

These considerations raise the question of how to use multiple-spindle machines efficiently for simultaneous production of two or more identical parts. It requires larger, more complex, and more expensive clamping devices, possibly with additional rotational and swivel motions for five-axis machining. A reasonable range of parts

for an FMS can be easily exceeded, thus exhausting the available capital investment. This can possibly result in excessive production costs with a particularly serious effect on "simple" parts.

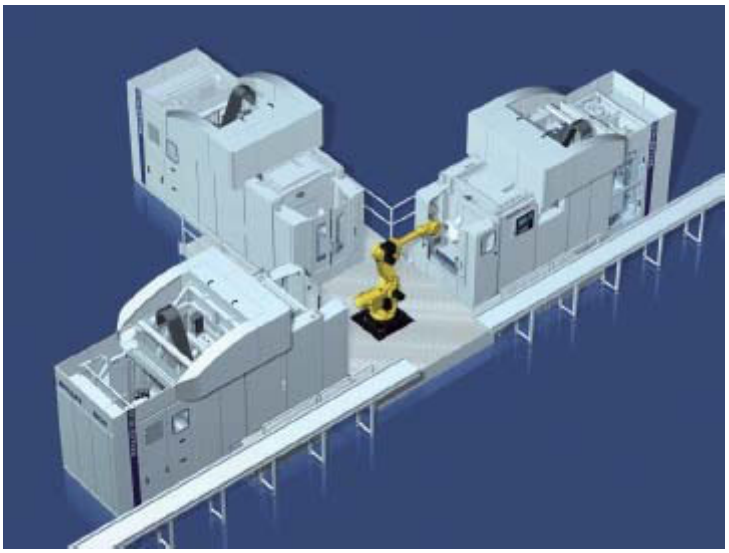

FIGURE 16.17 FMS with central loading robot Heller Company.)

Complexity of Products

Equipment and production costs are directly related to product complexity. To save costs, more and more production facilities are being modernized, automated, and computerized; personnel and warehouse costs are reduced. Nevertheless, the products still may be too costly if serious mistakes have been made in production planning.

If production and assembly facilities are planned too large, they also require a larger floor space, adding to production costs. In many cases, the system complexity that results from the technical planning phase is not necessary and should be reexamined for

appropriate savings potentials in the course of a second, economically oriented phase. The reasons for excessively large solutions can generally be found in overly ambitious planning objectives that far exceed the solutions that are actually necessary. Often design engineers do not adhere to the defined, carefully selected assortment of tools. This then leads, for example, to machines with overly large tool magazines and needlessly complex hardware. Therefore, every production operation should have its tools strictly subdivided into standard, series-production, and special tools with hourly rates staggered accordingly.

Flexibility in production is easier to achieve if the parts being produced do not pose any particular problems and if adequate attention has been paid to the subsequent manufacturing process, including the possible sources of problems. This is why it is in the interests of all responsible parties for the product—from the manager to the design engineer and the service technician—to make the overall system as simple and straightforward as possible. This will further a profitable, flexible, and economical production.

Fabrication Flexibility

Manufacturing flexibility is important in order to react quickly to changes of any kind. Appropriately applied, it must also lower overall costs. This can be achieved through a number of factors, such as:

- A well-structured organization

- Reduction of production and delivery times

- Adherence to deadlines
- Reduction or elimination of inventories
- Simultaneous production of different parts
- Production of different lot sizes
- Changing production priorities for rush orders
- Avoiding rejects and rework
- High quality standard
- Training and instruction of personnel concerning the capabilities and limitations of the system

This applies to all lot sizes in FMSs. These factors add up to overall cost savings, thanks to the capability for quick, uninterrupted changeover of the FMS to different parts.

SIMULATION OF FMSs

Simulations are used for the planning and use of FMSs with entirely different focuses and tasks than simulations used for CNC programs. In the simulation of FMSs, the emphasis is on the response of the overall system to changing requirements, with the main purpose being to determine its cost-effectiveness. The cost-effectiveness of an FMS does not depend, however, on the individual machines but rather on the interaction of all FMS components

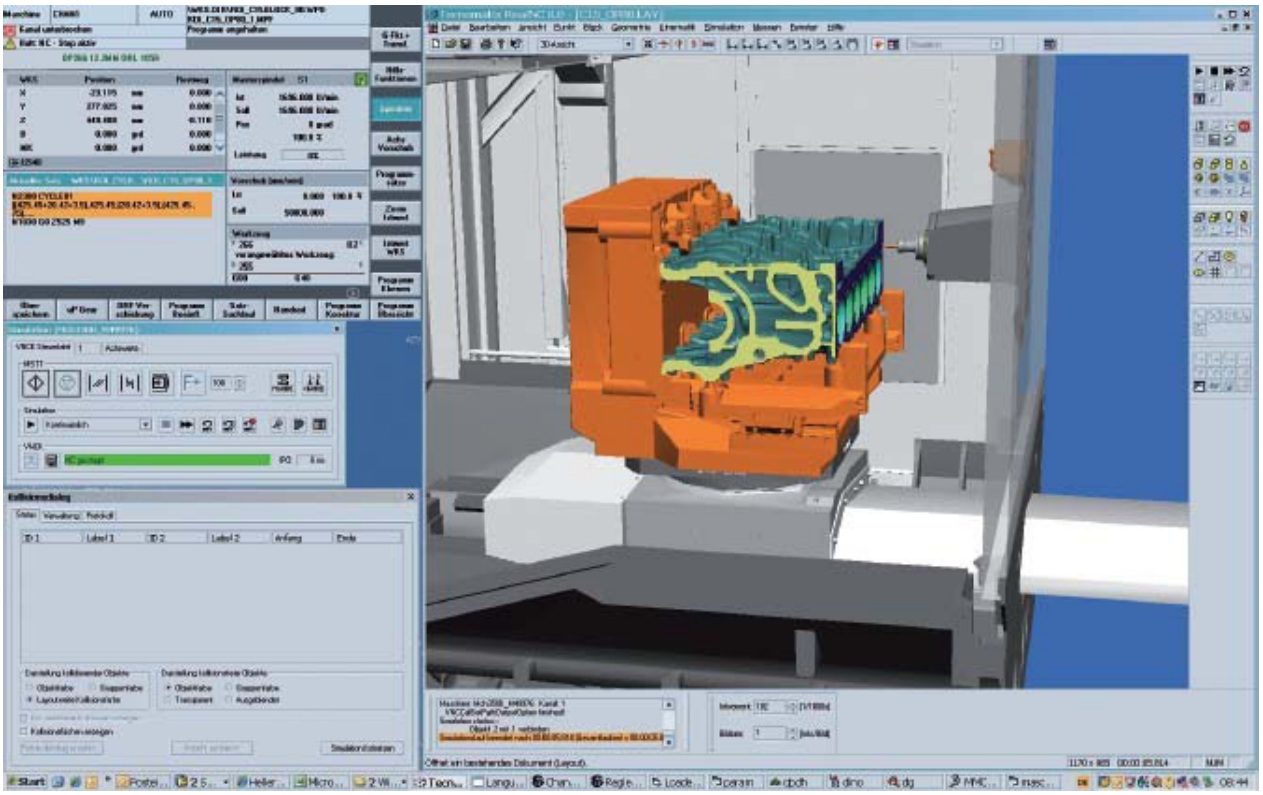

FIGURE 16.18 The simulation of an entire production process of an FMS or sequential FMSs can show errors and bottlenecks in advance so that necessary corrections can be made in the design. Improvements to the NC program often make it possible to significantly reduce production costs, especially in mass production.

However, the continuous variety and changes in the workpieces and lot sizes also require adjustments and generate unforeseeable changes. Therefore, it is virtually impossible to make reliable statements as to the future behavior of the system or to predict the effects of changes in parameters without a realistic simulation of the entire manufacturing situation.

As the size of the system and the investment increases, so does the scope of these unforeseeable risks, thus leading to doubts on the part of the buyer. For this reason, vendors and suppliers of FMSs use computer-assisted simulation at the beginning of the planning phase. This is done by entering the system layout and the data for the system into a computer program. It is then possible to change various details and test their specific effects on the production process. Bottlenecks or overdimensioning thus can be detected very quickly.

The system planner first uses static analyses based on data provided by the customer to make an initial statement about the number of machining stations required. Next, the suitable transport equipment, the number of clamping devices and pallets, and the number of setup and storage locations will be determined.

Given the complexity of FMSs, these static analyses are not sufficient by themselves but rather form the basis for the subsequent dynamic simulation. This dynamic simulation is more flexible, less expensive, and faster because the previous method was used to set up the entire system on a smaller scale using a technically sophisticated “toy construction set” to perform tests.

The money spent for simulation will pay for itself many times over and can be recommended to any buyer of an FMS. The simulation may reveal that a completely different system concept would be much more advantageous to better guarantee the required cost-effectiveness and profitability.

In most cases, the most important objective of simulation during the planning phase is to optimize the investment costs. The results of the various simulation experiments are shown on the computer screen in multicolor graphics.

Also, the system user can query the same simulation technology later to check how the system would respond under new conditions. One can make reliable predictions, detect bottlenecks, and plan ahead. Changes in the range of parts or new orders can be "played through," as can the effects of technical or organizational problems.

Advantages of Simulation

With simulation, the user can determine the following, among other things:

- Degree of utilization of the machines with a different product mix
- Optimal lot sizes
- Degree of utilization of the cleaning station and measuring machine
- Degree of utilization and bottlenecks in the transport system
- Number of workpiece carriers and clamping devices required

- Number of tools required in the magazine
- Effects of shorter or longer malfunctions
- Manufacturing time per workpiece
- Compliance with deadlines
- Activities of the system supervisor

Unlike planning simulation, which has to deal with defined values and various system configurations, user simulation assumes an online connection to the manufacturing host computer. This means that the simulation system can retrieve the relevant data directly from the process and can work in a process-oriented manner. The results of the simulation then can be incorporated directly into production planning Comparable simulation programs are also available for robots and assembly systems, although these have different tasks and emphases.

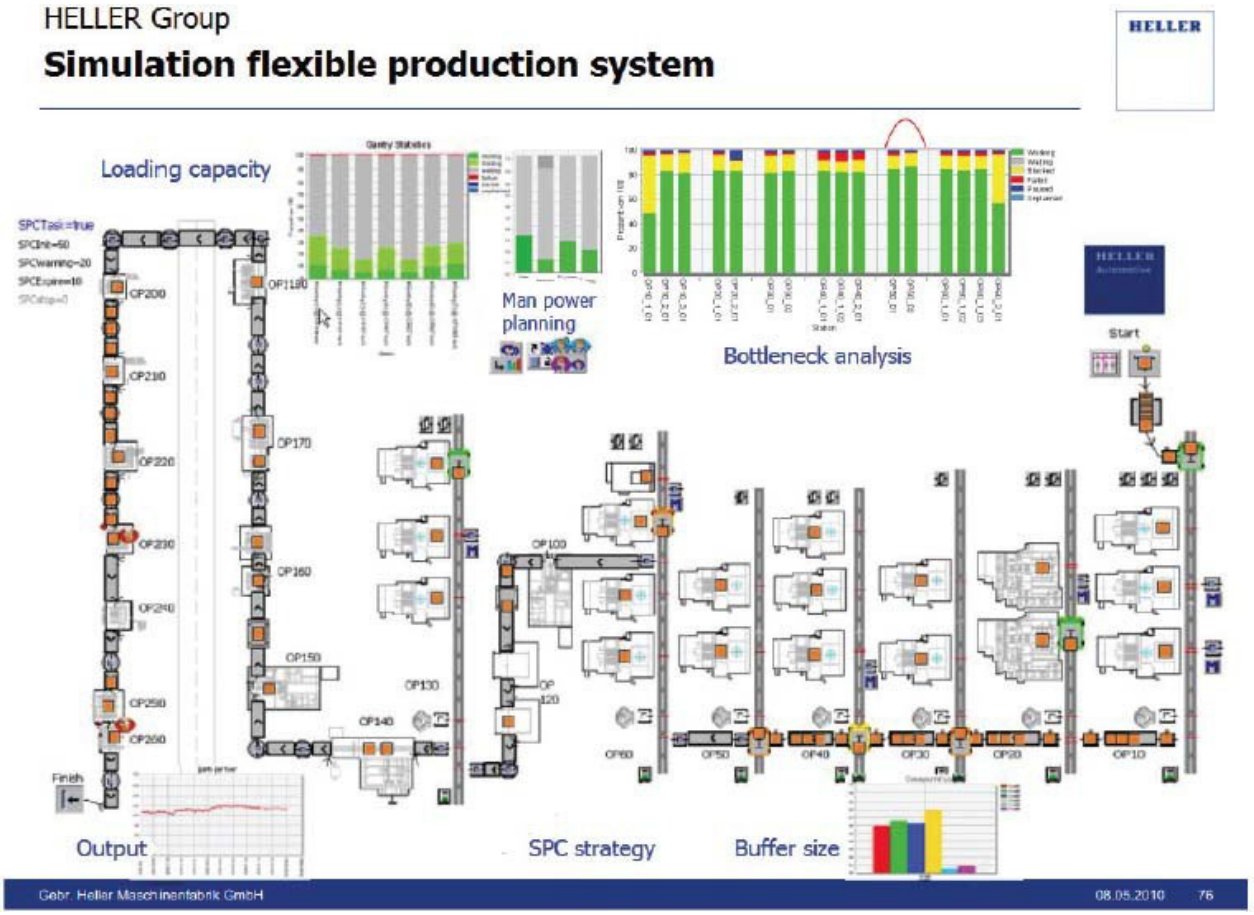

FIGURE 16.19 Simulation of the material flow of a production process. The simulation of the material flow of an FMS or grouped FMSs can also make errors and bottlenecks visible in advance so that corrective measures can already be taken in the construction stage. Even during operation, however, a simulation can help identify and optimize bottlenecks, downtimes, or energy-saving potentials.

System-Dependent Parameters

Analysis of a computer model based on different FMS configurations is performed by entering system-dependent parameters such as:

- Number and arrangement of machines
- Number of slots in the tool magazine and the tool storage facility

- Tool changing time (chip to chip)
- Strategy and time requirements for tool exchange
- Workpiece and tool transport system
- Number of transport locations in the vehicle
- Average velocity of the transport system
- Conveyor tracks
- Transfer time of the transport system
- Number of pallets in the system
- Number and variety of clamping devices
- Changeover times in production

After this, it is possible to enter the production-related parameters, such as:

- Production quantities and lot sizes
- Number of different workpieces
- Number of tools required per workpiece

■ Required system tools, special tools, or custom tools

■ Required machining operations and machining times (from the CNC programs)

■ Necessary clamping positions (three, four, five, or six-sided machining)

■ Changeover times

Based on these specifications, the simulation system calculates the results of changes to the production program or product mix, such as:

■ Utilization and idle times of the FMS components

■ Overcapacity, undercapacity, and residual capacity

■ Bottlenecks in the system

■ Throughput times and delivery dates

■ Effects of rush orders and changed production priorities

■ Possible emergency strategies in case of problems

■ Requirements for tools and replacement tools

- Costs, utilization time, changeover time, and idle time
- Personnel requirements

PRODUCTION PLANNING SYSTEMS

One of the main tasks of a production-related simulation system is to ensure that a cost-optimized production process is possible despite the large number of different manufacturing tasks. There are, however, a number of preconditions that must be met that are not taken into account by simulation systems because they have a strictly manufacturing technology orientation. This is the task of the *production planning systems* The strategic goal of a PPS is to control and optimize the order throughput time from the receipt of an order to shipment to ensure compliance with the required delivery dates and costs. Given the generally very complex interrelationships of these requirements, especially in the case of FMSs, a PPS is an absolute must for smooth operation.

A PPS has three basic areas of application:

1. *Planning* To plan all orders, administer them, and initiate their production on schedule.

2. *Control* To issue the production orders in accordance with the available manufacturing resources and supply of material and to monitor for compliance.

3. *Support* To support the sales department by forecasting future availability of capacity, time, and materials. In this way, the sales department will be able to make binding offers without disrupting or otherwise limiting current planning.

Concerning an FMS, one can make the basic assumption that the production of standard products in variable lot sizes is involved typically without customer-specific modifications. PPSs, however, may control the throughput times of orders in such a way that delivery times are as short as possible without impacting ongoing production. Nevertheless, owing to the competitive environment, many companies are forced to promise shorter delivery times and therefore have to integrate rush orders into their plans. This requires the change of existing production plans. Such demands cannot be met in the long run without help from a high-performance PPS. It becomes evident that PPSs have to be able to deal with various priorities, thus requiring a great deal of flexibility. To do this, the system must have access to comprehensive data that are updated on a continuous basis.

These data make it possible to identify in detail the inventories, schedules for incoming goods, material requirements, utilization of production capacity, costs, and so on. This information then can be incorporated into planning in such a way that the current production costs and additional costs for special customer requests are always available to the sales department. Prices, discounts, and commissions can be calculated much more quickly and realistically than with preliminary manual cost calculations.

Assuming that all the necessary parameters are available, such as bills of material and production times per workpiece, a PPS can provide the following data:

- Material and time requirements
- Material and capacity planning
- Production costs
- Purchasing control
- Shop-floor control
- Assembly times
- Fault messages and repair times
- Cost calculation

Also included are data interfaces for additional functions, such as:

- Quality control with statistics
- Production of repeat parts
- Prognoses
- Order management
- Account management

■ Payroll

The PPS should be able to calculate the production costs and delivery times for outgoing orders based on these data. There is an additional function that makes it possible to determine the latest possible start of production based on the specified delivery date and to use that as a basis for the incoming delivery deadlines for materials and purchased parts. All of this should be accomplished in a short time!

The machine assignments resulting from the PPS are followed by a simulation that shows whether the machine capacity is sufficient, whether other orders will be impacted, or how bottlenecks could be eliminated or bypassed by means of short-term redisposition. This wide range of functions makes a PPS a truly valuable planning tool—as long as it is continually supplied with current, relevant data and is used properly.

SUMMARY

The use of powerful CAD systems, coupled with the ability to make direct use of CAD-generated data in the manufacturing process, is allowing new products to be developed with increasing speed. The short lifespan of modern products no longer allows a company the comfort of installing relatively inflexible production equipment, secure in the knowledge that it will be able to use this equipment in mass production for several years without making any significant changes to it. The variety of manufactured parts also has increased steadily, and the buyer expects the system manufacturer to adapt to this increased variety. Because production is changing so rapidly from one type of part to another, there is also a risk that bloated inventories will very quickly turn into expensive, unmarketable scrap.

For these reasons, planning efforts are increasingly focused on the demand for automated solutions for manufacturing small and medium-sized lots. However, because there is no single manufacturing system that is ideal in all cases, profitability can be optimized only by using solutions that are specially designed for the requirements at hand. A sufficient number and variety of machines and automation devices are now available for this purpose. These can be combined to form many different variations. Most system concepts also allow incremental expansion so that the high investment costs can be distributed across several years. The experience gained in operating these systems makes it easier to prove their profitability.

The use of FMSs requires a thorough analysis of the manufacturing task at hand. It is also necessary to specify the main objectives and to consider growth rates and future changes. Numerous manufacturers now possess the necessary experience and offer their support and advice in accordance with this experience. This makes it quite possible to keep the risk within acceptable limits.

The economic gain of FMSs when used for various lot sizes can only be realized when the theoretical properties of such systems are applied. These are the improved use of the available machine-hours through:

- Operations through break times
- Tapering off operations in the second or third shift
- Reducing machine downtimes that arise for organizational reasons
- Changing to a new production order without interrupting operation
- Automated manufacturing with reduced personnel

From the start, all planning must include monitoring of these core objectives:

■ Does the FMS fulfill the technical requirements that have been defined in writing?

■ Is it assured that the many types of manufacturing-related data will be used automatically and consistently (i.e., CAD/CAM and tool data)?

■ What is the limit on the financial investment and the cost per machine-hour that will guarantee profitability?

■ Will the system operate profitably despite incomplete utilization of the machines?

■ Is the supply of blanks/raw material assured in order to keep the FMS running?

■ Will the system still be flexible, productive, and profitable after making all the necessary compromises in the planning phase?

■ Which, if any, alternative manufacturing concepts would be better suitable and more cost-effective?

Visualizing FMSs or simulating chained FMSs and material flows allows increased productivity of a fabrication process and possibly the entire installation.

Experience has shown that the best ideas for a new system will not emerge until the planning work is being carried out. The

stringent requirements imposed on FMSs are obviously being met in many cases; otherwise, there would not be an increase in installations of such systems.

IMPORTANT POINTS TO REMEMBER

1. Flexible manufacturing cell: a CNC machine, generally speaking a machining center, with a limited supply of parts that are processed consecutively. Typically without DNC or host computer, provided that the program memory within the CNC system can store the necessary programs.

2. Flexible transfer line: workpiece-based linkage of a number of CNC machines using the linear principle; that is, all parts pass through the individual stations and are processed by means of various sequential programs.

3. Flexible manufacturing system: a group of typically 6 to 10 CNC machines that are connected with each other via a common workpiece transport system and a centralized control system. The machines perform all the required machining functions on a limited range of parts without any need for manual interventions to support or interrupt the automatic sequence.

4. In an FMS, various production facilities are connected with each other via a common control and transports system in such a way that it is possible to accomplish the following in a cost-effective manner:

a. Production of a variety of workpieces

b. Use of a variety of machining methods

c. In any desired sequence

d. In lots of various sizes

e. In a fully automatic manner without manual intervention

5. FMSs do not contain any new machine concepts but rather represent a combination of already existing components:

a. Several interchangeable or complementary CNC machines

b. A workpiece transport system

c. A loading and unloading system for pallets and workpieces

d. Monitoring devices of the overall system

e. Removal systems for chips and coolant

f. A host computer

6. A transfer line is much more productive than an FMS but, unfortunately, is not a viable alternative.

7. The inflexible array of a transfer line does not satisfy the requirements for flexibility in production. Flexible production lines are becoming increasingly more relevant and replace transfer lines in mass production.

8. The simulation of an FMS has different functions and emphases than the simulation of a CNC program. Here the focus is the behavior of the installation as a whole and cost-effectiveness under changing conditions.

9. The most important objective of a dynamic simulation during the planning stage, in addition to system design, is optimization of the investment costs.

10. The future FMS operator can also recognize the behavior of the system in case of changed production specifications, errors, or failure of individual components.

11. The comprehensive digitization of design, production, and dynamic manufacturing simulation allows better evaluation of the productivity and offers targeted measures for its enhancement.

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INTRODUCTION

CNC machine tools now have reached a high state of development worldwide. Although the use of CNC technology has increased the speed of industrial metal-working machines to a maximum extent by means of appropriate equipment and programming, the introduction of robots has required completely new manufacturing concepts. The scope for reducing machining time even further is very limited. For this reason, the efforts at reducing nonproductive times and using industrial robots to streamline manufacturing processes have come into focus.

In industrial applications, robots work cooperatively with other devices and machines in the production process. This is also referred to as a *manufacturing* Therefore, the robot should not be viewed in isolation but rather as part of an interactive system comprising many components in the manufacturing cell. This becomes particularly evident when the robot CNC system exchanges signals and data with sensors, transfer equipment, machines, or other industrial robots.

Today, industrial robots have become an essential fixture not only in the automotive sector but also in any number of manufacturing industries. Robots were used even at the beginning of the 1970s for simple handling tasks and in particular for spot and seam welding. The main reason for this was increased efficiency, such as reduced processing times and costs and improved product quality.

Even technologically challenging processes such as the automatic assembly of engine components, the assembly of chassis components or transmissions, and the processing of natural materials such as wood, leather, and textiles or elastics and soft materials in general have been automated through the use of robots. Progress in the field of sensors has made it possible to use new applications in the fields of quality assurance and inspection.

Advances in microelectronics and in control and drive technology in the mid-1970s laid the foundations for industrial robot technology. The development started with hydraulically driven robots, but their performance in terms of precision and dynamics soon demonstrated their shortcomings and limitations. The next major development was the electrically driven robot. The first industrial applications of robots involved operations that were rather easy to implement. As the capabilities of industrial robots improved and suitable tools for joining and processing tasks were developed, new processes in related areas of application began to open up. Eventually, more demanding requirements for the dynamic performance and precision of robots emerged, and these necessitated robot CNC systems to perform on a new level and with special functions for processing tasks. The result was the industrial robot with an increasing degree of *integrated*

WHAT IS AN INDUSTRIAL ROBOT?

Previously, there was no uniform international definition for what an industrial robot is. Therefore, the term "industrial robot" has been defined in the ISO/TR 8373 Standard and the European Standard EN775 as follows.

Manipulation Industrial Robot

An automatically controlled, reprogrammable, multi-purpose, manipulating machine with several degrees of freedom, which may be either fixed in place or mobile for use in industrial applications.

The individual terms in this definition are also defined as follows:

The programmed motions or auxiliary functions may be changed without physical alterations.

The robot can be adapted to a different application with physical alterations.

Physical Alterations of the mechanical structure or control system except for changing programming cassettes, read-only memories (ROMs), etc.

An industrial robot must meet the following criteria:

- It is freely programmable.

- It is servo controlled.
- It has at least three CNC axes.
- It has grippers and tools.
- It is designed for handling and processing tasks.

STRUCTURE OF INDUSTRIAL ROBOTS

The task of the industrial robot is to pick up, hold, and guide workpieces and/or tools. A number of different components are involved in initiating and executing the motions that are necessary for this. Each of these subsystems contributes to the robotic system's solution of the motion and holding task.

TABLE 17.1 Components of a Robotic System

System System System
System System
System System
System System

System System System

■ The mechanical frame, including the gear units

■ The actuators for motions within the workspace

■ The sensors for detecting the axis positions and ambient conditions

■ The robot CNC system

MECHANICAL ELEMENTS/KINEMATICS

The mechanical structure of a robot is described in terms of its *kinematic* The following criteria are important:

■ The form of motion of the axes, that is, translational or rotational

■ The number and arrangement of the axes, for example, their sequence and positions

■ The length of the translational axes

■ The shape of the workspace

In general, industrial robots have the structure of an open kinematic chain with no branches whose elements or lever arms are linked to each other in pairs via joints Each joint has exactly one degree of freedom, either rotational or translational. One end of the kinematic chain is joined to the robot's base, which serves as the basis for the spatially fixed reference coordinate system; the free end is used as a mount for the end effector, which can be a gripper or a tool.

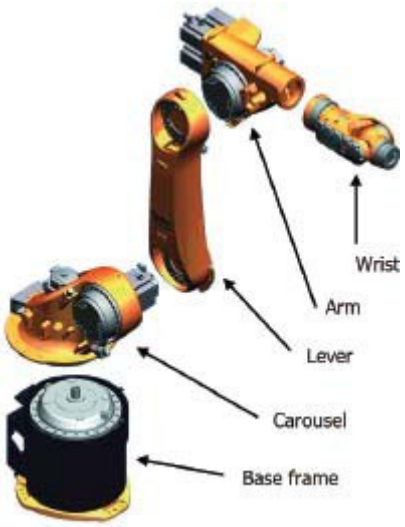

FIGURE 17.1 Structure of an industrial robot.

Each robot has an associated workspace that defines the set of positions that can be reached. A distinction can be made between various basic types of workspaces depending on the structure of the robot, as defined by the arrangement of its joints. When considering, for example, a robot arm with the joint arrangement RRT the first joint performs a rotational motion that the second joint expands to create a toroidal surface. This is contracted or expanded by the linear joint, thus forming the complete workspace of the robot. Common basic forms of workspaces are:

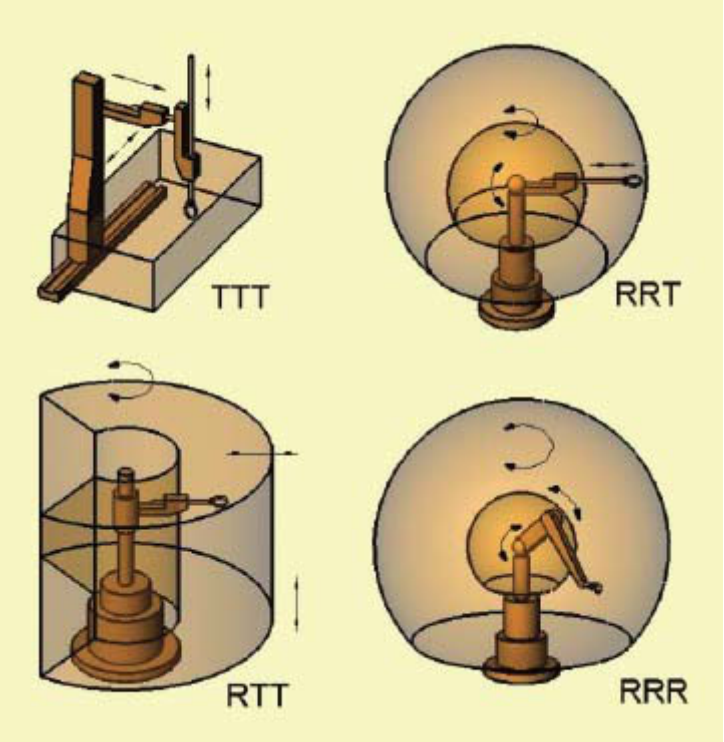

FIGURE 17.2 Workspace of an industrial robot.

- Cuboid or robot type TTT
- Cylinder, for example, RTT
- Sphere, for example, RRR, RRT

The toroidal form is not very common with most robots and generally mostly resembles a sphere. The function of the robot's wrist joint is to achieve any desired orientation at the required position. Quite understandably, it has shorter elements than the arm and it also does not have linear joints. The typical structures for wrists are TRT and TRR. The last element of the wrist is

connected to a flange to which the effector is coupled. A distinction is made between various types of industrial robots

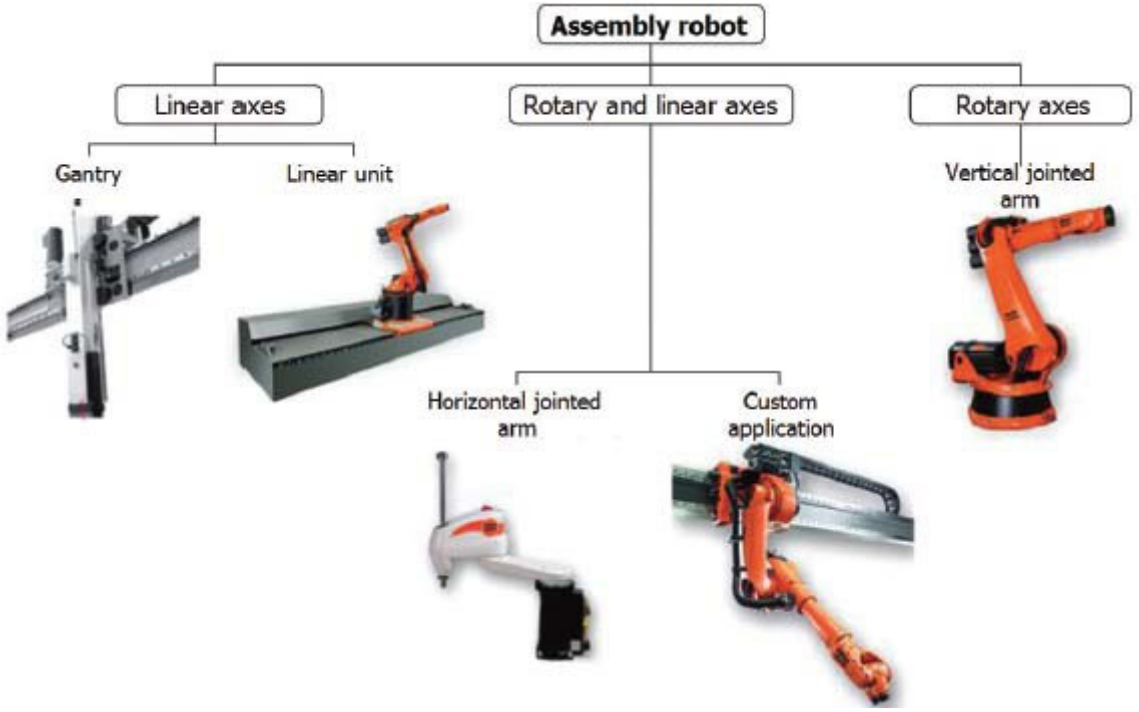

FIGURE 17.3 Kinds of industrial

GRIPPER OR EFFECTOR

An *effector* is the part of a robot that performs the actual handling operation. It is fastened to the robot's wrist and connected to power and control cables to enable it to grip, hold, and transport workpieces and to position them in the desired location. Depending on the specific handling task, sensors, assembly tools, or additional electrical cables for welding or hoses for painting may be used.

A total of three main axes are necessary to move to each point in the three space coordinates plus three additional *orientation axes* for the gripper to bring the workpiece into the desired spatial orientation via rotational, tilting, and swivel motions. Given the diverse applications of industrial robots, a broad spectrum of grippers has to be available for all sizes, constructions, functions, and applications. A distinction is made between the following grippers, subdivided according to their functional principle:

- *Mechanical* such as parallel, pincer and three-point grippers
- *Pneumatic* such as flexing fingers, perforation grippers, and pin grippers
- *Suction* especially suitable for workpieces with smooth surfaces
- *Magnetic* only used for paramagnetic materials

- *Adhesive* seldom used

- *Needle* for textiles, leather, etc.

Special gripper changing systems contribute significantly to the flexible use of industrial robots. Particularly when assembling small lots, grippers and assembly tools have to be exchanged frequently because in such cases the robot often has to perform a number of different operations one after the other. Here the changing system provides additional flexibility if the tool change takes place automatically.

The important factor here is not just a secure mechanical coupling but also the continuous flow of power and information. To ensure this, plug connections for electrical and pneumatic lines are provided in the interchangeable flanges. Spot-welding guns that require cooling also must have a cooling-water connection.

CNC SYSTEMS

The intelligence of an industrial robot, and thus its ability to operate flexibly, resides in the robot's CNC system. All necessary input data, such as the path, velocity, and operator interventions, are processed in the CNC system. As output data, they affect the robot drives or robot tools in accordance with the specified logic.

Today, most robot CNC systems feature a human-robot interface in the form of a programming system that runs on a standard PC. It is also possible to use custom-built control units for production operations or hand-held programming units, also known as *universally applicable teach pendants*

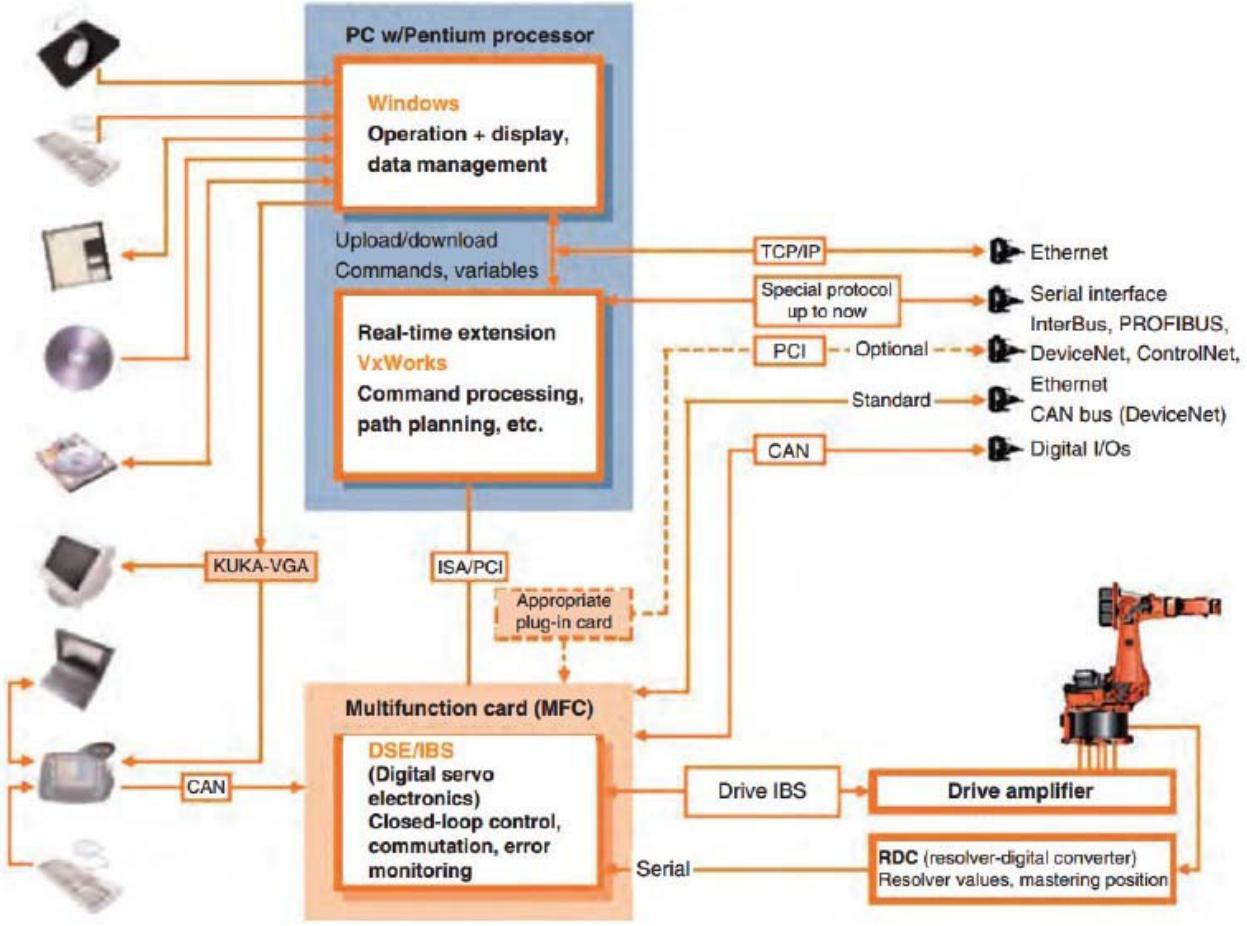

FIGURE 17.4 Robot CNC system, schematic structure, and interfaces.

Functions of the Robot CNC System

The robot CNC system contains all the components and functions that are necessary for operation, control, programming, and monitoring of a robot. It can perform an extremely wide range of functions within a robotic cell:

- Controlling the robot's motions
- Manipulating the process components in the system
- Manipulating the conveyor and in-feed components
- Controlling the gripper functions
- Receiving and evaluating sensor signals
- Receiving and processing information for influencing the process
- Diagnostic functions for error detection on the robot or in the process
- Providing support to the operator
- Supporting the programmer when setting up the automation cell

In order to perform all these functions, the robot CNC system needs a high-performance processing unit and interfaces with the robot, the periphery, the process, and the operator.

Operator Control and Programming Device

Various components are available for operator control and programming of robots. In regular circumstances, robots are operated and programmed using a *teach pendant* This device allows the input of all the necessary commands and activates all the functions of the robot CNC system.

FIGURE 17.5 Teach pendant.

Processing Unit

The processing unit consists of a main computer that carries out the overall coordination within the robot CNC system. Subordinate to this main computer are the axis-control computers, which perform closed-loop position-control and monitoring functions for the robot axes. Today, the main computer of a robot CNC system is equipped with high-performance multicore processors. These improve the

performance of the CNC system and allow it to carry out additional automation functions.

Power Unit

The power unit of the robot CNC system supplies the necessary power for the electronic units and the servo drive controllers. The technical requirements for this power supply with regard to uniform voltage and failure safety are very high because the constant load changes of the servomotors cause large load fluctuations.

Converters are used almost exclusively to power the servo drives. These consist of the power semiconductors, the drive circuit for the semiconductors, and voltage filters for compliance with the electromagnetic compatibility (EMC) limit values of the supply network. An upstream transformer adapts to the supply network as well as filtering high-frequency disturbances in the robot control and vice versa in the servo drives in the network.

Today, the connection between the servo amplifiers and the robot CNC system generally is implemented in the form of a bus system. It can be used not only to transmit the control commands to the servo unit but also to transmit the feedback messages and fault signals to the robot CNC system. This also allows centralized diagnostic functions for these system components.

The adjustment and adaptation of the servo drives to the individual robot axes take place in the same way. The necessary parameters for optimal control behavior are transmitted to the servo controller via the bus. This means that in the case of service, no adjustments must be made to the servo controller.

The power unit of the robot CNC system as a whole and the ballast circuit in particular are sources of heat. For this reason, the control cabinet generally is equipped with a cooling system.

Axis Control

The purpose of the closed-loop control for the axes drives is to move each axis according to the CNC's commands, including the speed and steady holding of positions. Because the entire kinematic system represents a potentially vibrating structure, the axis control must be adjusted to achieve an overall stable vibration-and resonance-free condition. This adjustment in modern systems can be done automatically.

Servo Drives

The servo drives are used to precisely move each NC axis and to hold the target positions. Robots mainly use speed-controlled and maintenance-free asynchronous or synchronous drive motors with closed-loop position control. The demands placed on the drives are very high because of the highly variable dynamic behavior of the robot given a range of workpiece weights and the more or less robust design of the kinematics within the working area.

Measuring Systems

The purpose of measuring systems is to measure the position and/or angle of all axes and the movement speed and acceleration of individual axes. Although these generally make use of incremental measuring systems, in some cases absolute measuring systems are essential. This is necessary, for example, in welding robots in order for them to recognize the positions of all the axes immediately after a power failure.

Safety Functions

Some of the safety-related functions of robot CNC systems include:

■ Hardware and software limit switches for all axes

■ Light barriers for immediate turn-off to protect personnel

■ Key-operated operating-mode switch

■ Monitoring of the switching systems for enabling switches and emergency-stop switches

■ Monitoring of speeds in setup mode

■ Switch-on diagnosis for all non-solid-state switching operations that perform safety functions (e.g., switching drives off, etc.)

■ Monitoring of voltage and temperature

■ Standards and codes for occupational safety (These are comprehensively revised at this time.)

SAFE ROBOT TECHNOLOGY

Robots and Operators Working Together Closely: Safe Operation

According to the current state of technology, industrial robots can only be operated in secured work areas for safety reasons People are always prevented from getting near the robot by protective fences or other complicated safety measures. In the production sequence, the robot is controlled and monitored by a higher-level programmable-logic controller (PLC), and only a minority of robots is additionally guided by external sensors. In a production operation, a robot must only move when it is ensured that no operator is present in the robot's work area. Through the use of *safe robot technology* it is now possible to overcome this separation between operator and robot for many applications. Besides being able to dispense with expensive safety systems, it is also possible to implement new system concepts, especially in the field of assembly technology. The result is an ideal combination of the strengths of humans (i.e., sensory capabilities) and that of robots (i.e., working performance). This makes it possible to provide cost-effective automation solutions for functions that previously were not economically feasible.

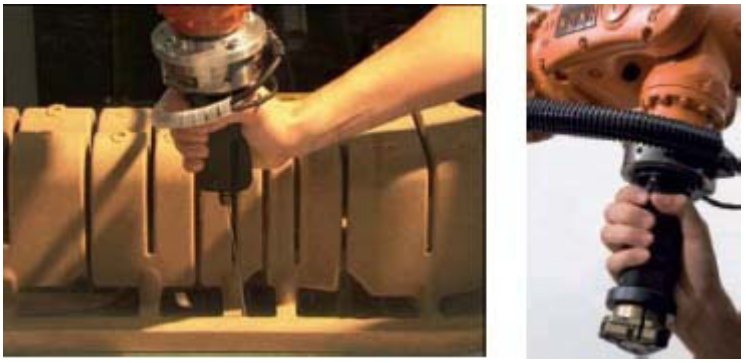

FIGURE 17.6 Design studies of a leading grip.

Using the SRT, the robot is equipped with redundant two-channel monitoring technology that will decide whether or not the robot is allowed to move into a restricted area. The current position of all axes is recorded permanently and continuously compared with the configured limit values within a few milliseconds. A much larger number of work areas or safety zones are thus available because this solution does not require any mechanical cams. If a zone is violated, the robot itself will immediately initiate the necessary stop. This significantly reduces the stopping distances in the event of a fault while also reducing the required floor space.

The Human-Guided Robot: Safe Handling

As described earlier, robots in the past could only be operated "behind bars." It was inconceivable that an operator could work in the working range of or even next to a robot. These safety requirements explain the low level of automation in automotive industry final assembly lines and also explain the slow rate of progress in the fields of mobile robotics and service robotics. This is changing now with *safe* The operator can move the robot using

a joystick that is fastened directly to the robot or the robot tool—without any program or additional PLC! In this way, it is also possible to teach the robot to move to a particular position on a certain path without having to write code.

The preconditions for this kind of cooperation between human and robot is the reliable limitation and monitoring of the velocity of the Cartesian robot system, reliable monitoring of the velocities of each individual robot axis, and a three-level enabling switch on the joystick.

Semiautonomous Systems:
New Areas for Robotics

Today, simple manipulators are used for many feeding and joining operations in assembly applications. For large components and high requirements in terms of positioning accuracy in some cases, two operators are needed to operate a single manipulator. Although the manipulator does compensate for the weight of the parts being moved, it provides only limited assistance to operators when it comes to applying the joining force. The greatest disadvantage of manipulators, however, is the fact that the operator is totally bound to the device.

This is quite different with a human-guided robot. In this application, the robot fetches the part being installed automatically under program control for example from a pallet, and brings it to a location close to the installation position. This takes place in a secured work area. The operator then takes control of the robot and performs only the critical joining operation. The power of the robot and the acute senses of the human complement each other

to form a highly efficient system. After the operator has guided the robot back to a secure working position, the robot will fetch the next part in automatic mode. This “division of labor” between operator and robot makes it possible for one operator to tend to two assembly stations at the same time.

Industrial production is facing a new revolution. What became known as *Industry 4.0* stands for the new conditions of tomorrow’s industry: volatile markets, a high number of variants, and shorter product lifecycles mean that production will have to quickly adapt to new conditions, that is, become more flexible. In many cases this means a shift away from the rigid, full automation and toward the flexible division of labor between human and robot. The use of a robot as a production assistant makes production as versatile as ever and enables completely new concepts in production. It opens up new avenues in robot-based automation, which are created in addition to the “classic” industrial robot.

The robot provides an important basis for these new production concepts. In order to be used as a safe assistant to a human, it will take a new generation of robots: the machines must be sensitive and sensible, such as the KUKA lightweight robot, LBR iiwa. This machine with seven axes is modeled on the human arm and can be operated in positional and compliant operations. Combined with integrated sensors, this lightweight robot has a programmable sensitivity. The highly developed collision-detection ability and integrated joint-torque sensors in all axes predestine the LBR iiwa for sensitive joining processes and make possible the use of simple tools. This sensitivity opens a

new chapter in the human-robot collaboration. It acts as “third hand” of the human without the hitherto required protective measures.

Progressive Degree of Automation

So far there were two extremes: on the one side, production was completely automated with the robot “behind bars”; on the other side, a task was performed completely manually, with no robotic help. Now, for the first time in the history of robotics, production tasks with a progressive degree of automation are possible; they can be individually automated and cost optimized. The separation between human and machine has been overcome when the robot is in the “human-led” mode

PROGRAMMING

When it comes to the cost-effectiveness of a robotic system, the amount of time required to create a dedicated flawless program is particularly important. The program itself is the sequence of the entire information that the handling system requires to execute a motion or work cycle. Various programming methods exist because of the facts that an analysis of the operation must be performed and that the operating conditions and the range of motions of the robot place different requirements on the programming. Every robot CNC system can process programs in at least one programming language.

Program Contents

An application program has to contain everything that is necessary for the complete work sequence of the industrial robot in the technological process. The individual components of this are described in Table

TABLE 17.2 Basic Components of Handling Programs

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Programming Methods

The creation of a robot program can be broken down into motion programming and sequence programming. *Motion programming* involves the definition of points along a path/motion segments. *Sequence programming* involves linkages between motion segments, defining process parameters, times, wait positions, velocities, accelerations, and communication with peripheral equipment. The programming methods for industrial robots can be subdivided as follows.

Online Methods

Process-linked direct programming and close-to-process programming include:

■ Programming in teaching mode, that is, moving to specific points

■ Playback methods, that is, moving along a path (the robot arm is guided directly by the operator)

■ Manual input using buttons or switches

Offline Methods

Not linked to process, indirect programming, and programming remote from the process 17.7 and methods include:

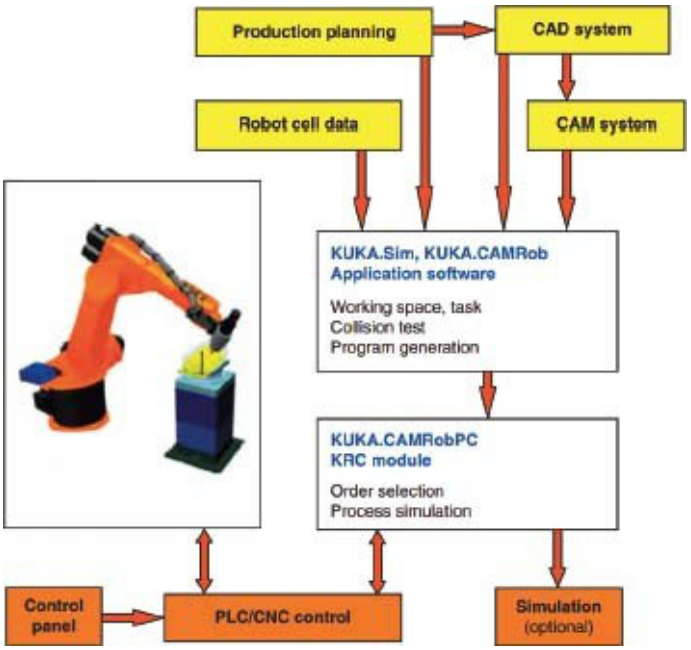

FIGURE 17.7 Programming concept for offline programming for KUKA robots.

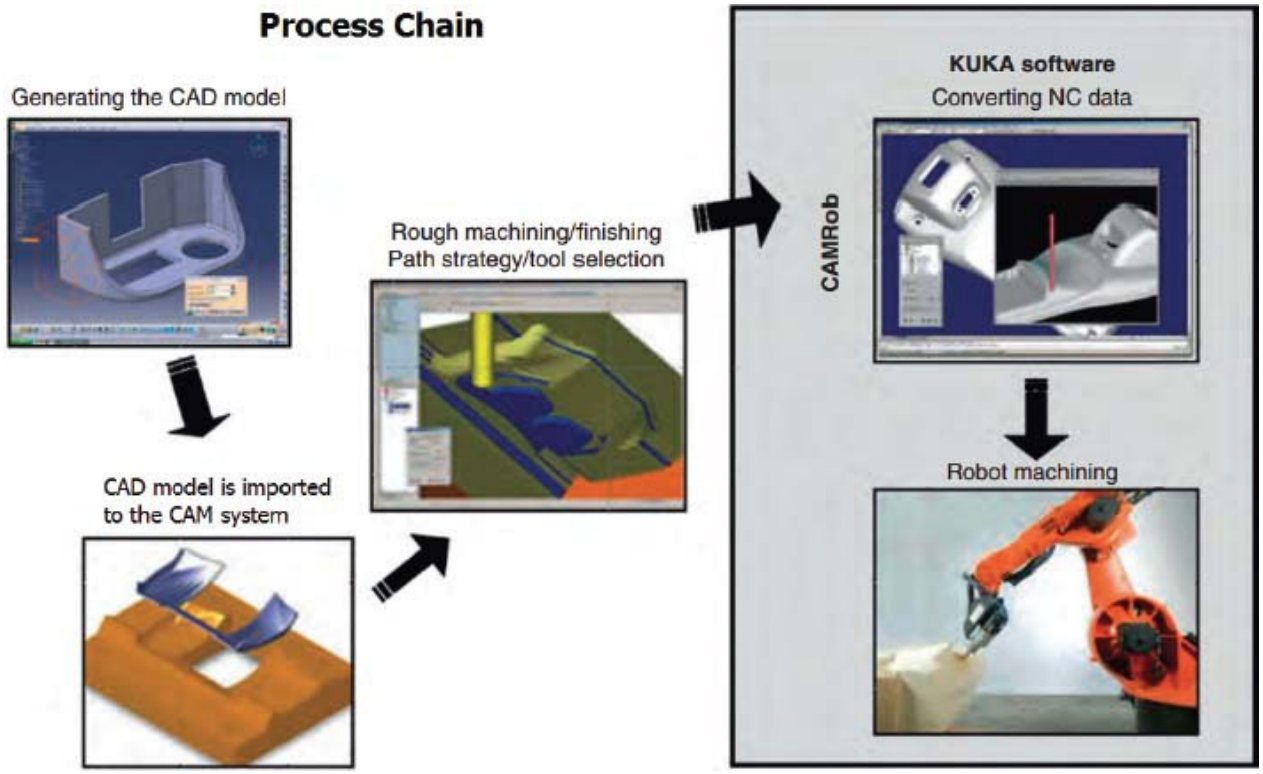

FIGURE 17.8 Process chain of the development of a fabrication program.

■ Textual programming using robot languages

■ Explicit programming languages (These specify the operation to be performed in elementary steps. Each motion element has to be described with an instruction. The programming is robot oriented.)

■ Implicit programming languages (The task to be performed is expressed globally. The robot generates the individual actions itself, which requires a certain level of "intelligence." The programming is task oriented.)

■ Programming in teaching mode with a "phantom arm"

■ Interactive programming on the screen with graphic assistance

■ Acoustic programming (input using spoken language and use of speech recognition)

Hybrid Programming Methods

These combine the advantages of online and offline methods. The geometric instructions, that is, paths and positions, are programmed using teaching, whereas the sequence, control, monitoring, and communication instructions are entered in the form of code or spoken language.

Automatic Program Generation

Once a target state has been defined, the appropriate system generates the required program automatically. This requires a program solver that breaks down the tasks into subtasks; of these, the actions that have to be programmed are planned, and a program is generated. Such approaches are already in use today for the automatic generation of path and process data, for example, in milling and bonding. Thus a robot program can be generated directly from CAD and/or CAM data.

SENSORS

The purpose of sensors is to detect and respond to irregularities such as changes in position, deviations from a pattern, or other external interferences. The increasing use of robots in manufacturing applications can be attributed to, among other things, the development of suitable sensors. Sensors serve to detect the internal state of a robotic system, the current interactions between the end effector and the environment, and the external conditions in the area where the robotic system operates. The function of a sensor is based on the conversion of a physical phenomenon, for example, a pressure, force, contact, or motion, into a quantitative electrical dimension. This electrical variable is digitized and evaluated by a sensor processor or by the robot's CNC system. The current state of the robot and its environment is recorded at discrete intervals, for example, to measure the opening width of the gripper jaws or to attain the parameters necessary for the ensuing actions directly from the environment such as identifying a part or a distance. Further operations are controlled based on the detected status.

During operational execution of accessory measurements, it is possible to implement sensor-monitored and/or sensor-controlled actions. Sensor-monitored actions are executed as long as the measured variables exceed the specified limit values. In the case of sensor-controlled actions, the specifications for execution of the operation may be corrected to ensure that the specified limit values are always observed

TABLE 17.3 Technical Sensors

Sensors Sensors

Sensors
Sensors Sensors
Sensors

In other words, a sensor is a device that takes in technical data, thus giving a robot a limited sensory capacity. It collects information about a characteristic, state, or action and makes it available in the form of an electrical signal. The primary piece of hardware that receives a nonelectrical measured value and forwards it as an electrical signal is also referred to as an *elementary*

APPLICATION EXAMPLES FOR INDUSTRIAL ROBOTS

The KUKA.CNC is the new generation of CNC systems for direct CNC program code processing on a KUKA robot. With this, it is possible to execute CNC programs according to DIN 66025/ISO 6938 directly with the robot CNC system. The complete scope of the standard code can be interpreted by the CNC system and implemented by the robot, such as G-functions, M/H/T-functions, local and global subprograms, control-block structures, loops, and so on. With these options, the areas of application of an industrial robot can be extended as follows 17.9 to

■ Milling of formed parts made of soft to medium-hard materials such as wood, plastic, aluminum, composite materials, etc.

■ Grinding and polishing of formed parts

■ Coating and other surface treatment of complex component surfaces

■ Trimming and cutting of complex components and component contours

■ Laser and plasma-and water-jet cutting of complex components

FIGURE 17.9 Milling cell in model engineering.

FIGURE 17.10 Passenger compartment assembly in the automotive industry.

The direct integration of the CNC kernel into the robot CNC system turns the robot into a machine tool with an open kinematic system that combines the advantages of an industrial robot, some of which are:

- Large work area
- High flexibility
- Low investment costs
- Six-axes processing

With the advantages of a CNC control system, some of which are:

- G-code programming
- CNC user interface
- Tool-radius compensation
- Large point projection
- Expanded spline path planning
- Convenient tool management

Integration of the CNC kernel also makes it possible to process the CNC program directly on the robot CNC system. As a result, it is no longer necessary to perform a complicated conversion of a CNC program into a robot program. This makes it much easier to use an industrial robot for typical machining jobs. Therefore, both CAD/CAM programmers and CNC machine operators can use

their existing know-how to program and operate industrial robots [17.13] and

FIGURE 17.11 Automatic tool change in a fabrication center.

FIGURE 17.12 Grinding and polishing of an implant.

FIGURE 17.13 Milling of a stone tub.

CNC-ROBOT MACHINING AND MACHINE TOOL AUTOMATION

Frequently, existing machine tools are supplemented by robots or existing robot cells with more machine tools. These stand-alone, independently operable systems, machine tools, and handling robots, therefore, must be connected to each other. However, both control systems, CNC control and robot control, have already been completed by the respective manufacturers. The control systems therefore have to provide interfaces to synchronize the production process of both systems. As a rule, these interfaces are designed in such a way that system integrators from third-party providers, such as machine vendors, can connect handling robots to machine tools without affecting the existing applications of machine tool and robot.

FIGURE 17.14 Arc welding.

Such an interface is based on PLC handshake signals according to the standard defined by the VDW/VDMA for connecting robots or handling systems to machine tools Predefined NC/PLC interface areas and alarms, diagnostic screens, and carefully documented application examples allow quick and easy system integration

Optimization of Human Resources

Robots and machine tools are usually systems of different manufacturers with different architectures and operating philosophies. Setup, programming, and maintenance of a handling robot require either additional operating and maintenance personnel or additional training of the existing personnel. Both options are associated with additional costs. Therefore, manufacturers of CNC systems and robots cooperate with the objective that operation, programming, and diagnostics of the handling robot can also be integrated in the user interface of the machine tool. A special interface is used to exchange pick and place commands between the CNC program and the robot CNC system. The program runs in an additional CNC machining channel, and the programming is done in the CNC system. Special cycles in the CNC system represent the command scope of robot control. The jog mode of the robot axes is also available and controlled through the CNC program. Also, error and operational messages are displayed on the user interface of the CNC system. Operation, programming, and maintenance of the handling robot and system integration of machine and robot are thus an integral part of the CNC application

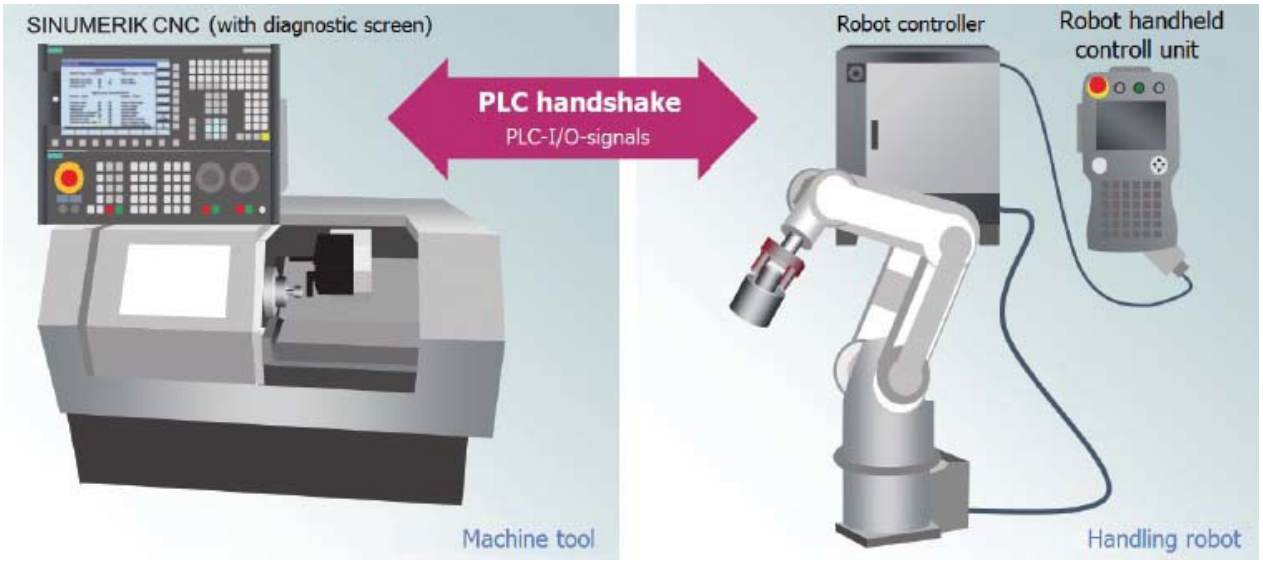

FIGURE 17.15 Schematic representation of a robot connection using the example of the SINUMERIK Integrate Run MyRobot/EasyConnect interface. Siemens.)

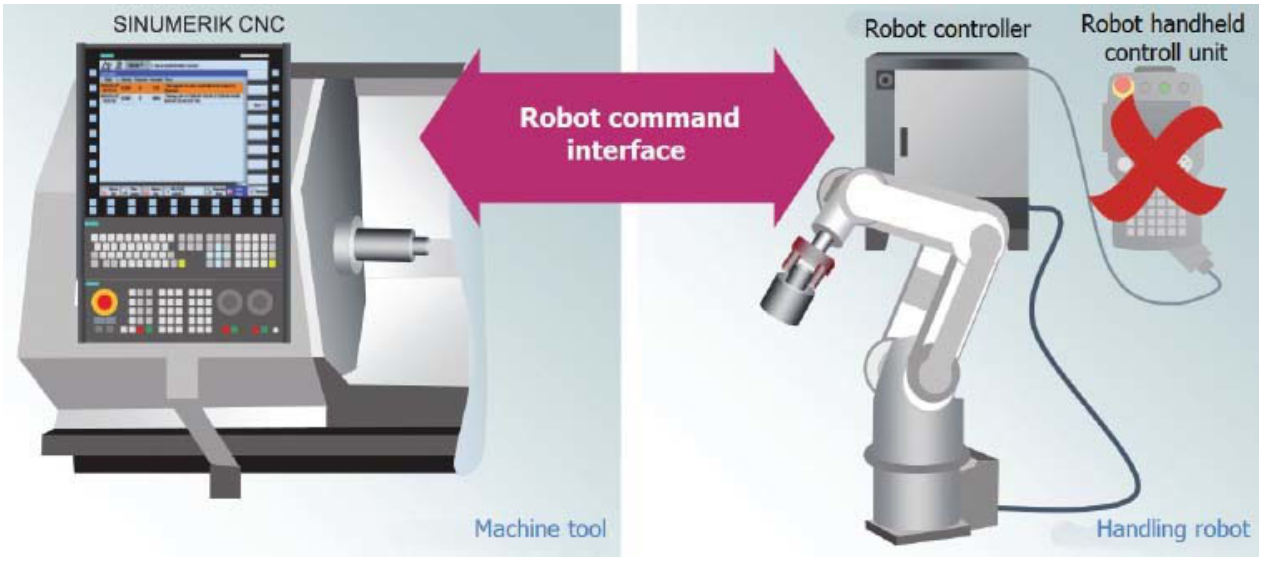

FIGURE 17.16 Schematic representation of a CNC-integrated robot interface using the example of SINUMERIK Integrate Run MyRobot/Handling.

ROBOT WITH CNC REQUIREMENTS

In addition to pure pick and place handling tasks, there are increasing applications of robots that require the basic characteristics of a CNC system, such as constant path speed, tool management, or typical CNC programming. Thus a robot in a path-controlled operation can be used to complement tasks of the machine tool such as bonding, deburring, and polishing. The robot can also perform milling operations on parts molded out of soft or medium-strength materials where the CNC system and the robot CNC communicate via a real-time position interface. The kinematic transformation for the robot mechanics is calculated in the CNC program. All the familiar CNC commands are available for movement of the robot, such as plane selection (G17), position commands (Go, G1, G2), and machining cycles. Additionally, control algorithms such as dynamic precontrol, jolt limitation, look-ahead function, and dynamic block compression are available for the machining of free-form surfaces. Also, a robot application specific CAD/CAM process chain might be added For optimal work preparation of robot jobs, a simulation of processes can be used that is based on actual robot kinematics and a postprocessor optimally adapted to the respective CNC system. Because the CNC robot is either an integral part of the machine tool or the machine tool itself, only the machine tool manufacturer is in the position of a system integrator.

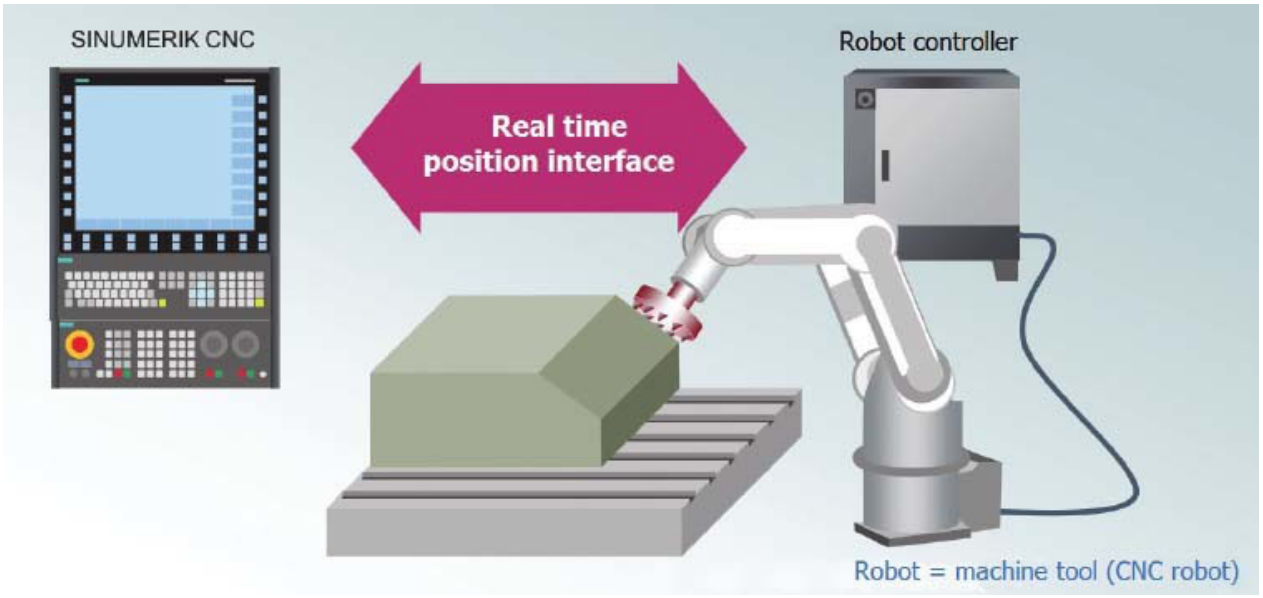

FIGURE 17.17 Schematic of machining with a robot controlled via a CNC system, for example, a SINUMERIK Integrate Run MyRobot/Machining.

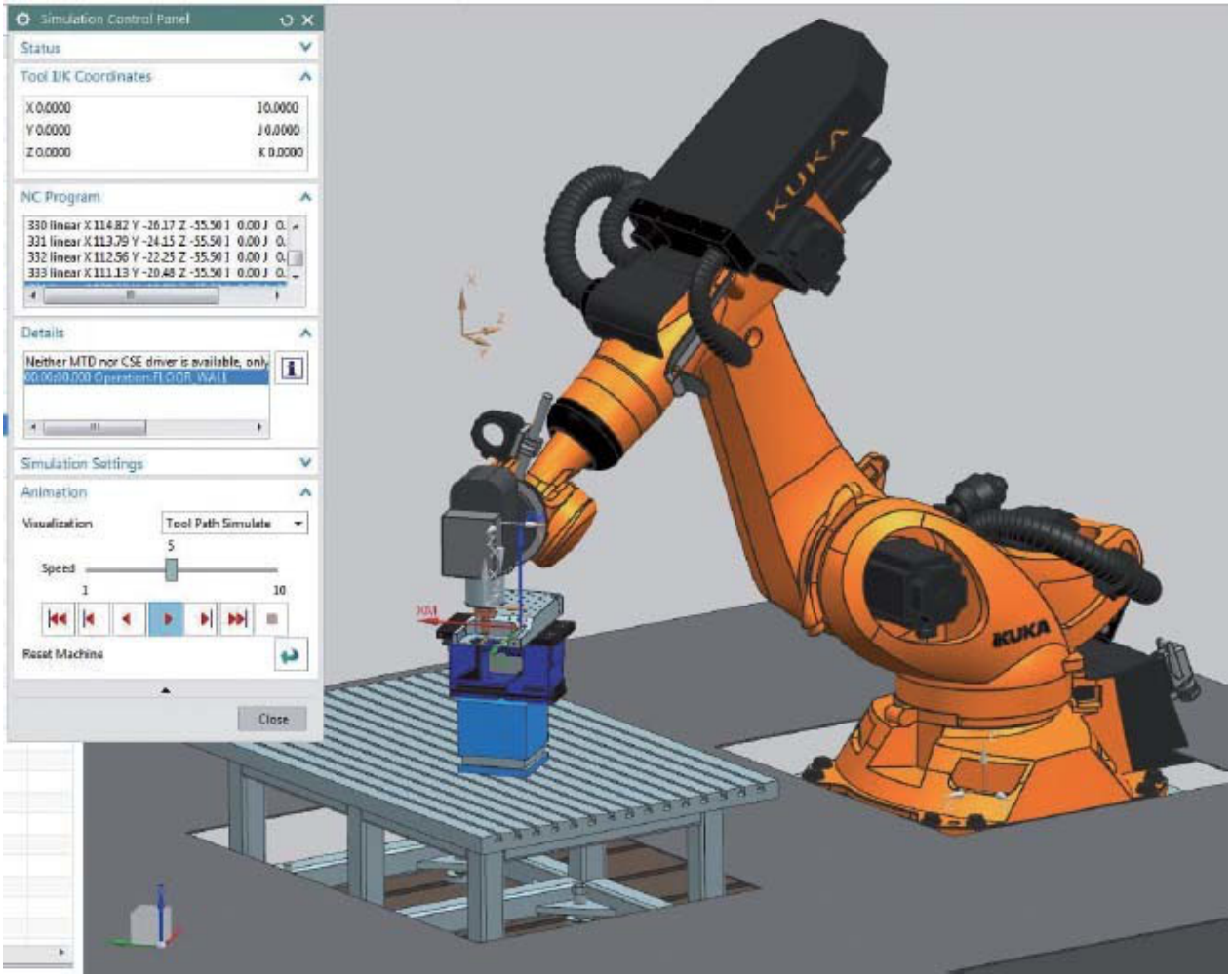

FIGURE 17.18 CNC CAD/CAM process chain for machining with a robot makes work preparation easier. Example: NX CAM machine simulation, SINUMERIK Integrate Run MyRobot.

APPLICATION CRITERIA FOR INDUSTRIAL ROBOTS

There are important reasons for flexible automation with robots, including the increasing variety of types and products due to market needs; shorter production times of the products and more frequent model changes; smaller quantities with high retrofitting times and low equipment utilization; conventional equipment; increased demands on the quality of the products; excessive throughput times, inventory, and capital commitment; onerous, monotonous, and harmful production conditions; cost pressure; and increasing product differentiation.

The use of industrial robots can depend on external conditions and on economic aspects:

■ *Environmental* such as clean rooms, toxic fumes, freezing and hot environments, etc.

■ *Occupational* such as hazardous substances, weight, noise, etc,

■ *Quality requirements in the* such as precision, zero defect production, etc.

■ *Labor* such as the rising cost of labor putting the industrialized countries at a competitive disadvantage

■ such as the use of robots increasing flexibility in production.

Several criteria are important when selecting a robot:

- The general application on the site
- The load, its point of application, and self-inertia
- The work area of the robot
- The process speed or cycle time of the processes
- The required accuracy, based on path behavior or position
- The type of control, including special requirements of the user
- The ability of the robot system to be integrated into the plant environment

The use of industrial robots can result in many advantages:

- *High* Unlimited production can be achieved at any given time.
- *Optimized use of cycle* Use of nonproductive time in the production process allows for additional tasks such as postprocessing.

■ *Increase in* The robot operates with a constant high speed while maintaining consistent quality, resulting in fewer rejects and higher throughput in production.

■ *Time* Optimal positioning of the robot leads to reduced cycle times.

■ *Cost* High availability, optimal production quality, and short cycle times lead to fast returns on investment (ROI) and more competitive production.

■ Higher processing speeds than manual processing with consistent high quality are possible.

■ Easy programming allows flexible responses to changing production processes and seasonal fluctuations.

■ High positioning accuracy even in continuous operation leads to increased product quality and lower reject rate.

■ *Investment* With an average age of 15 years, industrial robots have a very long life span.

SUMMARY AND OUTLOOK

Increasing globalization and the associated use of industrial products and systems require standardization of the interfaces, including the communication of robots and assembly systems. These should be consistent and easy to use worldwide. This provides robot users with investment security and gives robot manufacturers the stability to pursue new developments.

Modern automation technology will accomplish little without communication between the individual CNCs of a system. Especially with open bus systems such as Ethernet and TCP/IP, complete production plants can also be controlled in real time across locations. The robot manufacturers clearly follow the trend to equip and connect their own CNC systems with the same technologies that have been used in the computer industry for some time.

The shift to put more and more software resources into the robot itself opens new perspectives on the context of maintenance. In the past, maintenance activities were initiated either in response to a stoppage of the installation or in given cycles preventively. In the future, the individual robot will interpret meter readings, measuring points, or similar statistical data itself and schedule maintenance activities after reaching certain conditions or events. Also, service scenarios are foreseeable where the industrial robot is connected via web portals with the information technology (IT) system of the manufacturer to allow remote diagnosis and, if so

indicated by the diagnosis, to automatically order spare parts. During such an evaluation various databases in the robot can be used that store the maintenance history, the load profile of the drive-train elements, and case-based solutions to help solve the problem at hand. A broad knowledge base can be used via the connection to a service platform. If the criteria are met, maintenance will be automatically scheduled at the most appropriate time. Doing so allows interaction with production planning and control, spare parts management, and other relevant areas. Machine availability thus can reach a hitherto unprecedented level.

Industry 4.0

Companies can expect significant improvements in terms of productivity, flexibility, and efficiency through intelligent networking of all production-relevant components. The use of robots not only brings advantages in terms of handling or machining of workpieces but also provides additionally data that can be collected and made available to the higher-level production control via the CNC interface of the robot. Robots are often the links between different work processes. Therefore, they are an important tool for collecting smart data and will play an essential role in the future in the self-optimization of production processes.

Human-Robot Collaboration

Collaboration between humans and robots has been limited in the past because of safety concerns. Yet modern sensitive technology enables smooth human-robot collaboration. SRT makes it possible in many applications to resolve the separation between human and robot. In addition to the suspension of complex safety

measures, new production concepts can be realized especially in assembly technology. The strengths of humans, namely sensorial abilities, and that of the robot, namely work performance, will be combined in an ideal way. As a result, automation tasks that were previously not economically feasible can be solved with cost-effective partial automation.

Mobility for the "Smart Factory"

The sustainable flexible production is completed by mobile robots. They move independently on mobile platforms to transport goods. In a modern factory, mobile robots already are moving around controlled by navigation software and completely without ground markings, induction loops, or magnets. Mobile platforms can create maps of their environment and provide these to other entities, thus creating an infrastructure that coordinates all robot movements.

IMPORTANT POINTS TO REMEMBER

1. Definition of the industrial robot

A robot is an automatically controlled, programmable, multipurpose manipulating machine with several degrees of freedom that may be either fixed in place or mobile for use in industrial applications. Industrial robots:

a. Are freely programmable

b. Are servo controlled

c. Have at least three NC axes

d. Have grippers and tools

e. Are designed for handling and processing tasks

2. Mechanical elements/kinematics: Industrial robots have the structure of an open kinematic chain with no branching, whose elements or lever arms are linked to each other in pairs via joints. Each joint has either one rotational or translational degree of freedom.

3. Grippers/effectors: A distinction is made according to their functional principle: mechanical grippers, pneumatic grippers,

suction grippers, magnetic grippers, adhesive grippers, and needle grippers.

4. The CNC system: The robot CNC system can perform a number of functions within a robotic cell:

a. Supporting the robot's programming

b. Controlling the motions of the robot

c. Manipulating the process components of the system

d. Manipulating the conveyor and feeding components

e. Controlling gripper functions

f. Receiving and evaluating sensor signals

g. Receiving and processing information

h. Diagnostic functions for error detection on the robot or the process

i. Providing support to the operator

j. Supporting the programmer when setting up the automation cell

5. Application criteria for industrial robots: The use of industrial robots depends on the external and economical considerations:

a. Environmental conditions

b. Occupational safety

c. Quality requirements in production

d. Labor costs

e. Flexibility

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INTRODUCTION

First and foremost, production must be cost effective. What is measured is how many parts can be fabricated or processed in a given time and at what cost. In many cases, the flexibility of production plays a decisive role. Energy efficiency and productivity often contradict each other. This is why it is important to "turn the right screws" when tuning a system to realize savings.

The Institute for Production Management, Technology and Machine Tools at the Technical University of Darmstadt tracked the costs of cutting machine tools over a period of 10 years. It reported that 80% of the total costs were operational costs. Of these, energy consumption alone accounted for about 20%. Of this share, about a fifth is consumed by the actual machining process and the remaining 80% by operation of the ancillaries.

WHAT IS ENERGY EFFICIENCY?

Energy is applied power × time:

Electrical energy E = kW × h = kWh (kilowatt hours)

Energy consumption is generally a measure of the energy required to achieve a defined benefit. Energy efficiency is achieved when a particular benefit is achieved with minimal energy input.

Improved energy efficiency of a computerized numerical control (CNC) machine is understood to mean the minimum energy consumption during operation, including all nonproductive times, based on one workpiece or number of produced workpieces in a given time, including idle and nonproductive times.

WORK FLOOR

The work floor needs to be provided with bright light; ventilation; air purification and conditioning; hot water; energy; and possibly other essential systems in continuous operation, even if machines are not in operation. Bright light is a prerequisite for the safety of employees and is comprehensively regulated by standards. Supply systems are almost always operated permanently and often stay on a long time after machines have been turned off. Some supply systems must stay on, such as lighting and air conditioning.

The base load for production floor lighting is also very high and amounts to about 350 kWh/day for 1000 given that rather not up-to-date lighting technology is used. This equals an annual consumption of 87,500 kWh, based on 250 work days.

With the use of modern light-emitting diode (LED) lighting systems, the power consumption can be reduced to one-third this amount. Thus it will hardly make any sense to switch off auxiliary units on individual CNC machines for a short time to conserve energy. Whether it makes sense to search for energy-saving measures on CNC machines depends very much on the type of machine and the machining processes.

MACHINERY

One could assume that large machines offer significantly more opportunities for conserving energy than small ones. However, this assumption does not consider how these machines are used. An important role in energy use is the type, size, and material of the workpieces; the proportion of material removed; and the nature of the tools.

Therefore, it is not surprising that in previous energy-efficiency studies of machine tools, large lathes, milling machines, and grinding machines were not the center of attention. These types of machines are typically used in longer continuous operation, meaning that the ratio of main production time to nonproductive times is very high. A surface milling machine with one or more main spindles for processing large parts made of aluminum with 90% material removal has a very long peak cutting time but very few short interruptions that can be used to turn off auxiliary units.

Thus it is very unlikely to realize additional and significant energy-saving measures. The same applies to large boring machines, large lathes, and other machines with a comparatively high ratio of cutting and nonproductive times.

Smaller CNC machines for the machining of mainly very precise workpieces with small tools hardly offer worthwhile energy-saving opportunities. Suction devices for chips or dust, as in the case where processing graphite, are turned on and off simultaneously with the main spindle, the tool change times are very short, and

other options are missing. The energy footprint is not very large, and the worthwhile shutdown of auxiliary equipment is unlikely.

SPECIAL CASE: MACHINING CENTERS

Previously mentioned studies on improving the energy efficiency of CNC machines were almost always done for machining centers These are mainly medium to very large machines with additional automation components such as large tool magazines, a tool changer, a pallet changer, hydraulic pumps, chip-removal devices, and more. For this reason, these machines offer the most worthwhile opportunity to reduce energy use

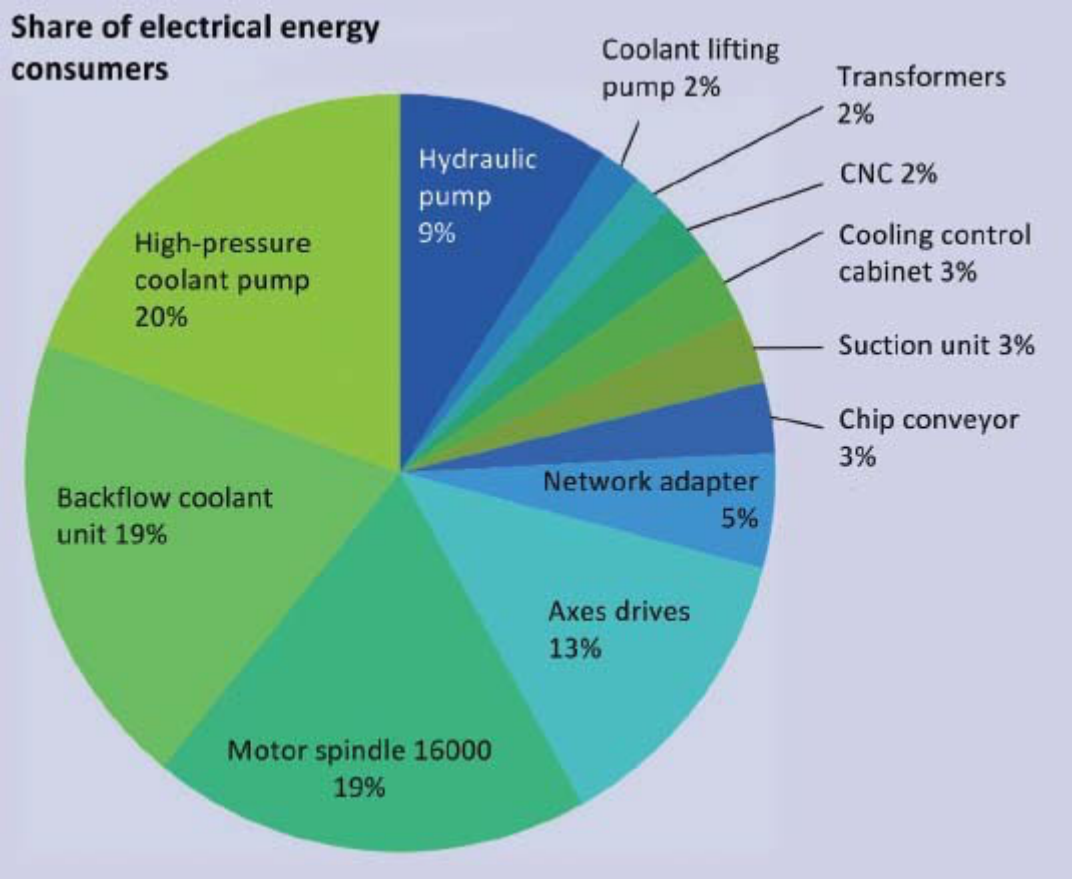

FIGURE 18.1 Energy consumption of machining center for a wet cutting operation.

Example Calculation

Energy consumption of a machine (kW values and $/kWh randomly chosen):

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ENERGY-EFFICIENT NC PROGRAMS

So far no emphasis has been placed on energy-efficient programming of the machining process, especially at machining centers. For mass production, it pays to reduce the number of tool changes, for example. In the past, it proved as best practice to strictly limit the approved standard tools rather than granting the programmer too much freedom in the selection of custom tools.

Also, parts programming often allows for an unnecessarily high safety margin when retracting the spindle to a safety level; reducing these margins to more reasonable distances results in noticeable time savings. These times add up significantly for large production runs. In addition, changes in machine movements do not require extensive investigation, investment, or even costly changes to the machines. These measures primarily affect the profitability of the plant and thus the operating result. If the measures mentioned also increase energy efficiency, it is welcomed as a positive side effect.

OPTIONS OF THE MACHINE MANUFACTURER

Because of the rather meager energy savings potential of existing machines, it is the manufacturer of CNC machines who can realize the greatest gain in energy efficiency. It is not just the big aggregates that consume much energy. A small pump in continuous operation uses more energy than a 2-kW tool spindle in 5 hours of full-load operation per day.

A machine tool buyer can assume that simpler energy-saving measures are already realized. Machine manufacturers do have quite a few options to implement energy savings on new machines. Some salient points are as follows

■ Hydraulic drives convert energy three times: electric motor, pump, hydraulic drive. The best systems achieve an efficiency of 50%. For this reason, energy-saving hydraulic pumps always pay off. The replacement of a hydraulic system with an electrical solution includes even more benefits.

■ *Electric* These are the most economical, realizing an efficiency of 50% to 90%. It must be distinguished whether three-phase motors are used for auxiliary units that are only turned on and off as needed, or whether controlled servo drives are used with higher energy requirements to drive NC axes and the main spindle.

■ *Axis* Linear drives, without considering the required cooling systems for temperature control, can achieve an efficiency of up to 98% because no friction losses occur in mechanical transmission elements. Servo drives for in-feed axes must also be constantly controlled to arrest a position during machining, although arresting an axis with less energy is possible.

■ *Servo* There is the possibility of back-feeding energy into the power grit for machines with multiple axes and a main spindle drive. The achievable saving effect should not be overestimated.

■ This is the worst offender in terms of energy usage. Energy conversion takes place three times, that is, in the pump, in the compressor, and in the actuators, in addition to waste of heat during air compression and problems with the incidental condensation. A pneumatic system rarely exceeds an efficiency of 5%.

■ Machines with a high idle power often have high friction losses. Friction can be reduced with rolling bearings instead of slide bearings and when machine components that move fast are equipped with streamlined shapes.

■ *Reduction of moved* Machine stands, tables, or headstocks that are often accelerated and decelerated should be as light as possible; however, this requirement is not easy to achieve.

■ *Better energy* Machines are often not turned off because experience has shown that it takes a long time from a cold start

to full operation. This experience may not apply to newer CNC machines if they are designed according to current standards.

■ *Automatic tool* Energy efficiency can be built in. For example, picking up a tool from a loaded heavy magazine chain costs more energy than from a light linear handling system with direct access to stationary tool cassettes. In addition, preparation and returning tools can be much quicker.

OPTIONS FOR THE USER

Machine users also have several options for saving energy without great effort:

■ *Selecting the right machine* If not explicitly called for in view of possible higher demands later, it makes sense not to buy a CNC machine that is larger than necessary for the intended current needs. Larger machines are always equipped with drive motors of greater power than smaller ones. This alone results in a larger base load and a higher proportion of reactive current, which contradicts a targeted energy efficiency.

■ *Degree of* Automation of the CNC machine should not be higher than actual, current, or medium-term foreseeable needs. It is of no use to replace a bottleneck machine with a highly automated CNC machine when waiting times arise because of emerging bottlenecks at another location. In such cases, modernization of the entire production should be considered.

■ *Flexible manufacturing* Even more critical is the case of linked machines with additional transport system for pallets, clamping devices, and workpieces. In particular, system-integrated, large tool racks with automatic feeding and storage for, say, multispindle heads, have proven to be uneconomical overautomation. When designing flexible systems, however, production-specific and economic requirements are more in the foreground than the energy efficiency of automation. It is more gainful to continuously

operate the entire system so as not to waste time and energy on long wait times.

■ *Choosing the optimal process for the* Milling steel requires about 30 times less energy than grinding or 100 times less than electrical discharge machining (EDM). Modern CNC systems support the user in the process in terms of energy efficiency Such systems provide options to measure and compare power use and provide profiles for a shutdown for nonproductive operations. The use of shutdown profiles requires the involvement of the machine manufacturer for only it knows about the ramifications of the operation of the auxiliary units. Another prerequisite for efficient machining is to always use the appropriate machinery and tools.

■ *2½D or 3D* If multi-axes CNC machines are available, they will also be used for parts for which 2½D machining is sufficient. Three-axis CNC machines have a lower base load; therefore, a cost comparison will conclude that a five-axis machine should not be used when a three-axis machine will be sufficient for the job.

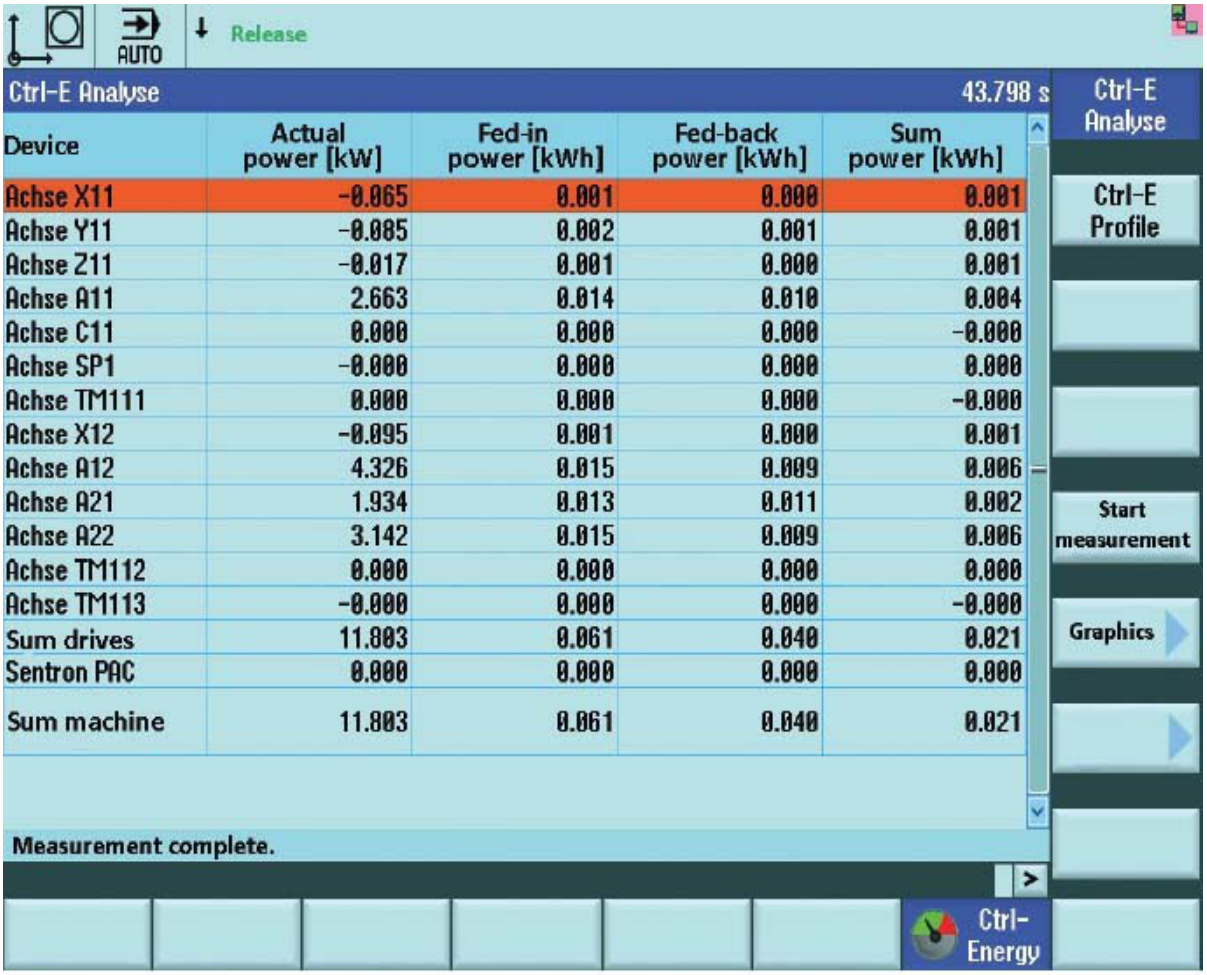
■ The part designer should do the first step in conservation of energy by keeping the efficiency of the machining operations of the part in mind. A directive should be given to the designer that only approved standard tools (i.e., drills, milling tools, thread cutters, etc.) should be used. This reduces the number of tools in the magazine and the associated tool changes. The savings lies in the number of necessary tools and the reduced processing time.

■ *Warm-up* Customary warm-up runs in the morning can possibly be reduced. It is advisable to consult with the machine

manufacturer for an acceptable procedure so that the first parts can be produced without loss of precision. If the variety of parts allows it, it is advisable to start the shift with parts that require more roughing operations. In general, CNC functions for automatic heat distortion compensation offer good temperature stability.

■ *Direct measuring* It has been proven that linear encoders are more precise and temperature stable than spindle/rotary encoders. Continuously changing axis movements warm up the spindles and negatively influences the dimensional accuracy.

■ *Full load or* The question is often asked: what is more economical, a short cycle with a high material removal rate or a slightly longer machining time with reduced speeds and feeds? Longer operating times result in a higher base load. This effect can be so great that when cutting with reduced feeds and speeds, the higher base load voids possible energy savings. A CNC machine operated at full power, for which it has been designed, allows short processing times and fewer operational hours. Machine tools are constantly improved to withstand high loads without damage. Therefore it is counterproductive to operate a machine under reduced load to save energy. In the end, it is always indicated to look in each case at the whole picture so that all measures in terms of energy use, processing time machine, and tool wear are duly considered.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Achse Y11 -0.085 0.002 0.001 0.001
Achse Z11 -0.017 0.001 0.000 0.001
Achse A11 2.663 0.014 0.010 0.004
Achse C11 0.000 0.000 0.000 -0.000
Achse SP1 -0.000 0.000 0.000 0.000
Achse TM111 0.000 0.000 0.000 -0.000
Achse X12 -0.095 0.001 0.000 0.001
Achse A12 4.326 0.015 0.009 0.006
Achse A21 1.934 0.013 0.011 0.002
Achse A22 3.142 0.015 0.009 0.006
Achse TM112 0.000 0.000 0.000 0.000
Achse TM113 -0.000 0.000 0.000 -0.000
Sum drives 11.803 0.061 0.040 0.021
Sentron PAC 0.000 0.000 0.000 0.000
Sum machine 11.803 0.061 0.040 0.021
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Start measurement
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Measurement complete.
Ctrl-Energy

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FIGURE 18.2 Modern CNC machines provide aide to the user to optimize the process in terms of energy efficiency: overview of current power consumption; curves of two measurements of energy consumption of a machine tool, Sinumerik 840o si, function CTRL-E. Siemens.)

REACTIVE POWER COMPENSATION

There is one more option to noticeably reduce energy costs, especially for large companies with a very high demand for electrical energy. For this, a capacitor of the appropriate size is connected in parallel with each inductive user or a central reactive power compensation installation is used for the demand-controlled turning on and off of the capacitors. Theoretically, reactive power can be completely avoided in the transmission network, but this does not happen in practice. It compensates up to cos ϕ of 0.95 to 0.98, which significantly relieves both the customer and the utility company. As a result, it may also be possible to use a smaller transformer to transform the kilovolt supply to the 400-V network, which also saves costs.

WHAT IS REACTIVE POWER?

The value × sin ϕ is called *reactive* Reactive power puts a load on the supply lines and supply transformers but does not provide any true power to the user 18.3 and

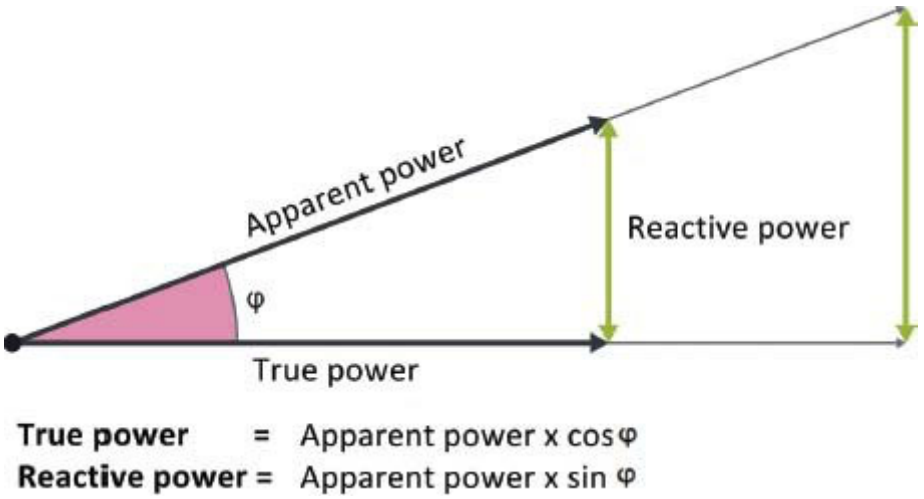

FIGURE 18.3 Reactive power triangle.

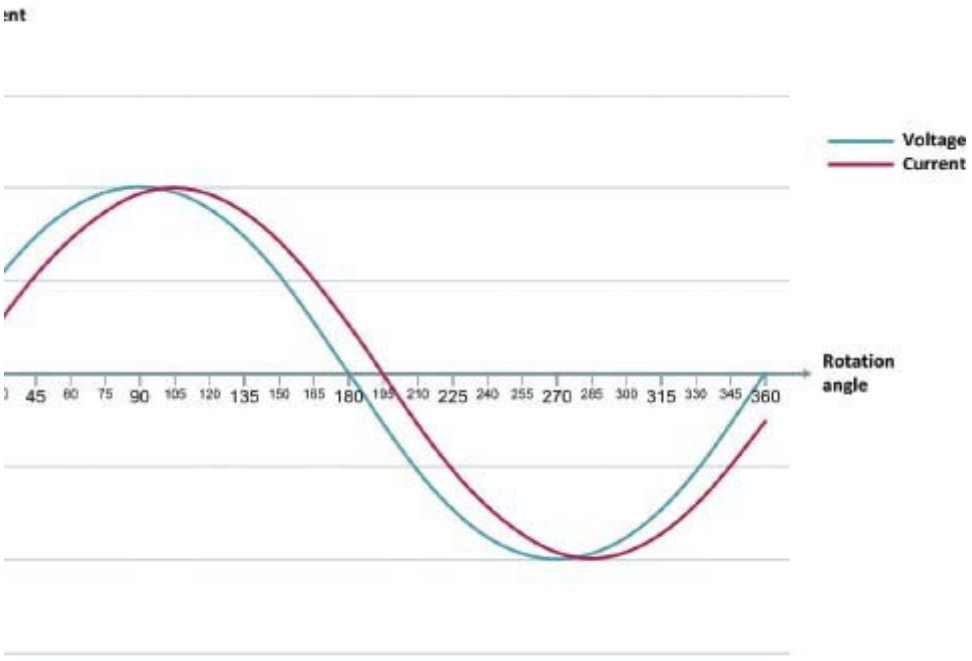

FIGURE 18.4 Graphs of voltage and current with inductive load with a lag angle of 15 degrees, meaning cos ϕ = 0.97. The share of reactive current amounts to 26%.

Calculation

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The reactive power share is often underestimated. Cos ϕ = 0.90 does not mean approximately 10% reactive power but rather 44%

TABLE 18.1 Numerical Values for cos ϕ and sin ϕ

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ϕ

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Calculating Example

An electrical device draws an apparent power S = 6,000 VA from a 230-V circuit at a power factor of cos ϕ = 0.80, which is equivalent of 36 degrees, or sin ϕ = 0.588.
The share of reactive power at cos ϕ = 0.8 = 59% of net power.
The true power results in P = 6,000 VA × 0.8 = 4,800 W.
The reactive power Q is not 1,200 W, the difference between apparent and true power, but is calculated like this: Q = S × sin ϕ = 6,000 × 0.588 = 3,528 VAr.

The electricity bill reflects when the specified limit of reactive power consumption has been exceeded. Depending on the terms of the contract with the utility company, the reactive current that exceeds the limit might have a higher unit price. These costs justify the investment in measures for reactive current compensation and, ultimately, energy efficiency.

SUMMARY

There are about 400 different types of machines, and it is understandable that there can be no blanket statements about "optimal" savings approaches, neither from the side of the manufacturer nor from the operator. All involved parties—machine developer, builder, and user—should strive for energy efficiency and conservation.

One of the reasons for the high base load of CNC machines is that manufacturers tend to design their machines as universal machines. For this reason, new machine concepts are routinely equipped with all previously requested and profitable components and dimensioned for maximum performance. In reality, however, many components are oversized for regular operation, for instance:

- High rapid traverse speed
- High acceleration
- High spindle speed
- High spindle torque
- Short chip-to-chip times during automatic workpiece change
- Fastest possible tool change

OUTLOOK

It should be considered that energy efficiency is important in manufacturing; savings measures are very diverse but may not be limited exclusively to CNC machines. The balance between energy efficiency and productivity is not easy to find. This “balancing act” is likely to become even more complicated with multitasking machines.

IMPORTANT POINTS TO REMEMBER

1. Definition

The energy efficiency of a machine tool is understood as the energy consumption:

a. Per number of workpieces produced

b. During the operating time of the machine

c. Including nonproductive times when no cutting takes place

d. Including idling time (standby mode) of the machine

2. Energy efficiency: A process is energy efficient when a particular benefit is achieved with minimal energy consumption.

3. Improved energy efficiency of a CNC machine is understood to mean that energy consumption reduced to a minimum during operation, including all nonproductive times.

4. Type of operating energy: mainly the electricity for powering axes and spindle movements, tool changes, compressed air, hydraulics, cooling, lubrication, and chip disposal.

5. Possible “levers” for reducing operating energy include:

a. Proper machine selection: size, power, degree of automation

b. Consumption-optimized parameterization of all drives

c. Consumption-optimized design of the NC programs with regard to as few tool changes as possible and optimized spindle retraction levels during operation and tool change

d. Use of energy-optimized components with electrical feedback, for example, electric drives for main spindle and servos

e. Complete shutdown of the machine during nonproduction times

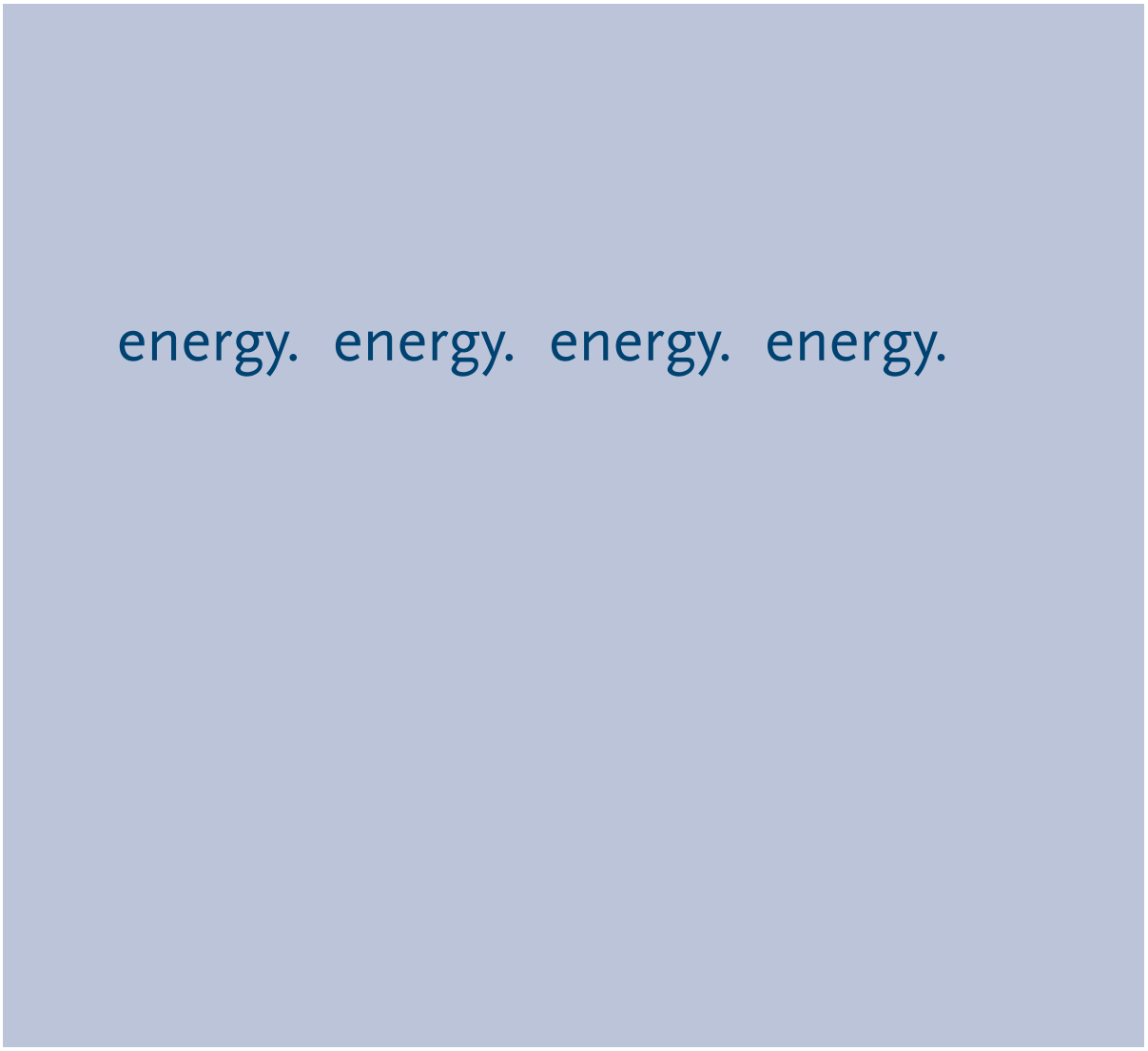
6. Adjust machine conditions and states according to the current demand, for example, clamp and turn off axes after reaching the target positions instead of using the hold torque of the motors.

7. Use hydraulic power aggregates that regulate pump output according to the specific needs or do not use hydraulics altogether.

8. Reactive power compensation: inductive power consumers generate reactive power that is credited by the energy provider. This savings option is often underappreciated and not used sufficiently.

9. The compromise between energy efficiency and productivity is not easy to find. This situation will become more complicated with the use of multitasking machines.

10. Energy efficiency is an important objective in the design and use of modern CNC machines. These machines come with integrated sensors and ways to measure and optimize the use of energy.



19 Tool Construction

20 Tool Management

21 Machine-Integrated Workpiece Measurements and Process Control

22 Machine-Integrated Workpiece Measurements in Series Production

23 Laser-Based Tool Monitoring

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INTRODUCTION

CNC machines work independently, precisely, and reliably. The prerequisite is that the CNC program is error free, the blank is properly clamped, and the correct tools are used in the machine. When setting up the machine, the tool is prepared and used as it is listed and described in the work instruction sheet. When creating the NC program, the programmer uses documented tools. It should actually be quite simple, given that everything is already prepared. On the one hand, however, the setup person must understand the work instructions; on the other hand, someone must be able to document a new tool for the job, given that no tool has yet been defined. This task also arises when the tools have to be selected for a new machine. In addition, it is appropriate to reconsider the expediency of existing tools so that possibly better suited tools can be procured. For this, technical knowledge of the different aspects of the tools is necessary.

REQUIREMENTS

Reliability

The reliability of a tool has a geometric and a technological aspect. Both are prerequisites for the economy of a CNC machine processing of workpieces.

The geometric reliability is based on the facts that a tool must not change its shape during machining and that a replacement tool with the same geometry is available. While this may sound obvious and simple, a close look reveals it to be a challenge. The force with which a tool acts on the workpiece always alters the geometry of the tool. Given a suitable design of the tool, this change can be kept within the limits of the tolerable deviation for the workpiece

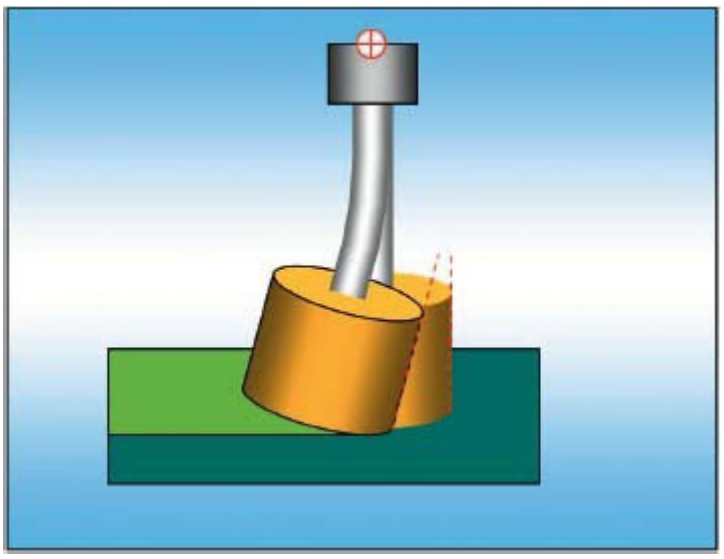

FIGURE 19.1 Aspects of the geometric reliability of a tool in use.

A certain tolerance must also be available to replace the cutting insert in a tool body. The accuracy of the geometry after replacing the insert depends on the quality and structure of the tool. The tolerance of a newly purchased tool depends on the supplier and its manufacturing quality.

The accuracy of the cutting result after replacing an insert can be qualified with a measurement. Ideally, the exchange of an insert does not require a remeasurement of the tool. The value of the possibly present deviation on the newly cut workpiece is entered into the CNC program.

The *technological reliability* refers to the constant cutting performance. It must be predictable how long a tool can be used until it is no longer sharp and therefore has to be replaced. The same service life must always result for a set of given cutting data so that a tool change can be planned in advance. In this context, *tool life* means how many minutes the tool can be used until it is dull and therefore needs to be replaced.

Cutting Data

Cutting data are the restraints under which a tool is used 19.2 and These are:

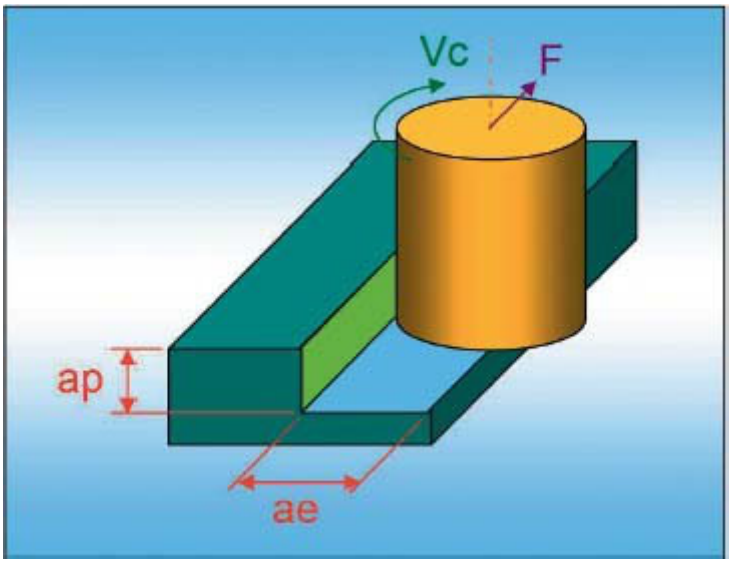

FIGURE 19.2 Width of cut depth of cut *ap* of a milling tool relative to feed *F* and cutting speed

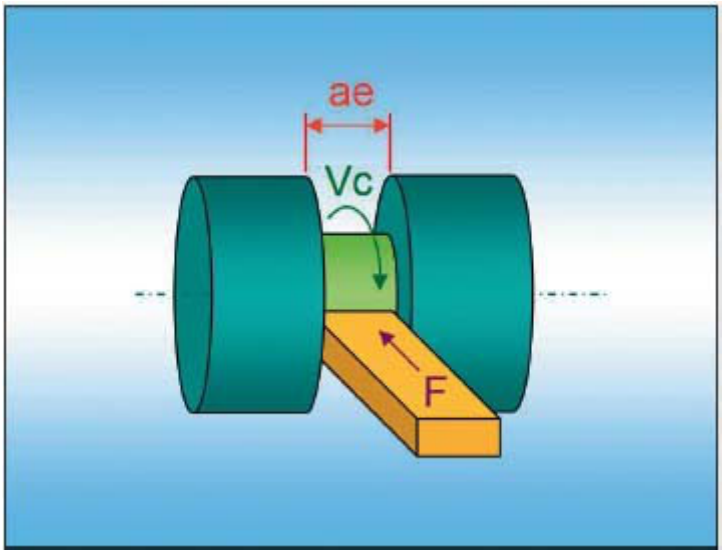

FIGURE 19.3 Width of groove *ae* relative to feed *F* and cutting speed

■ Cutting speed *Vc* in m/min. This is the speed with which the cutting edge moves across the workpiece surface.

■ Feed *F* in mm/min or mpr (mm/rev). This is the speed at which the tool moves forward.

■ In-feed. This is the amount of material removal across the machining orientation. On milling machines, two directions apply: engagement depth *ap* in mm, or how deep a tool engages into the material, and engagement width *ae* in mm, how much material is removed in one cut.

■ Cooling/lubrication. The differences that are made include

- Application on workpiece surface: inside or outside

- Kind of coolant: air or emulsion

- Intensity: mist or high-pressure application

■ Restraints regarding the workpiece. Material, quality of the clamping, possibility of removing the chips, changing engagement conditions due to existing features or varying material thickness of the castings.

NC programming requires values for *F* and In the tables for cutting speeds, the tool manufacturers typically provide information for *Vc* and Given feed rate *Vc* and diameter *D* of the tool (milling) or workpiece (turning), the spindle speed *S* can be calculated:

$$S = (2 \times \times$$

The feed F and the spindle speed can also be used to calculate the feed rate ft per cutting edge (tooth):

$$F = \times$$

where n stands for the number of cutting edges

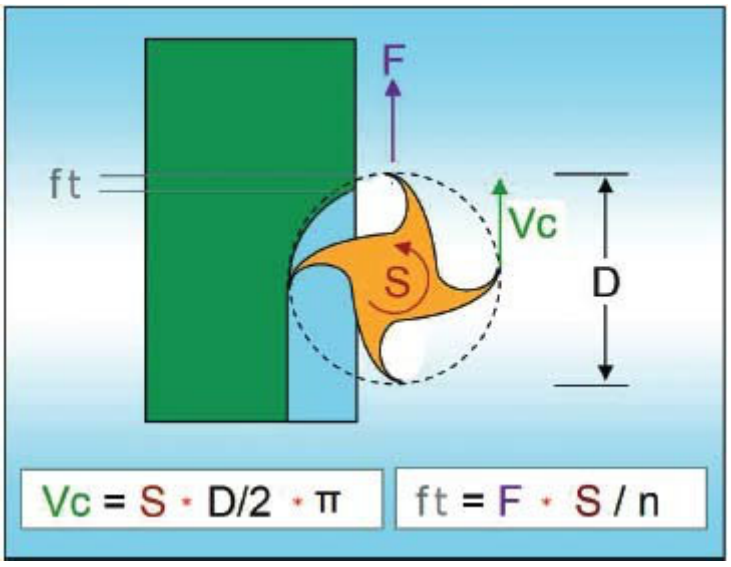

FIGURE 19.4 Feed per tooth ft and feed per minute F depending on the feed rate

Flexibility

In addition to the reliability of tools, flexibility is very important. A shop must often manufacture a new part on a short notice, as is typical for subcontracting companies, and must have the tools available for it. The solution to this situation lies in modular

tooling systems, in which new tools are combined from standard elements.

Handling

It is required of modular tool systems that handling is easy and mistakes are excluded. Easy handling allows the advantages of CNC technology to be used properly, which requires a fast conversion to changing machining tasks. Below is an example of the balancing between ease of use and reliability, illustrated for the clamping of an end mill.

An end mill can be clamped quickly and simply in a drill chuck, meeting technological and geometric requirements. Using a collet, a higher quality is achieved, but one collet must be procured for each diameter. The highest quality of chucking can be achieved with a hydraulic expansion chuck, but the requirements for acquisition, maintenance, and handling increase.

OUTLINE OF TOOLS

In order to formulate properties and features for a variety of tools, it is helpful to divide them into groups.

Stationary/Rotating

Stationary tools are used on a lathe, and the tools move in the The workpiece rotates around the The cutting speed *Vc* is determined by the number of rotations of the workpiece per minute and the diameter that is to be machined

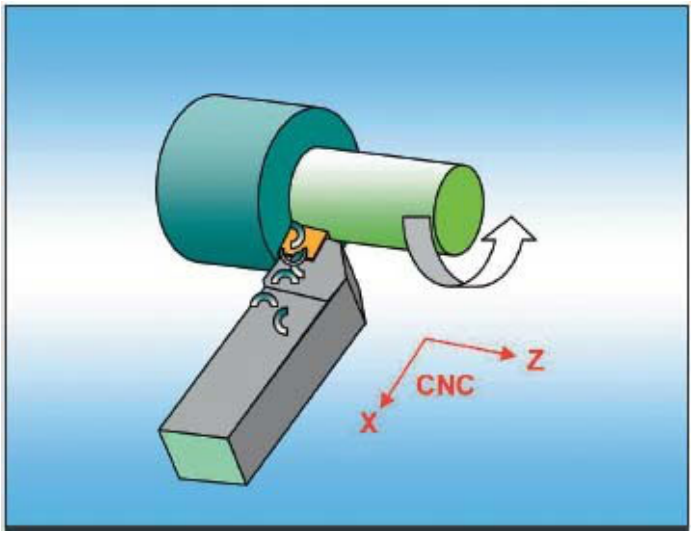

FIGURE 19.5 Axis orientation of the coordinate system for the NC program of a lathe.

The CNC program provides the command G96 for constant cutting speed constant), so it is not necessary to calculate the appropriate spindle speed to keep the cutting speed constant (as the diameter gets smaller, the spindle speed increases). Accordingly, the

feed rate *F* is set with the command G95 for an advancement per spindle revolution, so regardless of the spindle revolutions per minute, the workpiece advances the same distance.

For rotating tools used on a milling machine, the spindle speed *S* is usually set with the command G97 (revolutions per minute), and G94 is used for constant feed rate *F* per minute

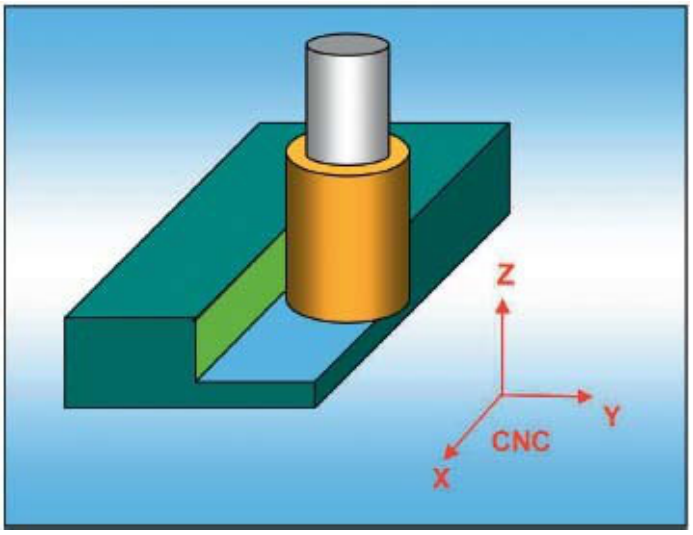

FIGURE 19.6 Axis orientation of the coordinate system for the NC program of a three-axis milling machine.

The tool typically rotates around the (plane selection G17), and it moves in all three axes. Unlike stationary tools, rotating tools usually have more than one cutting edge (tooth). This must be taken into account when calculating the feed rate When producing many chips in tight conditions, for example when milling a groove, it is important that not too many cutting edges obstruct chip removal.

Component/Complete Tools

When talking about a tool on a CNC machine, for example, a 20-mm end mill, one thinks of an assembled, ready-to-use tool. In contrast, when purchasing a tool, one thinks of a tool, for example, a 20-mm end mill, only as one component A complete tool is therefore a combination of several components. Complete tools must always be provided for CNC machines. In terms of tool storage and purchasing, one speaks of tool components, which are assembled to complete tools according to instructions provided in the tool sheet.

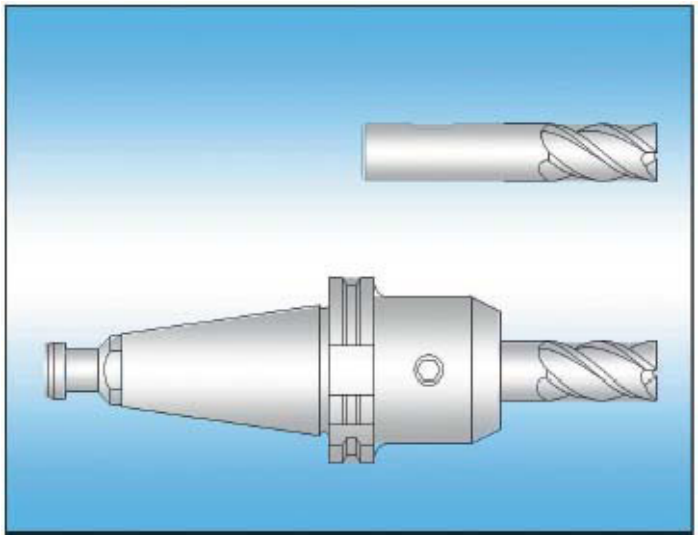

FIGURE 19.7 Difference between a single component (end mill, and a complete tools (end mill mounted in a tool holder,

Tool Type

Tools have names, like any other object, in order to express what the tool is or does. Everybody knows what a hammer is or a chisel, drill, or lathe tool. These are common names. The more tools are in use and the more detailed in which one talks about them, the finer the terminology must be in order to distinguish them. An official structure was created early by the German Institute for Standardization (DIN).

The most important tool types according to DIN 4000 are:

- FSJ: milling cutter with shank and inserts
- FSN: milling cutter with shank without inserts
- FBJ: milling cutters with bore and inserts
- FBN: milling cutter with hole without inserts
- BNJ: drills with inserts
- BNN: drills without inserts
- BGN: drill bit for thread
- DDJ: turning tools
- MHX: holder for rotating tools
- MFX: holder for standing tools
- SPJ: inserts
- SKJ: cut off tool (inserts for grooving)

For each tool of a type, the DIN standard contains a list of parameters that are used to geometrically describe the tool. Within a

tool type, for example, BNN, different-looking tools are grouped together, for example, straight drill bits, drill bits with step. Therefore, the standard also contains suitable pictures that explain where the values, for example, A1, B4, etc., must be measured 19.8 and

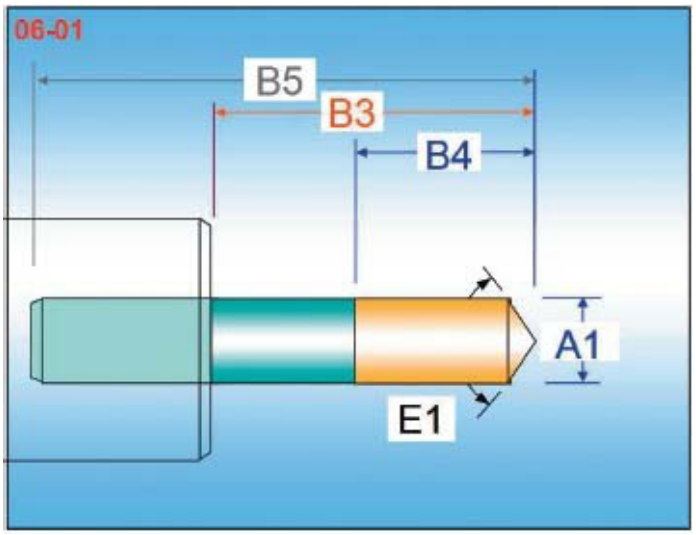

FIGURE 19.8 Schematic for geometric data of spiral drill.

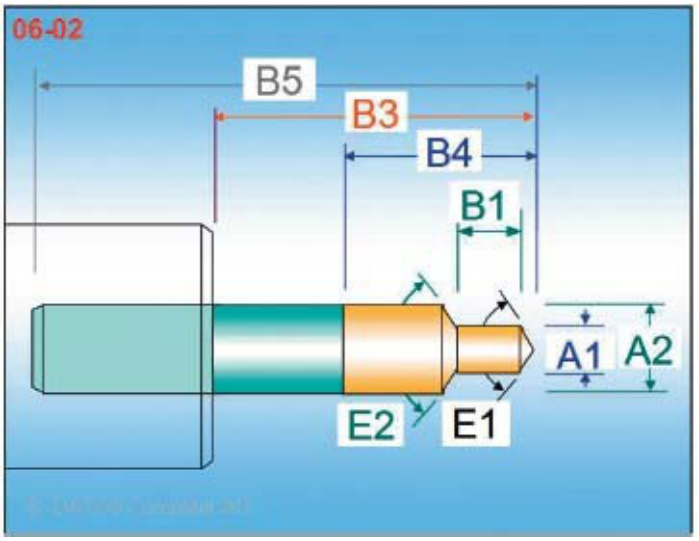

FIGURE 19.9 Schematic for geometric data of step drill.

By specifying the tool type and the values for the parameters, such as A1, B4, etc., a tool thus can be uniformly and systematically defined geometrically. This standardization ensures that the supplier and customer understand each other. If the customer asks the supplier for a tool with a larger rake angle, the supplier will be able to service the request because both parties understand what is meant If the customer asks for a cutter according to DIN 844, it is clear that the cutter has a cylindrical shank and not one with a Morse taper. The DIN standard is also used as the basis for software applications in the manufacturing environment and for data exchange. These aspects were included in the newer and more comprehensive International Standards Organization (ISO) 13399 standard.

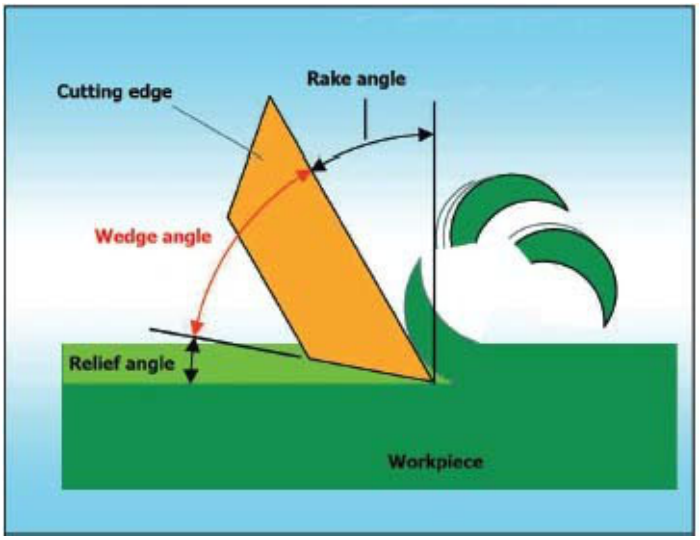

FIGURE 19.10 Relevant angles on a cutting edge.

List of Characteristics

The DIN standard contains a list of the parameters used for the description of each tool type. This list of parameters is called a *feature* To describe a tool, each feature contains the corresponding value

Picture	Diameter A1	Diameter A2	Length B1	Length B2	
06-01	10.00			50.00	
06-01	12.00			50.00	
06-01	14.00			55.00	
06-02	10.00	14.00	22.00	60.00	

FIGURE 19.11 List of characteristics.

This representation is suitable for lists. The characteristics can be listed side by side or in a vertical arrangement. This is the known format of data sheets of index cards. It uses the term but it is merely a different form of data collection 19.12 and

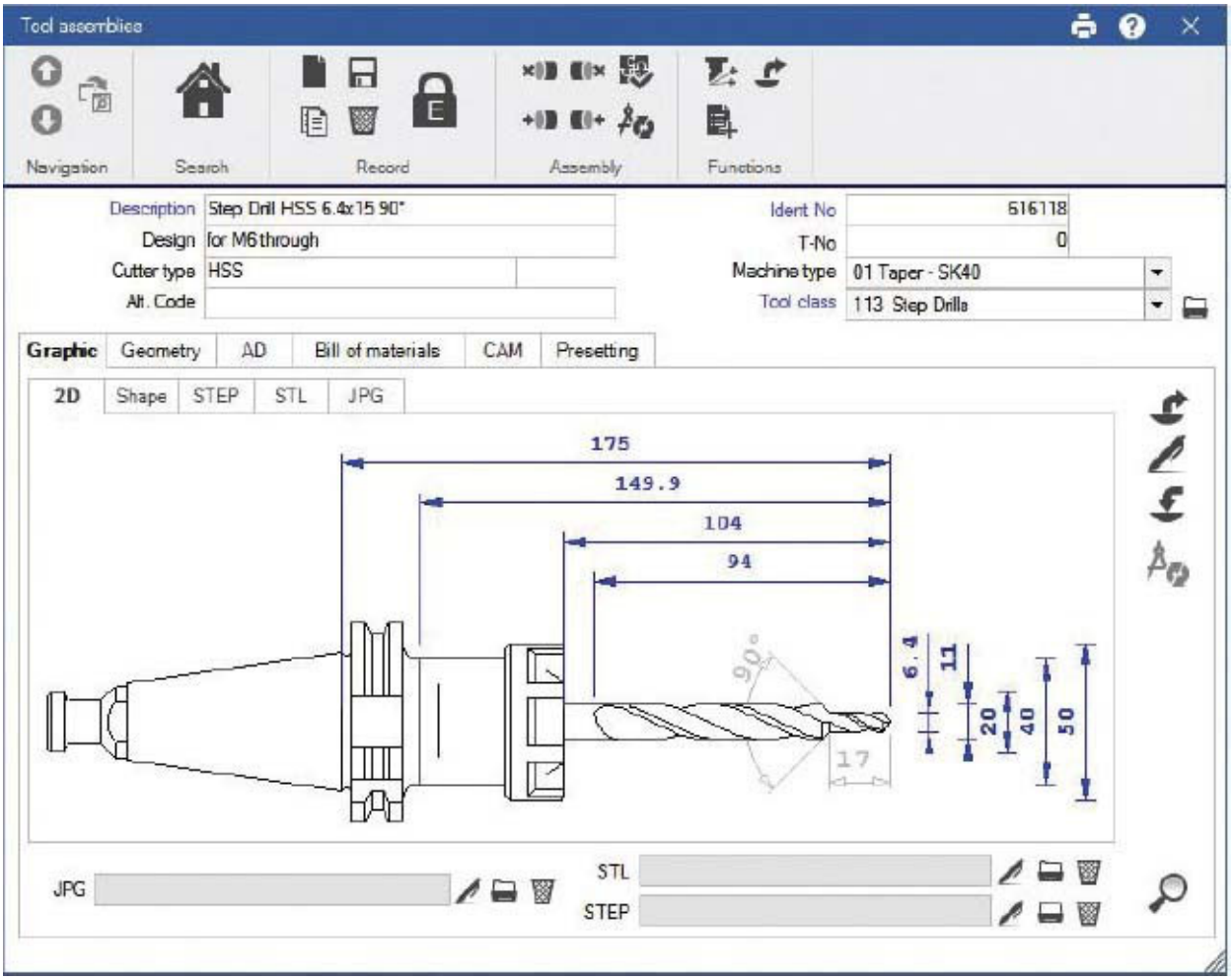

FIGURE 19.12 Representation of the characteristics of a mask in an application.

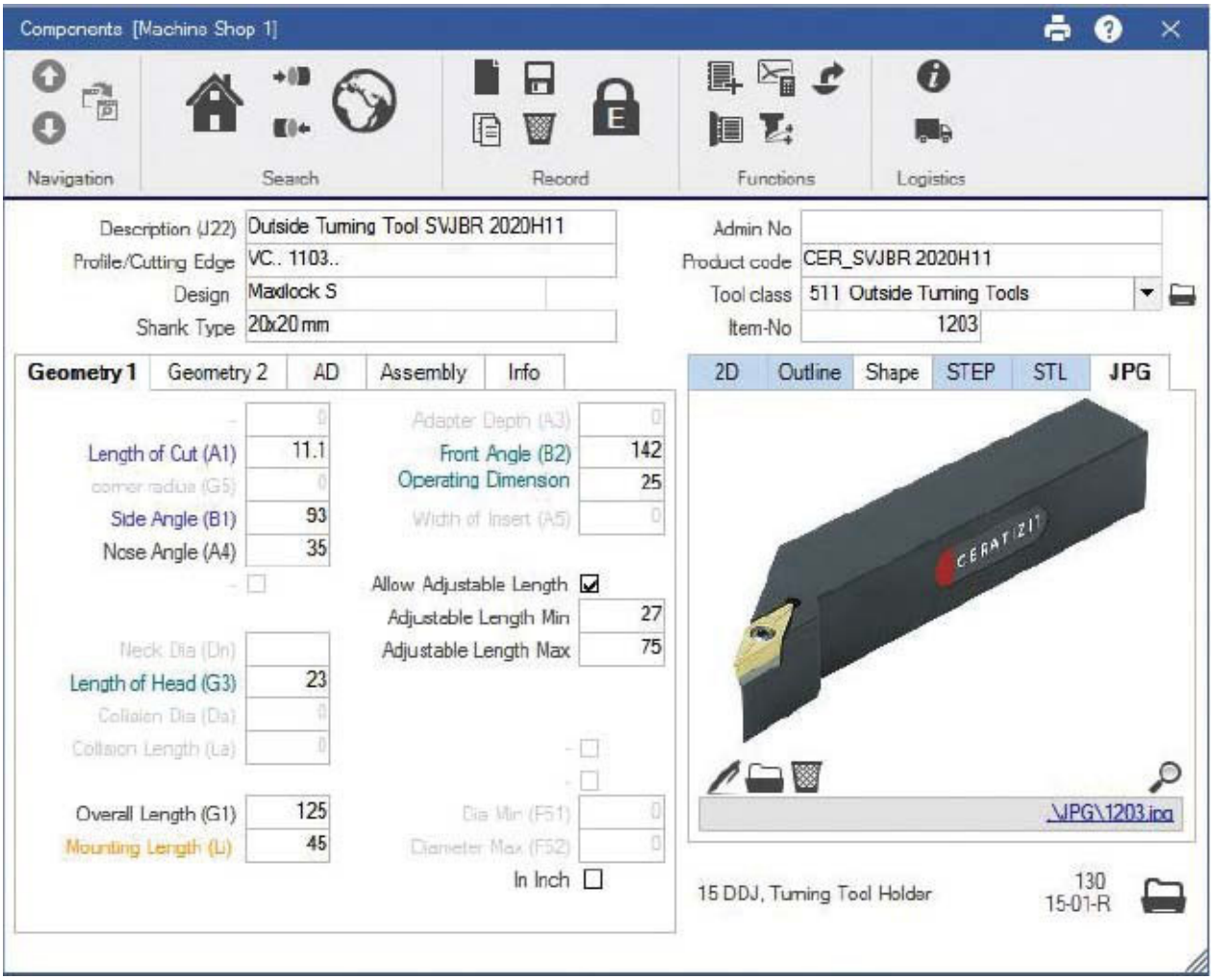

FIGURE 19.13 Different characteristics of different tool types.

In the same way that address management collects other data than article management, different fields are required for the different tool types. Here it makes sense to place fields that are relevant for all tool types at the same place in the form, for example, diameter, price, and order number.

It is obvious that in an in-house application, in addition to the descriptive features, internal and organizational data fields are needed; these could include SAP (Systems, Applications, Products Company) number, stock status, warehouse location, and use history.

Tool Classification

In contrast to the tool type, which has a cross-company meaning, the classification of the tools is an internal task. Classification of the tools ensures easier understanding within the shop. The tools are classified according to their type and shape (e.g., tap, metric for a blind hole). It is customary to combine several classes into one higher class and multiple higher classes to a main class. This results in a three-stage company-specific structure by means of which the desired class is easily identified

TABLE 19.1 Example of a Customer-Specific Classification

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The classification is a detailed gradual organization of tools. Each class is comprised of similar tools of different sizes. In most companies, the classification corresponds to the structure of the cabinets in which the tools are stored. When designing a new classification, it is advisable to start with a large outline so that the details remain clear.

Cutting Material

Tools are not classified according to the material of the cutting edge. It rather details what material can be processed and provides technical data for the processing.

Tools often have a coating applied to the cutting edge to reduce wear. Tool manufacturers select various designations for these coatings, but the purpose is always the same. The material of the cutting edge can be differentiated between:

- High Speed Steel (HSS) and HSS-E denotes a higher quality)

- Solid carbide

Cutting insert materials can include:

- HSS
- Carbide with/without coating
- Cermet (ceramic-metal composite material)
- Diamond (polycrystalline [PCD] or monocrystalline [MCD])
- Cubic boron nitride (CBN)
- Ceramics (oxide, nitrides, mixtures)

The choice of cutting material and the cutting speed mainly depend on the material and the type of machining, such as roughing, finishing, etc. Based on the standardized structure of the materials according to DIN ISO 513, the range of application for the various cutting materials can be characterized clearly and quickly. The materials are divided into the groups P, M, K, N, S, and H The machining itself is divided into the grades 01, 10, 20, 30, 40 and 50, where 01 corresponds to fine machining, 30 roughing machining, and 50 very rough machining with irregular engagement conditions (e.g., an interrupted cut).

TABLE 19.2 Cutting Properties of Materials

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MACHINE-BASED TOOL HOLDERS

When assembling a complete tool, special attention must be paid to the machine-based mounting so that the tool can be used in the machine. Different requirements must be considered for rotating tools, such as in a machining center, and stationary tools, such as on a lathe.

Rotating Tools

The spindle of the CNC machine must receive the tool exactly centric and transfer the rotation without vibration. In addition, when a large amount of power is transferred, as is the case with a large tool, the cutting force must be transferred to the cutting edge, and the tool must not slip in the holder. Because NC programs use several tools, the holder or receptor in the machine must be designed in such a way that an automatic tool change can be performed quickly and safely.

The tools needed for processing are placed in a chain or cassette before use. The tool changer picks up the tool from there, controlled by the command M06, and exchanges it with the one in the spindle.

All tools must have the same holder because the spindle of the machine is designed for a particular type. The tool changer requires the gripper to have standardized grooves so that the tools can be picked up accurately, removed from the spindle, or reinserted. To prevent the tool from falling out of the spindle again, it must be pulled and held firmly in the receptor.

For this to work, the steep taper holders have a screwed-in retraction bolt that must match the retraction mechanism of the CNC machine holder. HSK tool holders have a bore with an undercut, and the machine has a matching mechanism and a draw bar.

The different machine-based holders have standardized sizes, and the customer chooses the appropriate spindle for the CNC machine. The steep taper according to DIN 69 871/ISO 7388 has become standard as tool holders for machining centers with sizes 40, 45, 50, and 60. Other steep tapers per DIN 2080, the Maharashtra State Board of Technical Education (MASBTE), and Catapillar taper (CAT) work with the same principle but are not compatible The HSK holder DIN 69 893/ISO 12 164 has been developed for high-speed cutting (HSC). It is characterized by high accuracy and high rigidity

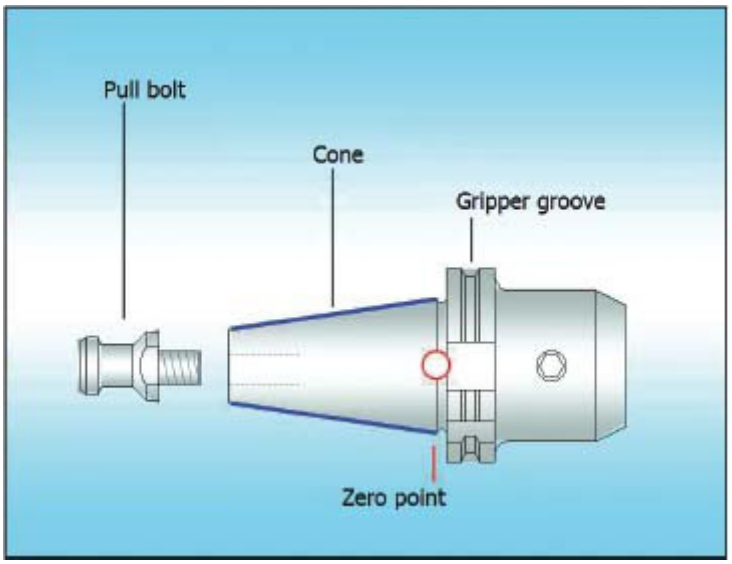


FIGURE 19.14 Sketch of tool adapter with designations.

FIGURE 19.15 Tool adapters: HSK adapter per DIN 69 893; steep cone per DIN 69 871.

For applications with relatively low power (e.g., a milling spindle on a lathe center), the spindles are often equipped with CAPTO, ABS, or UTS interfaces that were originally intended as a coupling for modular tool systems. This allows the direct use of tools of modular tool systems.

Stationary Tools

The requirements for tool holders for stationary tools on a lathe differ naturally from those of rotating tools. It is important here

that the tools remain stable and take up little space. Easy handling is important because most lathes are not equipped with an automatic tool changer but use a turret for this purpose. The number of tools on a lathe is generally smaller than for milling machines. A tool turret can easily be loaded with tools, and it takes little time for a tool change compared with a milling machine. Turrets are typically equipped to accept the interfaces VDI (DIN 69 880/ISO 10 889), CAPTO (ISO 26 623), Prisms (DIN 69 881), ABS, and HSK 19.16 through

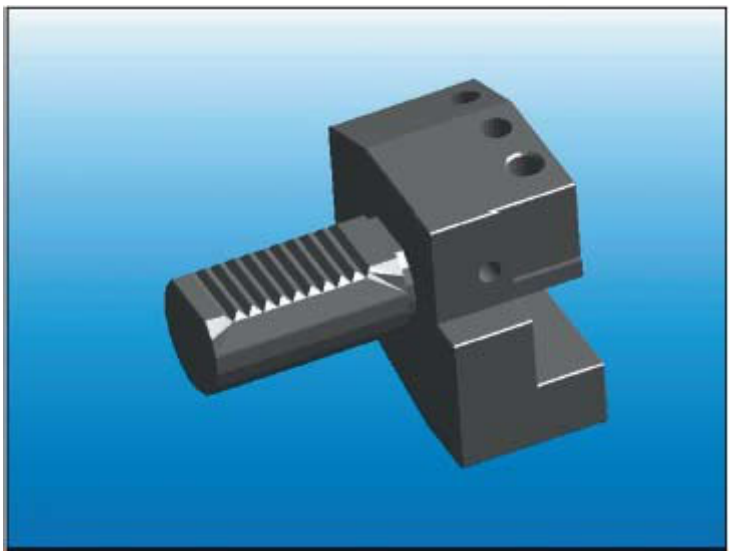


FIGURE 19.16 VDI tool holder for lathe tools with a square shaft.

FIGURE 19.17 CAPTO adapters of various sizes.

FIGURE 19.18 Prismatic tool holder for boring bars per DIN 69 881.

FIGURE 19.19 Schematic of an ABS coupling.

Tools on a turret lathe are clamped into the numbered spots in the turret. For example, Roughing Tool 636 101 is placed in Station 1 as a tool T5 on the turret 1. In the NC program, the tool is activated as T5 M06. When forwarding the turret, the CNC machine brings the station into the working position that holds tool T5. Figure 19.20 shows a star turret with 12 stations. No tools are inserted at stations 2, 5, and 12.

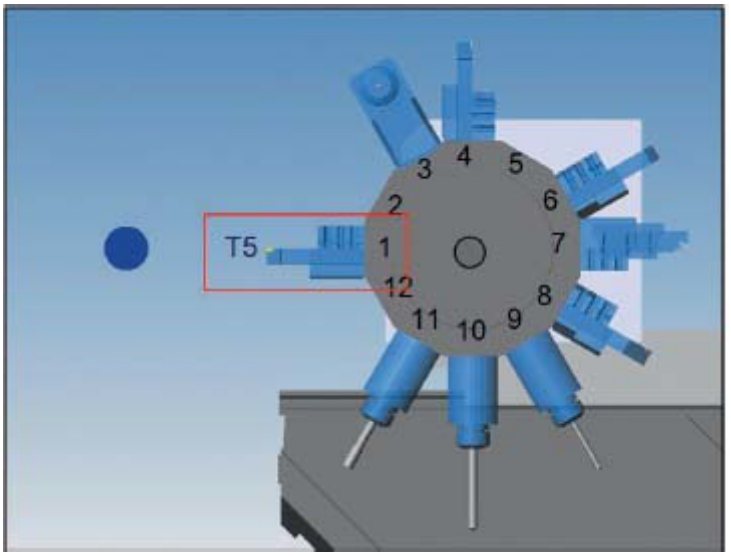


FIGURE 19.20 Star turret with numbering.

Manufacturers of CNC lathes develop tool turrets so that they are tailored to the workspace and the overall concept of the machine. The machine designer takes into account the stability, quick insertion of tools, and the ability to operate as large a workspace as possible without causing collisions. In essence, all designs can be attributed to one of the two following principles:

1. On a star turret, the tools are positioned on the outside, radially on the turret. The requested tool is put into position by advancing the turret accordingly

2. On a disk turret, the tools are mounted laterally

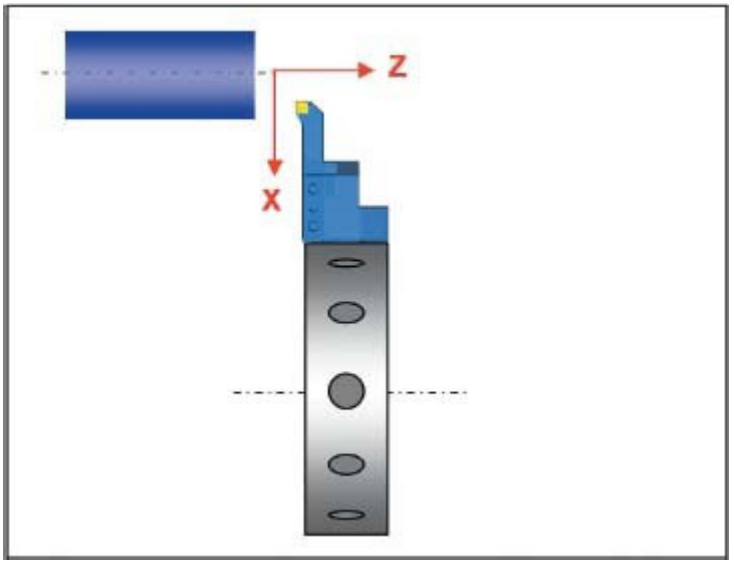


FIGURE 19.21 Principle of a star turret.

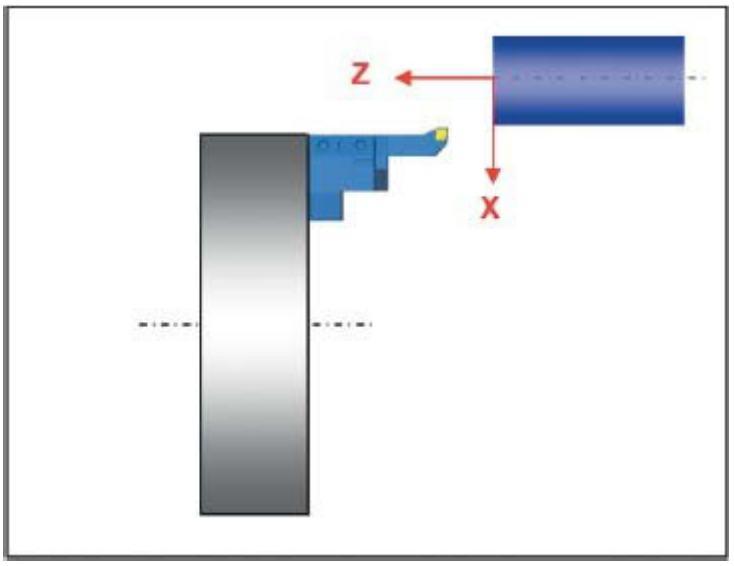


FIGURE 19.22 Principle of a disk turret.

Live Tools

In contrast to the holder in the spindle of a milling machine, the tool in a lathe is static and does not rotate. Because the workpiece rotates, a drill bit can drill a hole on a lathe precisely in the center of the workpiece. The use of live tools on a lathe can expand the scope of machining. When using a live tool, the spindle with the workpiece is stopped and arrested in a determined position. A live drill bit can then drill a hole at any position. Here it is distinguished between radial and axial use of the live tool:

■ Radial machining acts perpendicular to the spindle axis at the periphery of the workpiece

■ Axial, eccentric machining takes place at the face of the workpiece

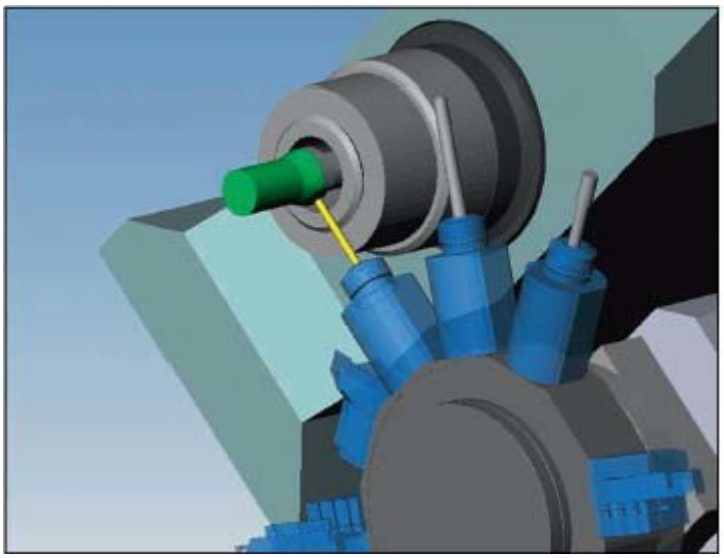


FIGURE 19.23 Live tools on a star turret to apply radial holes.

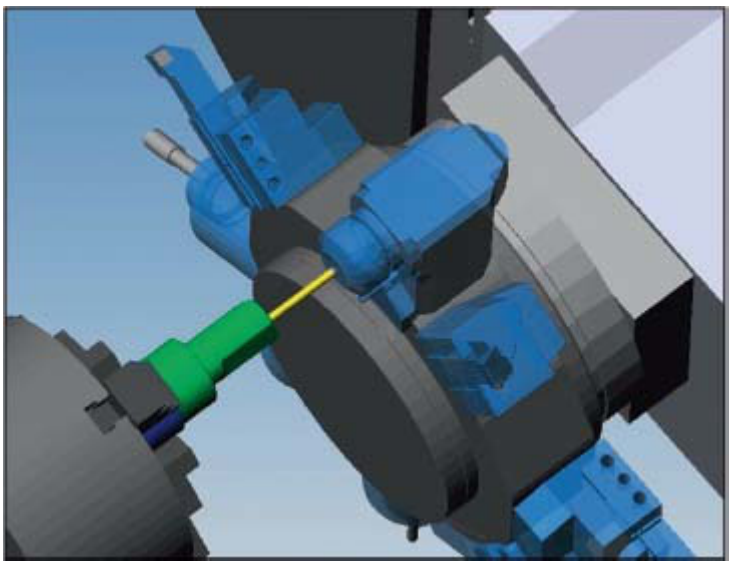


FIGURE 19.24 Live tool on a star turret for axial processing.

A lathe must be designed to work with live tools. The holder on the turret has a machine-specific clutch/transmission element that transfers power. In addition, the main spindle that carries the workpiece must have a numerically controlled (indexed) to provide for defined positioning and arresting of the workpiece.

A lathe-milling machine is used so that other than axial and radial machining operations can be performed. This type of machine possesses an additional live spindle on a pivoting head that allows the workpiece to be machined in two axes using rotating tools, similar to a CNC milling machine The advantage of such a machine lies in the fact that parts can be finished without a second clamping, saving setup time and achieving the required tolerance of the finished part

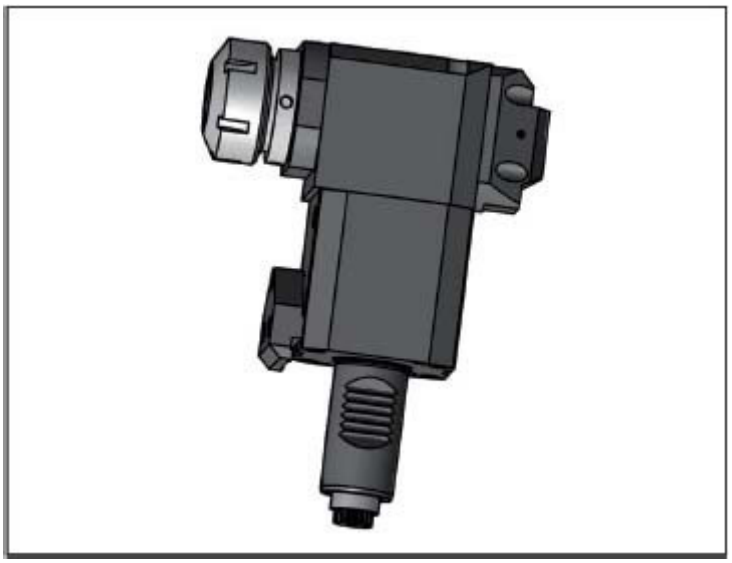


FIGURE 19.25 Angle head with VDI adapter for live tools.

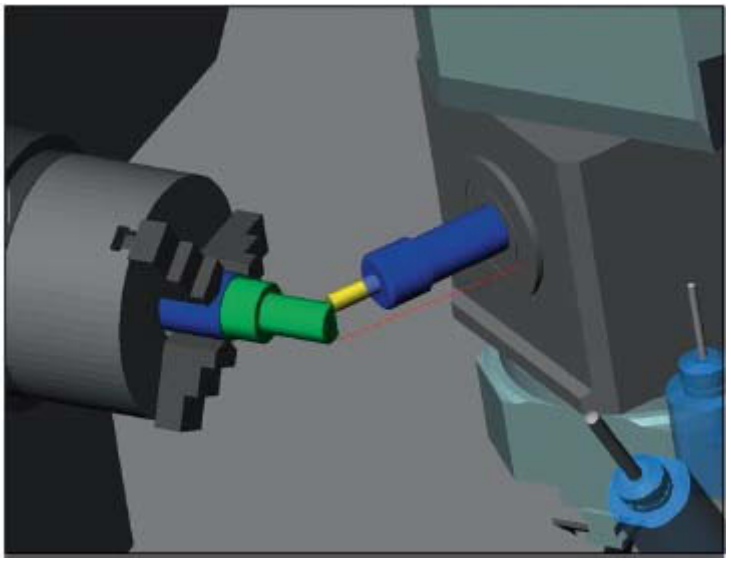


FIGURE 19.26 Lathe with for live tools.

MODULAR TOOL SYSTEMS

In modular tooling systems, the tool body consists of individual elements. On one end it fits the machine holder, and on the other end it holds the cutting tool. Combinations of standard tools, indexable inserts, elements, assemblies, bases, cassettes, and adjustment mechanisms can realize various tools for machining

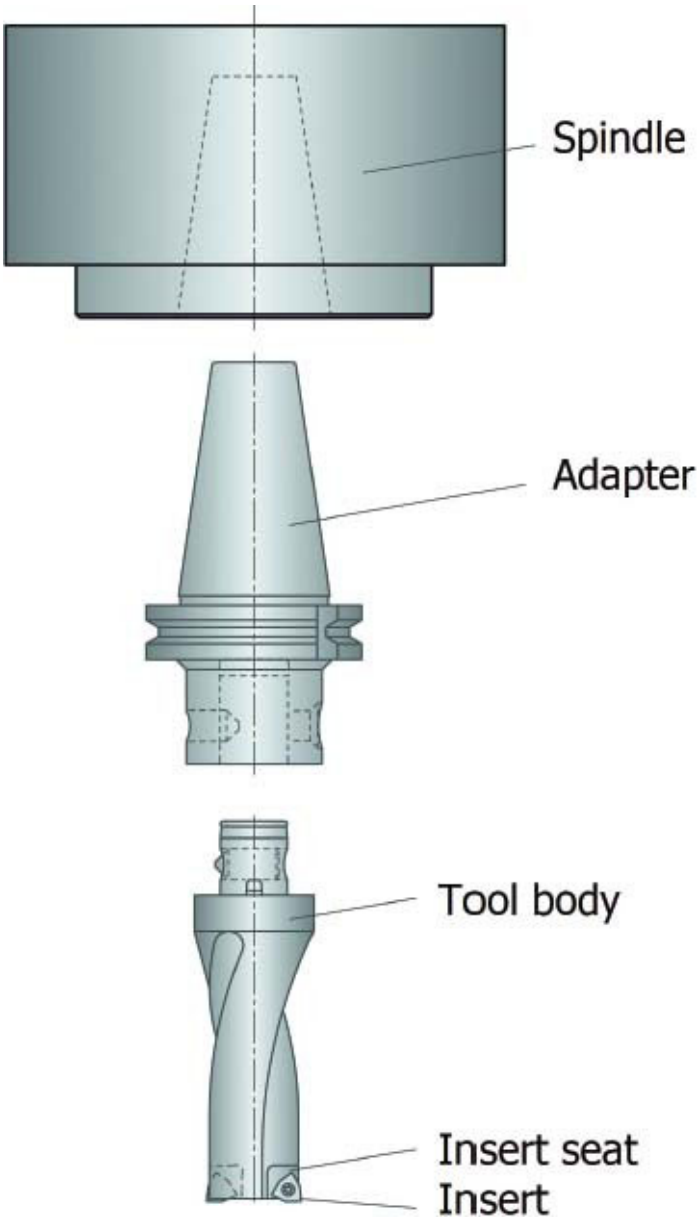


FIGURE 19.27 Components of a modular tool.

The requirements in production are constantly changing. Different from the past, lot sizes are becoming smaller and the variety larger as a result of ever shorter product lifecycles and the desire for individual products. The machine tool and precision tool industry respond to this individualization with appropriate product structuring. Successful approaches of this principle include the formation of series, subassemblies, platforms, modules, and kits 19.28 and

FIGURE 19.28 Universally combinable modular components.

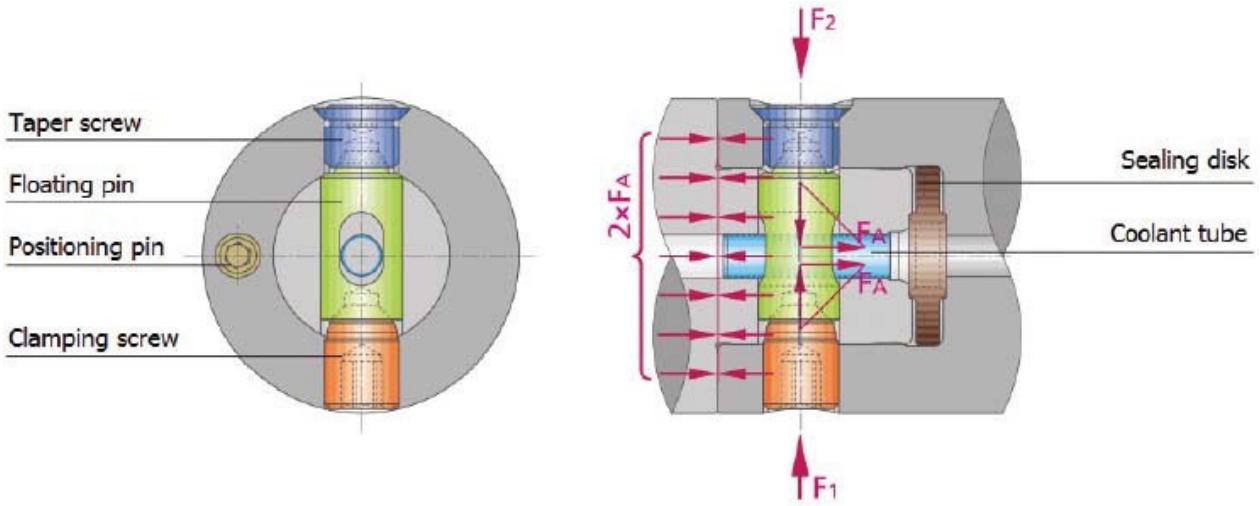


FIGURE 19.29 ABS coupling: a modular coupling system for all rotating and stationary tools. Tool holders with the ABS system can accommodate tools, extensions, or adapters. KOMET.)

Product structuring enables both the tool user and the tool manufacturer to respond quickly to changing requirements. Against the background of economical manufacturing, the tool spectrum can be expanded within a short time. The tool user can produce in smaller batches with a reasonable cost and time frame. Thus, individualization and standardization do not contradict each other.

ADJUSTABLE TOOLS

Fine Machining of Bore Holes

The objective of finishing is to improve a hole in terms of dimensional accuracy, shape, location, and surface finish. The bore dimension itself is established with the cutting edge of the tool. The cutting depth *ap* is usually 0.1 to 0.25 mm but not more than 0.5 mm This cutting edge can either be permanently affixed to the tool or radially adjustable. If the rotating tool has a cutting edge, this is also known as a *spindle-out* Such tools are not used much anymore. Tools with radial adjustment of the cutting edge serve the following purposes:

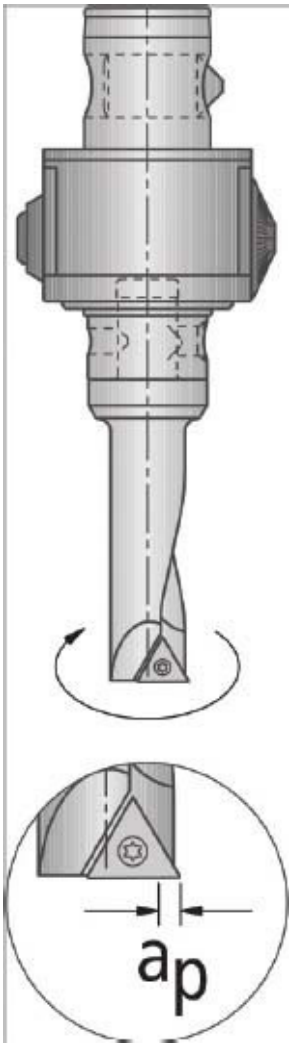


FIGURE 19.30 Adjustable tool for fine finishing.

■ One tool can be used to fabricate different diameters.

■ *Surface* Surface finish depends on, among other things, the corner radius of the cutting edge. The radial adjustment tool uses exchangeable inserts with various cutting tip radii. When exchanging an insert with a different corner radius, the distance of the cutting edge to the center axis of the tool changes and must be adjusted to maintain an identical diameter.

■ *Wear* Adjusting the cutting edge is realized by one of the following five constructive principles:

● *Insert fine* These act directly on the insert. The adjustment travel is limited from 0.01 to 0.1 mm. The indexable insert is attached by means of a clamping screw. The center of the screw is offset by a small amount; in this way, the insert is being pulled into the seat when the screw is tightened

● *Adjustment of cassettes and short clamp* The adjustment is made by adjustment screws, pins, or wedges. Depending on the design, the adjustment path is approximately 0.1 to 0.3 mm on the body of a boring bar.

● *Adjustment* The cutter is directly attached. The use of such boring bars is waning because adjustment and flexibility are limited.

● *Boring bars with precision turning* These are rather conventional spindle tools. The modularity is evident in the fact that precision turning inserts are used to accommodate various diameters as well as the use of inserts. Precision turning inserts are designed for different types of bores, such as flat-bottom holes or through holes. Boring bars with a larger diameter/length ratio thus also can be realized. The tools are usually custom-made boring bars, and precision inserts are available as standard modules.

● *Fine adjustment heads with integrated adjustment* This principle employs a slider that moves in radial direction. The slider incorporates a separating mechanism for the holder of boring bars that feature integrated inserts, cutter holders, or swap bridges. For the first three design principles, the adjustment of the cutting edge

is usually performed on a presetting bench. The other two design principles use a dial disk to visualize the adjustment.

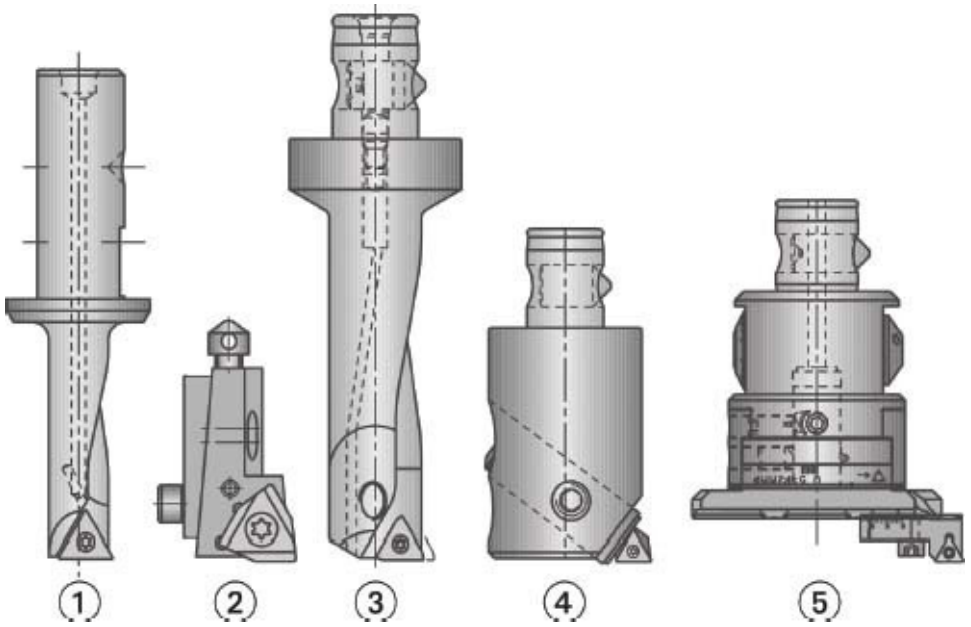


FIGURE 19.31 Adjustable heads with indexable inserts for fine finishing.

For fine-adjustment heads, the user has the choice between an analog and a digital display

FIGURE 19.32 Fine-adjustment head with digital display.

Modulation with Fine-Adjustment Heads

Modulation of fine adjustment is available in a variety of combinations for different adjustment paths and uses boring bars, blade carriers, and swap bodies. The basis is a fine-adjustment head or a series of fine-adjustment heads

FIGURE 19.33 Fine-adjustment heads for different diameters.

For the diameter range 0.5 to 25 mm, boring bars with a cylindrical shank or a modular separation point are used; for the range 25 to 60 mm, form boring bars with serrated bodies and cutter holders are used; and for the diameter range 60 to 125 mm, swap bodies with cutter holders are used In high-speed applications, especially for small diameters, fine-adjustment heads with automatic balancing are used. The balancing mechanism uses a mass element that automatically moves in the opposite direction when the slide is moved

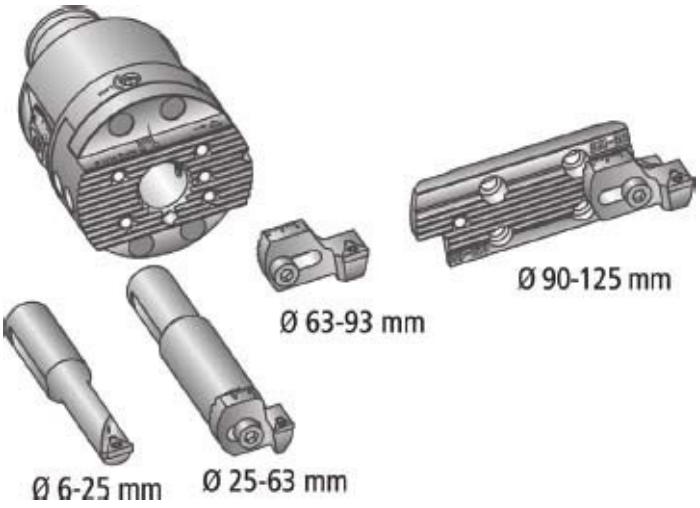


FIGURE 19.34 Elements for modular combination.

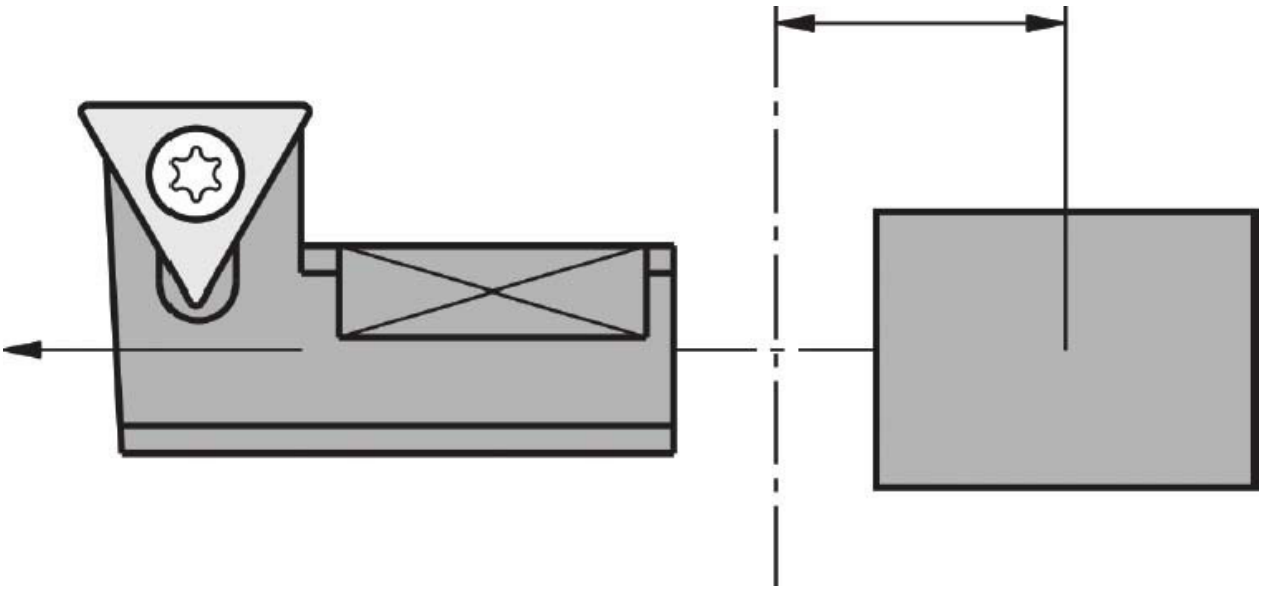


FIGURE 19.35 Dynamic balancing.

This principle works very well for small bore diameters because the corresponding boring bars have a low mass. Fine-adjustment heads with automatic balancing can be used from 18,000 to 40,000 rpm. For larger holes with diameters between 103 and 206 mm,

swap bodies are available, featuring a lightweight design to keep the adjusted mass low.

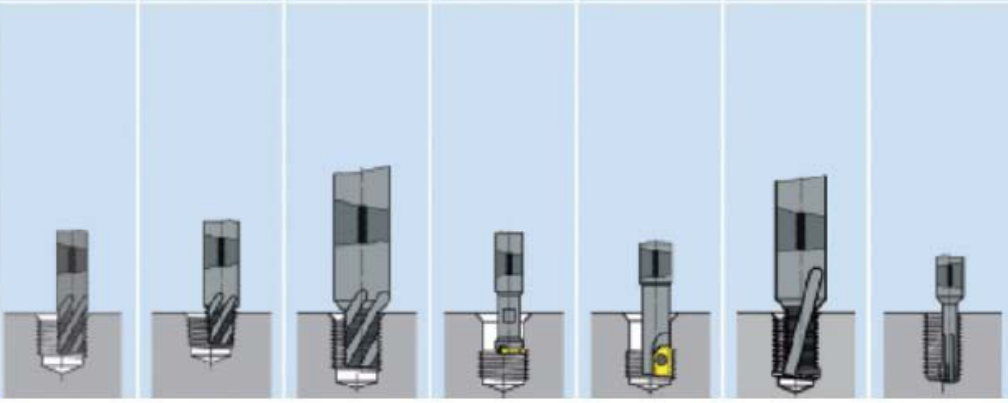
Imbalance of rotating tools means that the mass of the tool is not distributed completely rotationally symmetrically. One distinguishes between static and dynamic imbalance. Usually both forms occur simultaneously. Due to the imbalance and centrifugal forces arising during the rotations, vibrations result at high speeds; these have a negative impact on the feature, the wear of the tool, and the spindle bearings

FIGURE 19.36 Swap bridges with lightweight design reduce imbalance.

THREAD MILLING

Internal threads are increasingly created on CNC machines by thread milling and boring/thread milling in addition to the well-known processes of tapping with or without compensating chuck. These methods offer the advantage that not every thread diameter requires one or several custom tools, thus requiring fewer places in the tool magazine. It is a prerequisite that the machine has 3D path control in order to precisely control the required simultaneous axis movements. Figure provides an overview of the different thread milling processes. Figure shows the procedure for internal thread sink milling with a predrilled core.

(a)

Area:	Internal thread milling					Bore thread milling	
Preparation:	Drilling the core hole (countersinking) except for thread milling with countersinking					None	
Process:	Thread milling with solid carbide tools			Thread milling with drilling inserts		Bore thread milling	Circular bore thread milling
Type:	GF	Conical thread milling	GSF	EP	WSP	BGF	ZBGF
Process-principles:							

(b)

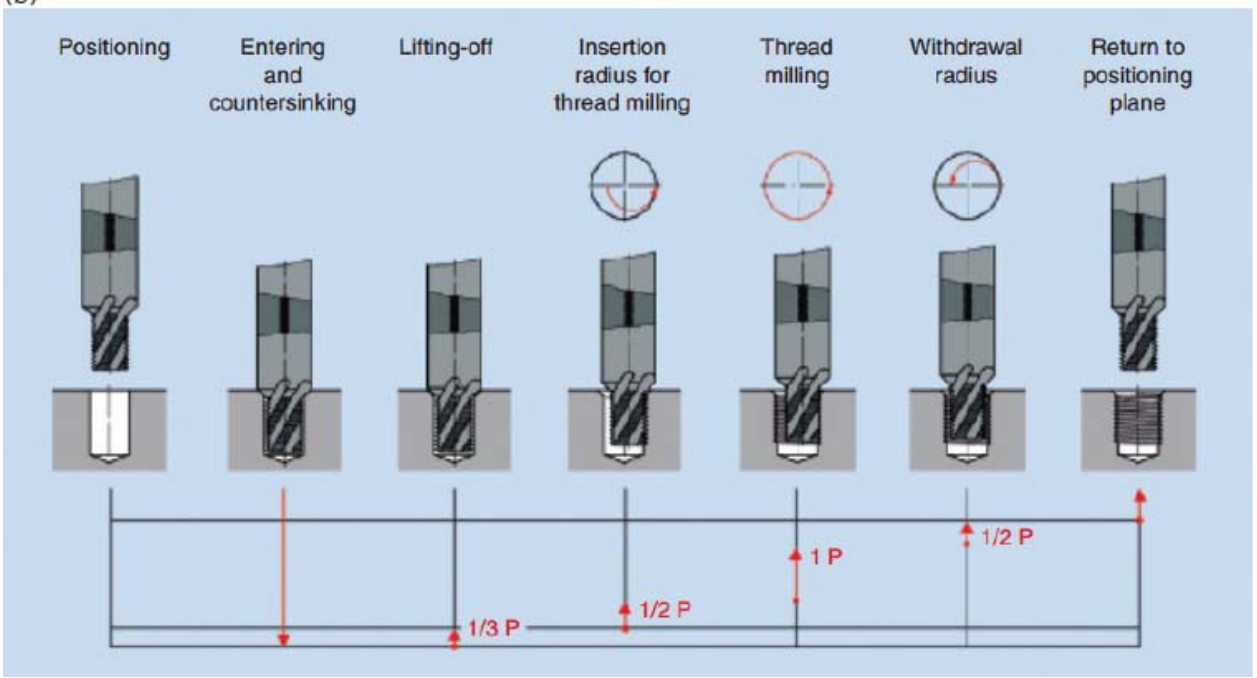


FIGURE 19.37 (a) Various inside thread milling processes. (b) Sequence for inside thread countersink milling (with a predrilled core hole).

For conventional internal thread milling (GF, GSF), the core hole must be drilled first. Depending on the tool and thread depth, different tools can be used, resulting in different machine movements. In this process, a conventional thread cutter dives centrally into the core hole, moves in a circular path to the thread contour, and then moves one thread pitch upward in a single 360-degree helical interpolation. This completes the thread; next, the cutter moves to the center of the hole and then out of the hole. When thread sink milling the thread hole will also be countersunk.

In circular thread milling (EP, WSP), a thread milling tool with one or more cutting edges on one level is used. The threading takes place in several helical movements (circular motion in the and simultaneous linear motion in best from bottom to top. For staged thread milling, a milling cutter with one or two cutting inserts is used, which, depending on the thread depth, is displaced in one or more steps above and produces the thread in individual stages. Both methods are used for larger thread depths and diameters. Using a holder and inserts, several thread pitches can be cut.

In general, it is distinguished whether dimension-bound or dimension-independent thread milling cutters are used. Dimension-bound tools are designed for a certain thread diameter range, and the possible thread sizes are fixed. With dimension-independent tools and a given pitch, any thread diameter can be produced starting with a determined cutter/thread size ratio. It must be observed that a certain ratio may not be undercut. A guideline of a 2:3 ratio applies for metric standard threads; for metric fine threads, the ratio is 3:4. This results from the generated profile distortion during thread milling. In this process, a straight thread profile moves in a helical interpolation that causes the resulting thread profile to be distorted.

This distortion must not exceed a certain tolerance or the thread gauge will render it scrap.

The process of thread milling requires the core hole. In contrast, thread bore milling does not have this requirement BGF, ZBGF). The tool penetrates into the full material, drills the core hole, and mills the thread, during the retreat, in a spiral interpolation with moving in a circular fashion and *Z* linearly. This method is only used for short-chipping materials such as ductile (cast iron).

In the process of circular bore thread milling (ZBGF), the tool is already engaged in helical interpolation as it enters the full material and mills the thread from top to bottom. After reaching the programmed thread depth, the tool moves to the center and out of the thread hole. Concerning starting radii, one must differentiate between a 90- and a 180-degree movement. This approach should keep the wrap angle of the tool as low as possible and thus prevent tool breakage. The more stable the tool, the shorter is the starting loop.

Advantages of Thread Milling in General

- Large range of dimensions and tolerances is possible.
- One tool only for right- and left-handed threads
- Small "comma-shaped chips" can be easily removed from the hole
- No change in the direction of the spindle rotation
- No axial deviation of the threads

■ Low cutting pressure, advantageous for thin-walled workpieces

■ Thread depth is almost the same as the core hole

■ Easy removal in the event of tool breakage; expensive reworking is no longer necessary.

Disadvantages

■ Depending on the tool, a thread depth of maximal $4 \times D$ is possible.

■ The diameter of the thread milling cutter should be two-thirds to three-quarters of the thread diameter, or the tool profile must be corrected.

■ Not all thread systems can be manufactured.

CUSTOM TOOLS

Custom tools are used if a standard tool for the job at hand is not available, for instance, a reamer with a specific diameter and a particular tolerance. More often, however, one custom tool is used if otherwise a number of different tools would have to be used. Because of the price, the custom tool only makes sense for mass production.

The achievable savings with a custom tool are shorter setup and processing times; these should be compared with the cost of conventional machining with multiple tools

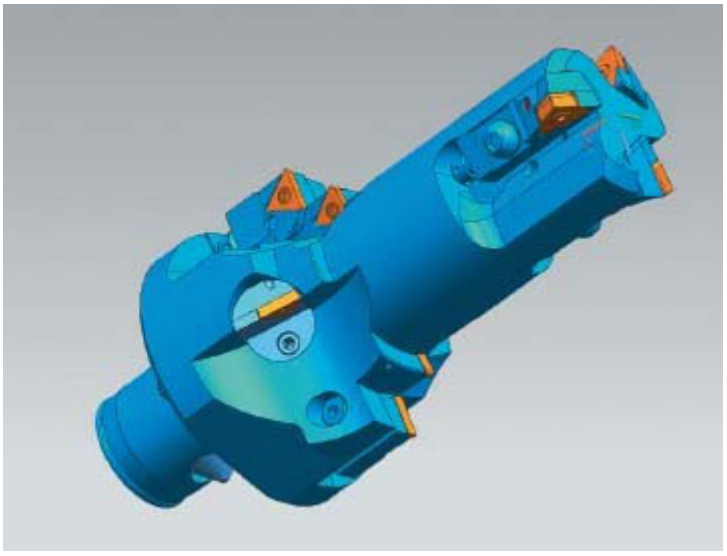


FIGURE 19.38 Custom tool for complete machining of break disks.

TOOL SELECTION

Different aspects should be considered and balanced when choosing a tool. In most cases, the choice will be the most suitable among the tools at hand in the shop. The decision will be made mainly on the basis of the technical suitability.

Further-reaching considerations must be entertained, however, if:

a. A new machine must be equipped.

b. The existing tool inventory is newly assessed.

c. A new specter of parts calls for the procurement of new tools.

An essential aspect, of course, is the cost, followed by technical aspects:

- Easy handling
- Good results in machining
- Optimal cooling option
- Stability

■ Multiple usage (This is especially true for modular systems that can be combined, given the machine-sided holder with several different tool adapters or extensions.)

Modular systems are available for diameter-adjustable tools for boring and fine boring. When selecting tools with changeable cutting inserts, part of the consideration should be the variety of available inserts and the many ways they can be combined.

IMPORTANT POINTS TO REMEMBER

1. Good tool preparation is indispensable both for the modern demands on quality and for avoiding down time of the machine.

2. A large inventory of tools must be planned far in advance when working with CNC machines.

3. The prerequisite for high-quality CNC production is the geometric and technological reliability of the tools.

4. One distinguishes between stationary and rotating tools.

5. A complete tool is composed of several components.

6. Tool components for a rotating modular tool are:

a. Adapter with a steep taper and tightening bolt

b. Gripper groove matching the hardware of the tool changer

c. Tool body with the insert holder

d. Exchangeable/reversible cutting inserts

7. Cutting tools are made of different cutting materials:

a. HSS

b. Solid carbide

c. Cermet (ceramic-metal)

d. Ceramic (oxide, nitride, mixtures)

e. PCD

f. CBN

8. Different tool adapters are required to insert and hold the tools in the machine.

9. Tool holders must meet high requirements:

a. Transmit the cutting forces

b. Ensure a precise tool fi t

c. Allow automatic tool changes

10. Tool holders are standardized according to DIN.

11. Adjustable tools are available for fi ne machining of bore holes.

12. Custom tools should only be used if standard tools are not available.

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MOTIVES FOR INTRODUCTION

Use of New Technologies

Increasing demands in design and quality, combined with time and cost pressures, are forcing companies to be permanently investing in more efficient equipment and procedures. Modern CNC machines (e.g., turning/milling machines) are highly productive, but they are very demanding in preparation and application. As a prerequisite for the successful use of new technologies, companies must provide for the storage and retrieval of additional information. This required knowledge can be integrated in the operational process and be made available for the task at hand, thus avoiding the misuse of resources, tools, and instructions and any possible interruptions of the production process

Provide Suitable Information

When purchasing new equipment, the required tool information for use is provided (e.g., cutting values). However, this information is provided in supplier-specific terms (e.g., the maximum setting diameter of a fine boring tool). Before the new machine can be used, this information must be adapted to the company-specific format (e.g., the exact settings for a fine boring tool). In addition, this information must be made available to all relevant workplaces. For example, the exact setting diameter must be communicated to both the NC programming and the tool storage departments. The company-specific information is then available as a set of general

or part-specific instructions (e.g., suitable cutting values for specific materials) and must be managed and integrated into the order process. This is necessary to avoid losing valuable capacity or reducing tool life as a result of inadequate cutting values.

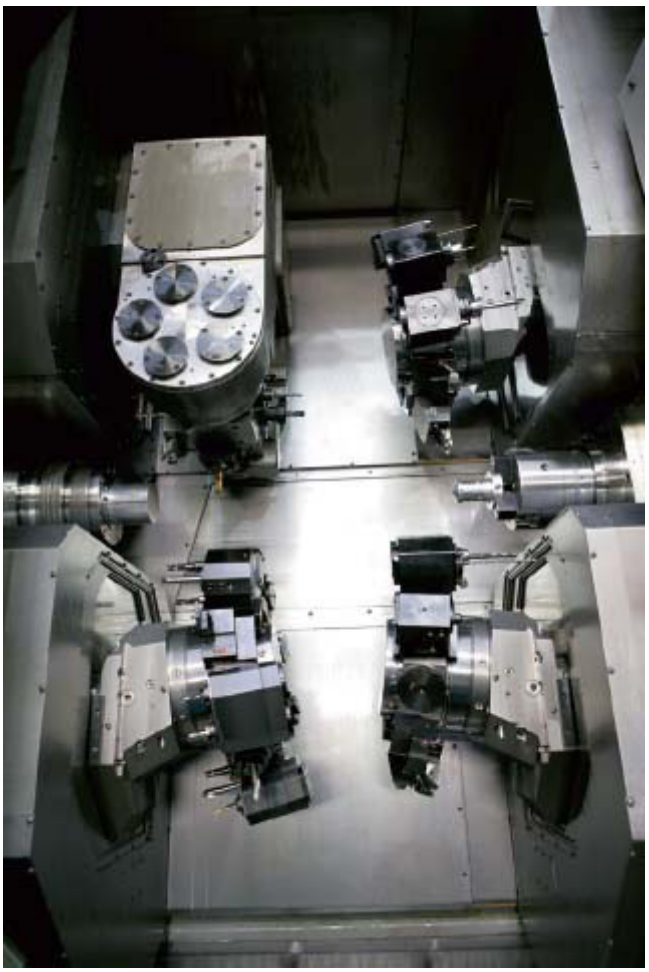


FIGURE 20.1 Work area of a lathe-mill machining center.

Making Information Available

Tool and production data are managed in databases in a company-specific form. For this purpose, a software program is used with which the same information is shared across departments by different users without having to capture the data multiple times. For the tool data to also be used by other

software applications, appropriate interfaces are necessary. Different workstations (e.g., CAM system, presetting device, and workshop logistics) access the same database, thus ensuring a smooth workflow. The central data management avoids errors and down times in manufacturing caused by forgotten updates to specifications or incomplete instructions.

Planning and Preparation

Relevant tool information is necessary for the planning of machine utilization, shift change, purchasing of consumables, and the decision to invest in new machines. The structured management of all information pertaining to tools makes it possible to disseminate such information at short notice.

Need for a Solution

The importance of tool information exchange between company departments varies from company to company. As a general rule, missing and unclear tool information is a significant source of error and manifests itself in capacity loss, rejection rate, delays, and inefficiencies. Manual interfaces and verbal information exchange are potential sources of problems and obstructions for new employees.

The more people involved in the manufacturing process, the more important are binding instructions and clear procedures. Frequently performed activities need to be organized more efficiently than seldom-performed work. Binding specifications for complex machining jobs are particularly important:

- For machines to avoid machine damage

- For products with special risks in the case of a faulty delivery

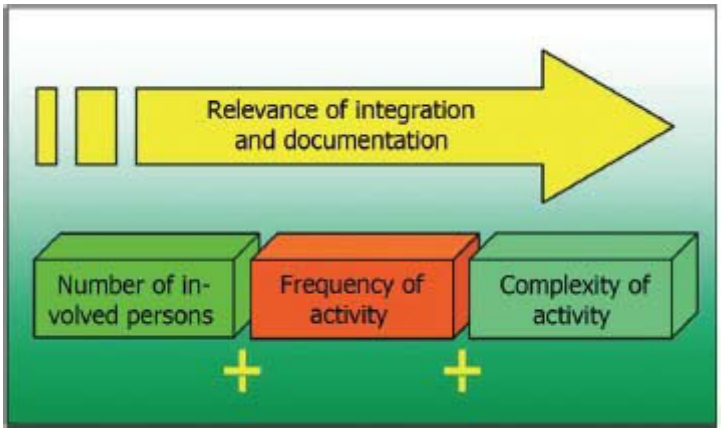


FIGURE 20.2 Relevance of systematic documentation to error-free processes.

EVALUATION OF A TOOL MANAGEMENT SYSTEM

Typically, the need for a tool management system arises after repeated problems in the workflow (e.g., the constant search for tools or machine damage due to errors), or, as a positive example, because new technologies are introduced (e.g., a central presetting device is introduced), the organization must adapt to the new requirements in a timely manner. Even if the need is relevant only to a single work area (e.g., reducing a large and obsolete tool inventory), the problem can only be permanently solved if the information from all work areas is linked in a meaningful way. For various reasons, this task can only be satisfactorily achieved with one specialized solution. The anticipated benefits of a good tool management system can be determined with few characteristic data and compared with projected project costs.

Before a tool management system is acquired, what problems and weaknesses it must address must be analyzed as well as any additional benefits that should be gained. This compilation describes the tasks and goals, without determining a method and thus narrowing down possible solutions. The various tasks are assigned different priorities depending on the type of production (e.g., series or prototypes), the kind of industry in which the company operates (e.g., medical technology or mechanical engineering), and the manufacturing machinery that is used. The description of the tasks refers to all departments concerned and serves as the basis for a liability log.

Liability Log

A *liability log* is a systematic list of requirements for the planned solution. It serves as the basis for the offers to be drawn up by the possible suppliers and is divided into the following chapters:

■ The introduction describes the background and objectives in general terms.

■ The constraints lay out the makeup of the pertinent data, requirement for the numbering system, number of required workstations for the various tasks, the information technology (IT) including the integrated applications, information on the form of the organization, and planned implementation phases.

■ The process requirements are broken down by workplace. They describe the employees' requirements for the solution from the point of view of workflow as part of the manufacturing process (e.g., printing a net requirement list with barcodes and storage locations).

■ The functional requirements describe non-self-evident constraints for specific tasks and often correspond to the detailed knowledge of individual employees who are currently performing the task. For example, it should be noted whether the tool size must be taken into account in the tool list for a given manufacturing job on a CNC machine.

■ The nonfunctional requirements describe constraints and wishes that relate to the whole solution and do not concern individual functions. For instance, it could be noted that the installation of updates can be performed by the IT (Information Technology) department of the customer without external service. The nonfunctional requirements are usually subdivided into specifications of IT, requirements of quality assurance, and general wishes of the users (e.g., the desire for an easy-to-understand, intuitive operation).

Instead of creating a liability log, the requirements can also be discussed with potential suppliers, who then submit suggestions to the company. Suppliers have experience working with similar companies and can incorporate such information. Depending on its level of competence and reputation, the supplier can possibly make a better proposal than would be possible with a self-drafted liability list.

ASSESSMENT OF SOLUTIONS

When assessing a new solution, the user should pay special attention to the aspects that are the primary reason for procurement. This could be, for example, capacity loss because of recurrent problems such as searching for tools and the possible remedy, such as the reduction of costs through the implementation of central tool storage. Management must view this task as a global issue and provide a structural response rather than providing temporary ad hoc relief. Because it is a common problem of CNC manufacturing, the solution does not have to be reinvented, but an appropriate solution can be selected from the available means and introduced in meaningful steps. Regardless of the technical facts, the background of the manufacturer should also be considered. It should be evident that the company has a clear vision and sufficient resources and is not limited by a multitude of other projects and products that would keep it from paying sufficient attention to new challenges.

An implementation plan should be written laying out the responsibilities and projected time frame before the gradual introduction.

INTRODUCTION OF A TOOL MANAGEMENT SYSTEM

The introduction of a tool management system begins with the assessment in the enterprise. The expected benefit can only be achieved if all parties involved have recognized the advantages of the structured tool organization. It has worked for many companies that management set up workshops with sufficiently allotted time to address the questions and concerns of personnel and illustrated the innovation in form of a test installation.

The introduction primarily concentrates on the collection of the master data, where also the variety of tools is reduced to the necessary level. This already represents a palpable benefit of a tool system because CNC programming, tool dispensary, and planning make use of a uniform system.

The next step introduces logistics, followed by the process-oriented use for further tasks and integration with other systems. The collaboration with suppliers helps to make realistic time and cost planning possible.

OUTLINE

Tool management in mechanical production is necessary to uniformly organize and integrate the information about existing tools. Tool data are stored in a database, recorded, and used with the tool management software. Tool management includes, unlike the administration of consumables, fields for special technical data, graphics, and parameters that are required for use in process planning.

Unlike a hand tool, a tool in CNC manufacturing usually consists of several parts. The correct assembly of the individual components is a prerequisite for a defect-free production process. Typically, several complete tools are required and are documented in the tool list for machining a part on a CNC machine. Every component, complete tool, and tool list has an identifier that lets the user find the corresponding specification.

Tool management is divided into tool documentation (i.e., master data), logistics (i.e., inventory management), and tool tracking. Documentation includes at least all the information necessary for a smooth and traceable manufacturing process. It also can be used to manage spare parts and relevant information from former production runs and related files. There are functions to maintain, print, and exchange the data with other applications.

Logistics deals with the requirements planning, inventory, and location of the tools. On the one hand, it includes warehousing and purchasing of the individual parts with corresponding tracking

of the tool usage. On the other hand, it allows planning and coordinating of the movements of the complete tools within the company.

INTEGRATION

The purpose of tool management is to ensure an efficient and error-free order processing in production. Existing knowledge is generally made available, and the specifications detailed in the master data are followed. To make this possible, the information for the different tasks must be available at the respective workplaces. The integration of tool data allows other applications to use the data that are maintained within the tool management system. These applications either access the tool management database directly, or the data are exchanged via interfaces. The integration avoids mistakes, delays, and multiple instances of data collection, especially in CNC manufacturing, where several people are involved in the manufacturing process.

If there is no central tool management system, information about the tools is likely to be collected and stored at different workstations in spread sheets, tables, and lists. This means a multiplication of the data maintenance effort, the risk of using outdated information, and the thankless effort to have to collect relevant information all over the production floor.

TOOL IDENTIFICATION

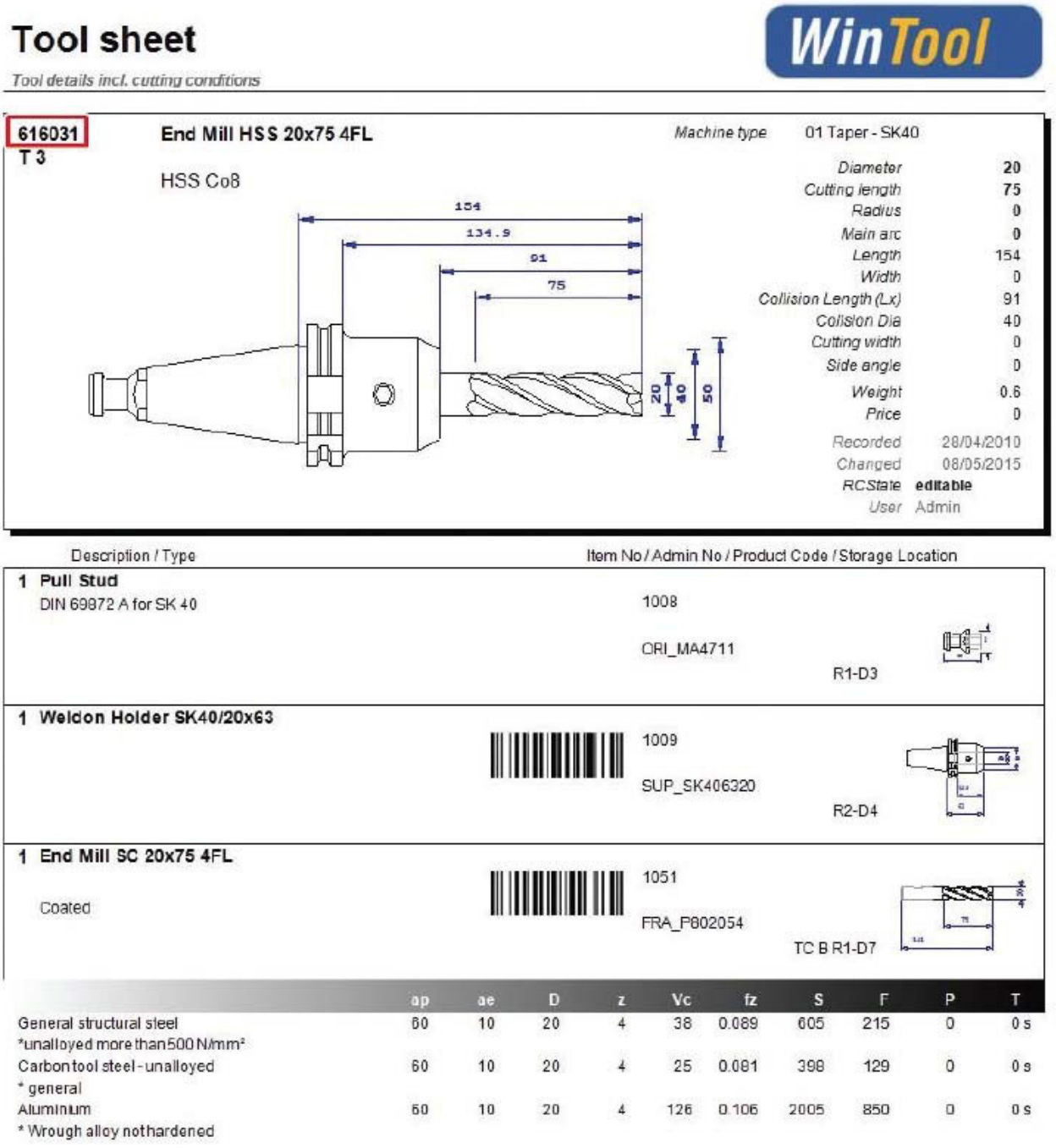
Tools must be unambiguously documented in lists so that the workflow can progress flawlessly. Given that a large number of tools are at hand, a clear textual description is very time consuming and cumbersome. The database of the tool administration should contain an essential description and a short, clear identification number, similar to a telephone number that serves as identification of a telephone owner.

The advantages of a tool identification system apply to the whole enterprise because the system allows a simple retrieval of the desired tool information. Whether it is the order number, geometry data, storage location, or cutting data—any information is always and immediately available. A short number can also be entered quickly. It is not advisable to use the tool ordering number. These numbers would not comply with the chosen format, and upon changing the supplier, the number would no longer have a connection with the article.

When assigning the identification for a tool, individual components must be distinguished from the completely assembled tool. To avoid misunderstandings, it is useful to assign an array of numbers for components (e.g., such as 50 001, etc.) and one for complete tools (e.g., 60 001, etc.; Figure

As identification for the tool lists, a number string starting with, for instance, 7 001 001, can be used. The tool list contains all the tools that are required for one operation. The list includes the tool

ID and the applicable operation (e.g., 100 1004 – 20; Figure Identification of the process steps uses a combination of print and part numbers and the number of the operation, for instance, 100 1004–20. Operations management collects all documents, such as instructions for the operator. If possible, the same principle for identification should be applied to these documents as to the tool lists. Thus the NC program and the setup sketch are also named 7 001 001.



Tool sheet

Tool details incl. cutting conditions

WinTool

616031
T 3

End Mill HSS 20x75 4FL

HSS Co8

Machine type	01 Taper - SK40
Diameter	20
Cutting length	75
Radius	0
Main arc	0
Length	154
Width	0
Collision Length (Lx)	91
Collision Dia	40
Cutting width	0
Side angle	0
Weight	0.6
Price	0
Recorded	28/04/2010
Changed	08/05/2015
RCState	**editable**
User	Admin

Description / Type	Item No / Admin No / Product Code / Storage Location
1 **Pull Stud** DIN 69872 A for SK 40	1008 ORI_MA4711 R1-D3
1 **Weldon Holder SK40/20x63**	1009 SUP_SK406320 R2-D4
1 **End Mill SC 20x75 4FL** Coated	1051 FRA_P802054 TC B R1-D7

	ap	ae	D	z	Vc	fz	S	F	P	T
General structural steel *unalloyed more than 500 N/mm²	60	10	20	4	38	0.089	605	215	0	0 s
Carbon tool steel - unalloyed * general	60	10	20	4	25	0.081	398	129	0	0 s
Aluminium * Wrough alloy not hardened	60	10	20	4	126	0.106	2005	850	0	0 s

FIGURE 20.3 A running six-digit number as an identifier of a complete tool.

RETRIEVING TOOLS

An important advantage of tool management is the possibility of easily retrieving tools. Instead of rummaging through the tool storage and checking with a pair of calipers whether the cutting edge length is sufficient for a particular machining job, this can be ascertained by querying the tool management system. If the order number is known, the pertinent tool data can be retrieved. If a tool is needed for a particular job, such as tapping an M8 thread, the search criteria will contain the relevant filters for geometry, technology, and availability in the warehouse. The database of the tool management system can also be queried as to which tool list contains a specific tool component. This query could be useful if a component is no longer available so that it can be replaced on all tool assemblies involved or when information on a component can be retrieved from an already existing NC program

Tool list

Sorted by position in WinTool list

100 1004 - 20 C
51 - Chiron (SK40)
7004

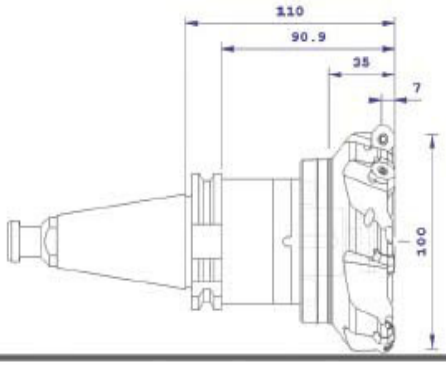
Hydraulic block
O-1112-M1

24/01/2019
General structural steel

T 123 Face Mill 100x3 43° 7FL

616093 OFEX 05T305

T25M
D 123 0 0
H 2 0 0

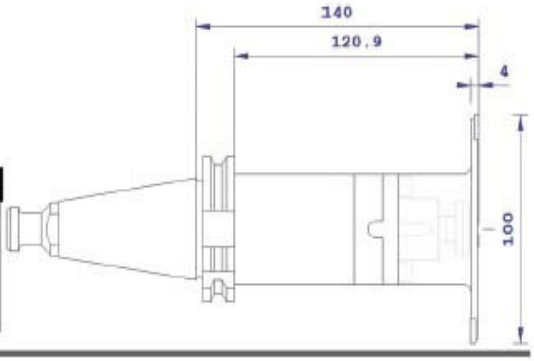


Quantity	Component	Item-No
1	Pull Stud	1008
1	Shell Mill Holder SK40/32x60	1167
1	Face Mill 100x3 43° 7FL	1165
7	Insert OFEX05T305TN-M08 T25M	1173

T 3 Disc Milling Cutter 100x4 6FL

616102 335.19-1102**

T25M
D 3
H 3

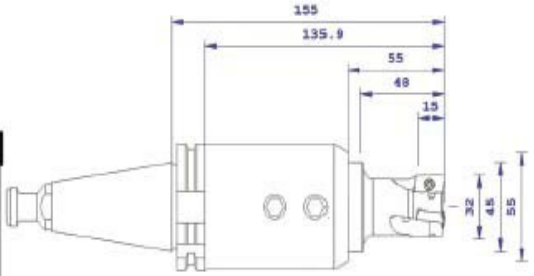


Quantity	Component	Item-No
1	Pull Stud	1008
1	Shell Mill Holder SK40/27x100	1171
1	Disc Milling Cutter 100x4 6FL	1177
12	Insert 335.19-1102T-MD09 T25M	1178

T 9 Square Shoulder Mill 32x15 3FL

616097 AP** 1604.

T25M
D 9
H 9

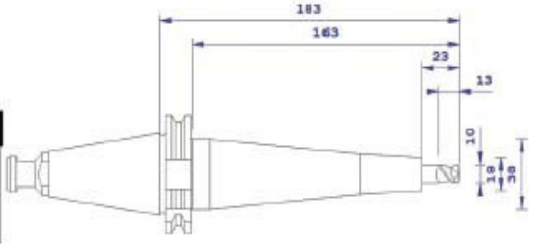


Quantity	Component	Item-No
1	Pull Stud	1008
1	Weldon Holder SK40/25x100	1080
1	Square Shoulder Mill 32x15 3FL	1176
3	Insert APFT 160430R-M13 T25M	1172
3	Insert Screw C04008-T15P	1321

T 14 Bull Nose End Mill HSS 10x13 R2 2FL

616122

HSS Co8 TiCN
D 14
H 14

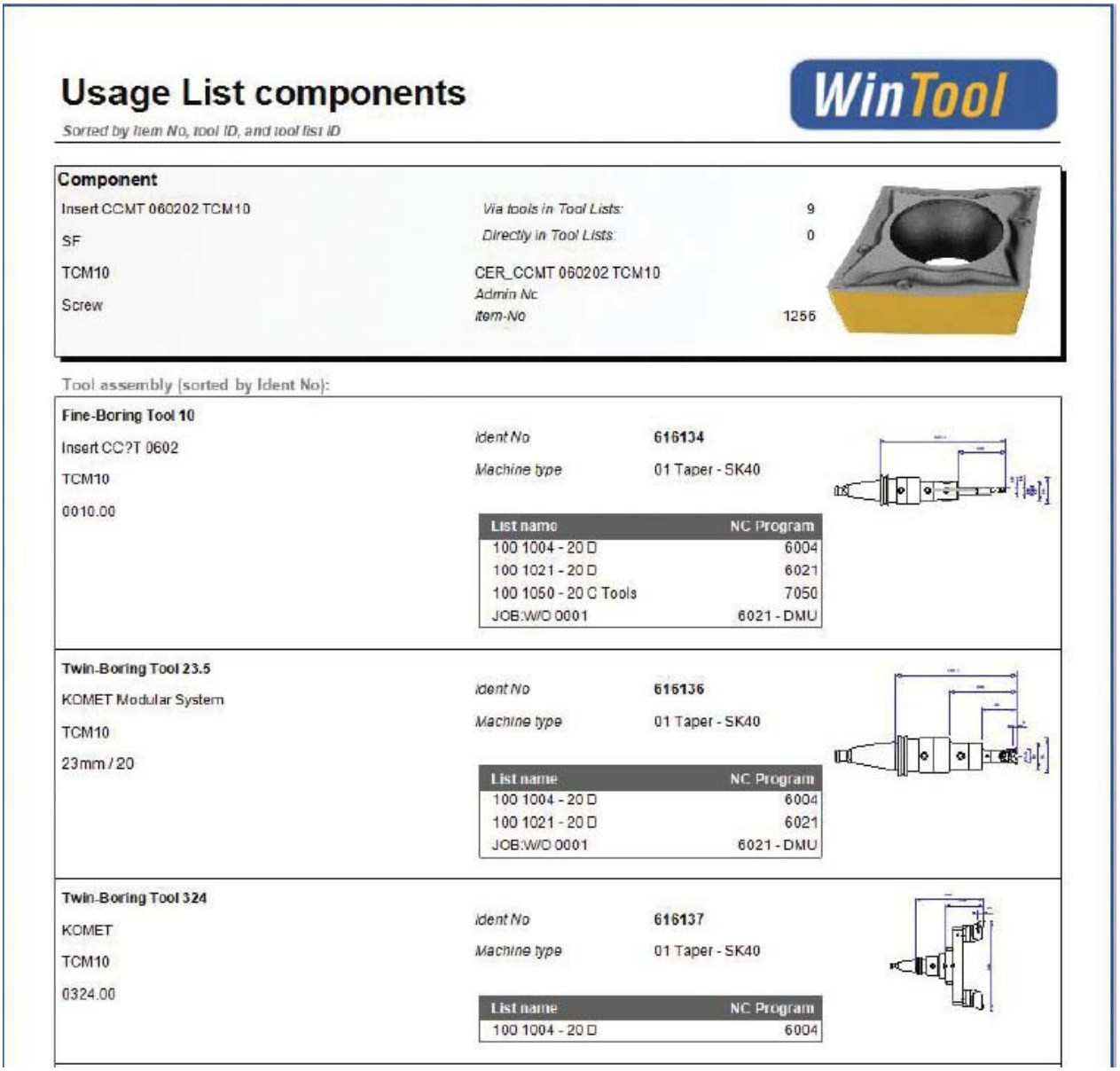


Quantity	Component	Item-No
1	Pull Stud	1008
1	Shrink Fit Holder SK40/10x160	1218
1	Bull Nose End Mill HSS 10x13 R2 2FL	1214

FIGURE 20.4 Running four-digit number for tool lists (the operation number is also listed).

TOOL CLASSIFICATION

Typically, if a tool is needed for a particular job, either a component or a complete tool, the identification is not yet known. Thus the search criterion should be the classification, because all tools of a classification are similar. It could be “end mill, HSS, for roughing.” The classification is a hierarchical structure. A previously unidentified tool can be found by searching the relevant class via a three-step process. If one of the records is selected, all details and the identification are displayed. Depending on whether a component of an entire tool is searched for, the matching record will be found.



Usage List components

Sorted by Item No, tool ID, and tool list ID

WinTool

Component

Insert CCMT 060202 TCM10

SF

TCM10

Screw

Via tools in Tool Lists: 9

Directly in Tool Lists: 0

CER_CCMT 060202 TCM10

Admin Nr.

Item-No 1256

Tool assembly (sorted by Ident No):

Fine-Boring Tool 10

Insert CC?T 0602

TCM10

0010.00

Ident No 616134

Machine type 01 Taper - SK40

List name	NC Program
100 1004 - 20 D	6004
100 1021 - 20 D	6021
100 1050 - 20 C Tools	7050
JOB:W/O 0001	6021 - DMU

Twin-Boring Tool 23.5

KOMET Modular System

TCM10

23mm / 20

Ident No 616136

Machine type 01 Taper - SK40

List name	NC Program
100 1004 - 20 D	6004
100 1021 - 20 D	6021
JOB:W/O 0001	6021 - DMU

Twin-Boring Tool 324

KOMET

TCM10

0324.00

Ident No 616137

Machine type 01 Taper - SK40

List name	NC Program
100 1004 - 20 D	6004

FIGURE 20.5 Proof of use of a tool component as part of a completed tool and a process step.

TOOL COMPONENTS

Tool components are individual parts that are combined to form a complete tool. Components are purchased as a unit and kept in tool storage. One differentiates between cutting components (e.g., indexable inserts) and noncutting components (e.g., collets). Cutting components wear out during use and therefore must be replaced periodically. Noncutting components have a virtually unlimited life span under normal use. They are usually procured together with a new machine.

The headers for all components are uniform and contain a designation, order number, and unique article identification. Each component is assigned to a tool type which determines the number and meaning of the descriptive data fields. In addition, each component is assigned to a tool class so that it can be found via the classification. The descriptive data with geometric values differ depending on the tool type. There are fields to record particular features and characteristics

The tool management system also includes graphics in addition to data fields. The graphics are either stored directly in the database or assigned via file associations. One can usually find graphics of one of four types:

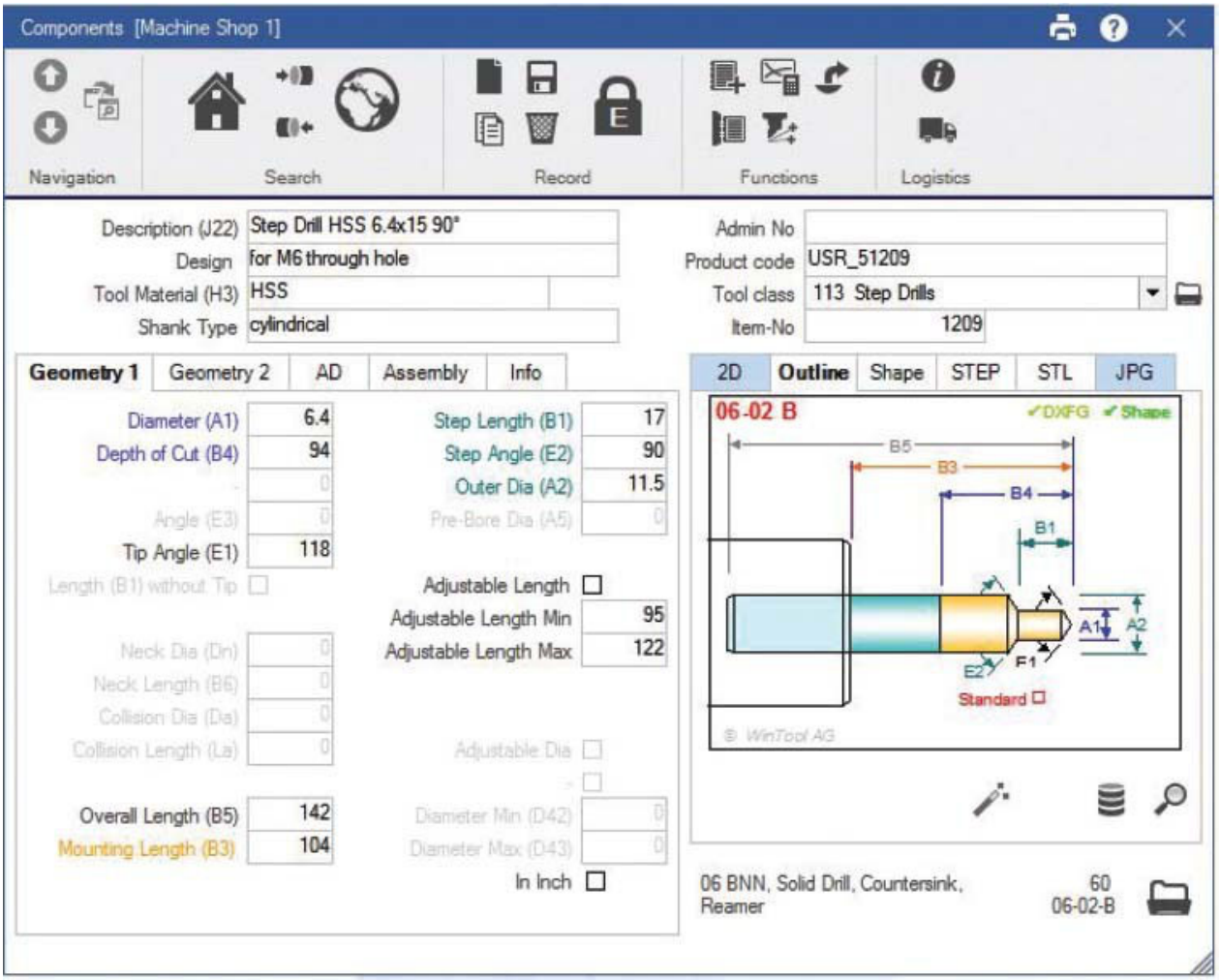


FIGURE 20.6 Use of a standardized sketch is a prerequisite for error-free data acquisition.

■ *2D graphic* This format contains dimension lines and geometric information that is relevant for assembly of the complete tool and accords to BMG 3.0/DIN 69874 in terms of use of the layer, alignment, and zero point. Applications for tool management usually have a built-in function to automatically create the 2D graphics based on the geometric data

■ *3D* These are needed especially for lathe tools to generate models of complete tools. Zero point and orientation are governed by ISO standards

■ *Photo or graphic from the* These are used with more complex components to better explain form and use.

■ *PDF* Such a file from the catalog of the tool manufacturer is included if it is indicated for explanation of the correct handling.

Tool manufacturers often provide data and graphics in a suitably prepared form in order to reduce the effort of first time recording of the components in the tool management system. DIN 4000 and ISO 13399 exchange formats are currently used

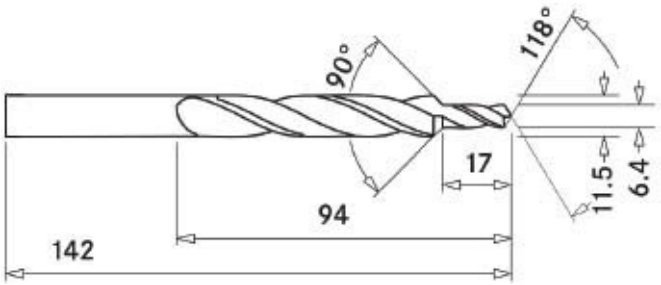


FIGURE 20.7 DXF graphic with complete information and assembly of a complete tool.

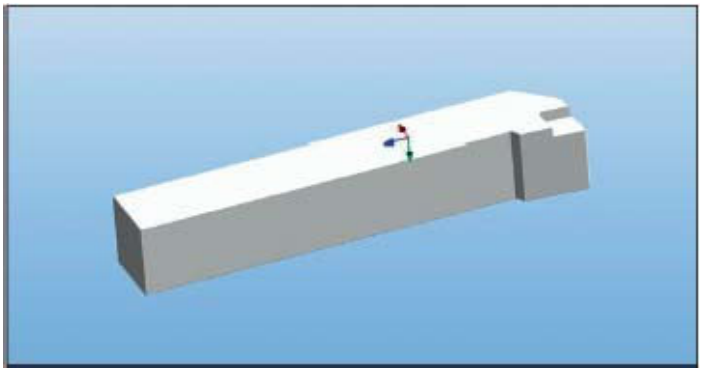


FIGURE 20.8 Model of a lathe tool for assembly of a complete tool.

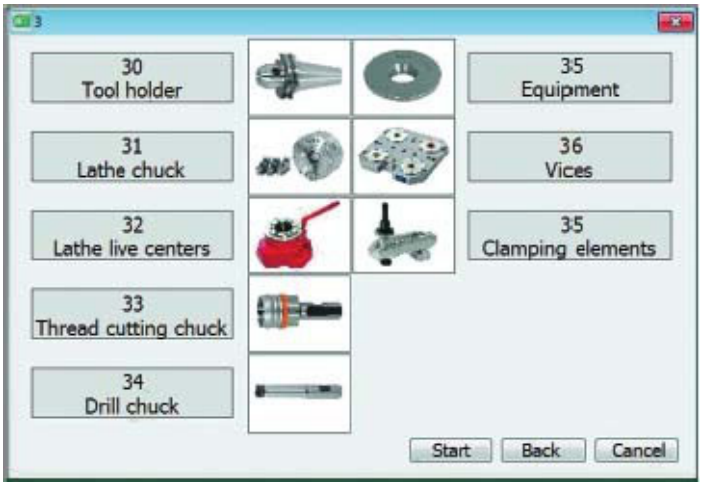


FIGURE 20.9 Integrated tool catalogs simplify data collection.

COMPLETE TOOLS

A complete tool is made up of several components: the part that is inserted into the machine holder, an extension or collet, and the cutting tool (e.g., a drill bit or insert). Tool components contain instructions for the assembly and CAD drawings or sketches if required

The header data of a complete tool contains the unique identification, designation, and allocation to the tool class. The geometric fields are automatically calculated from the values of the components when the tool is assembled. For adjustable tools, such as a fine boring tool with adjustable diameter, additional information is stored with the complete tool. The parts list contains all components in the respective quantity and order. Additional information for assembly of the specific complete tool can be recorded, for instance, a setting tolerance +0.03/-0.01 mm or the minimal protrusion value.

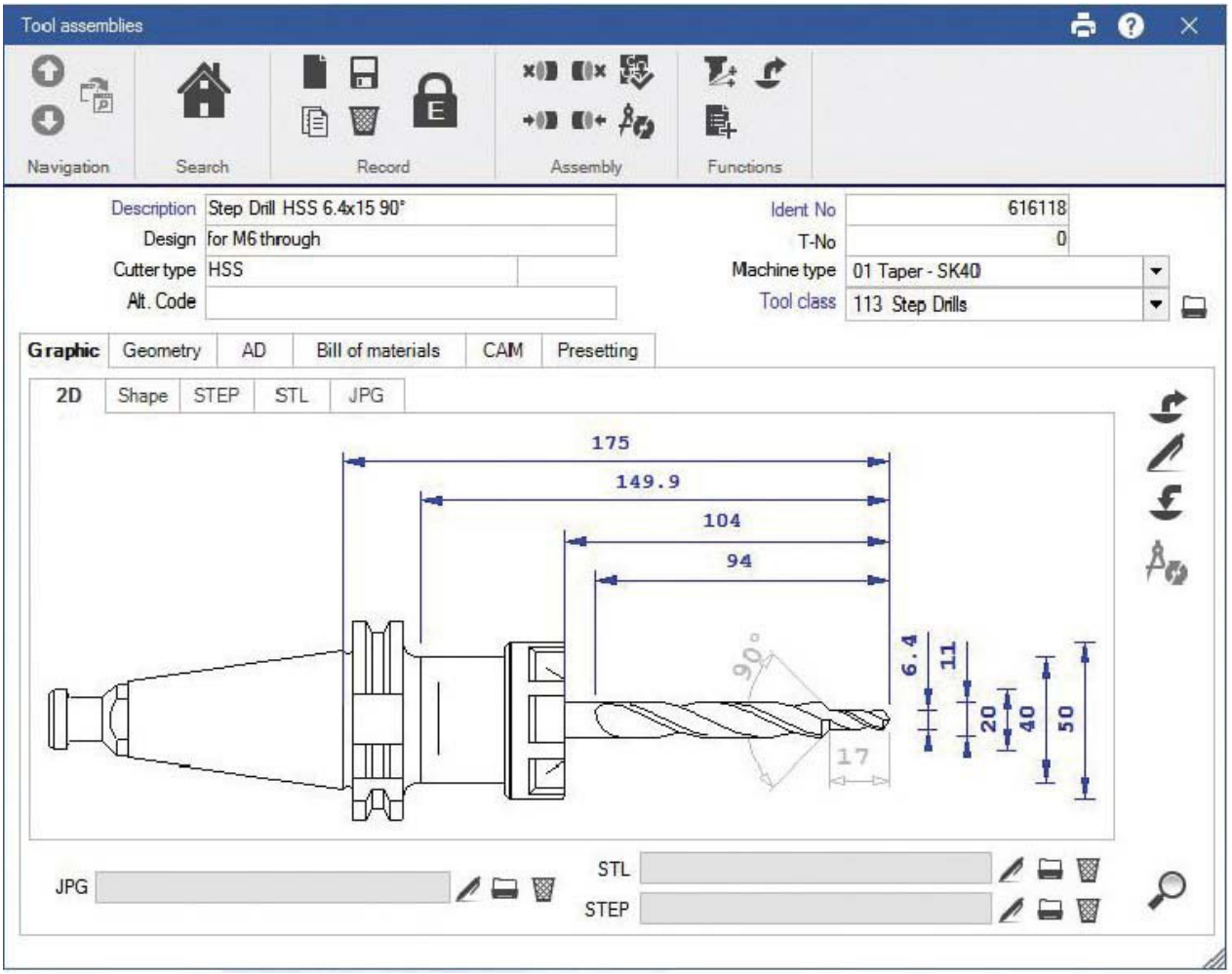


FIGURE 20.10 Screen shot of completed tool with header, graphic, and special registers for a variety of subjects.

Each complete tool contains the values for presetting the tool on the presetting device. In addition, more pertinent information can be provided about how measurements should be performed so that, for instance, it is obvious whether the left or right cutting corner of a grooving tool is measured. The cutting values of the cutting component are provided as a suggestion. They have to be adapted to the specific situation; for instance, a tool with a large protrusion requires other cutting data than one that protrudes only a short distance.

To create documentation in a tool management system is much easier than doing it by longhand. The individual components are selected and added with a mouse click. The drawing of the complete tool and the parts list are generated automatically. Most of the data retrieved from the components are automatically calculated and entered by the software.

TOOL LISTS

The tool list notes all the complete tools needed for a single operation and the designated place in the tool magazine of the machine (T-number, turret). The tools are listed in the order they are used in the NC program. The list is printed as a setup list and will be used to pick and provide the complete tools. The print format is open. The list contains the required components with storage locations and the most important geometric details and tolerances of the complete tool.

The header data contain the clear identification, assignment to the operation, and designation. The list might contain pertinent information for the operation at hand, such as minimum cutting edge length.

OPERATIONS

To make a part, several operations are needed, such as sawing blanks from bar stock, CNC processing, cleaning, and packaging. The description of the operations is stored in the *production planning system* (PPS). The associated technical information is available in the shop, such as NC program or tool sheet with parts list. Tool management can provide additional documents required for CNC machining, such as hard copies of CAD drawings and the NC program. This part of the job is often called *NC program management* or *NC*

Such NC folders can be color coded so that unauthorized NC programs, obsolete setup lists, or obsolete drawings are not accidentally used. Barred folders cannot be used, archived data can be hidden, and only released folders are ready for immediate use

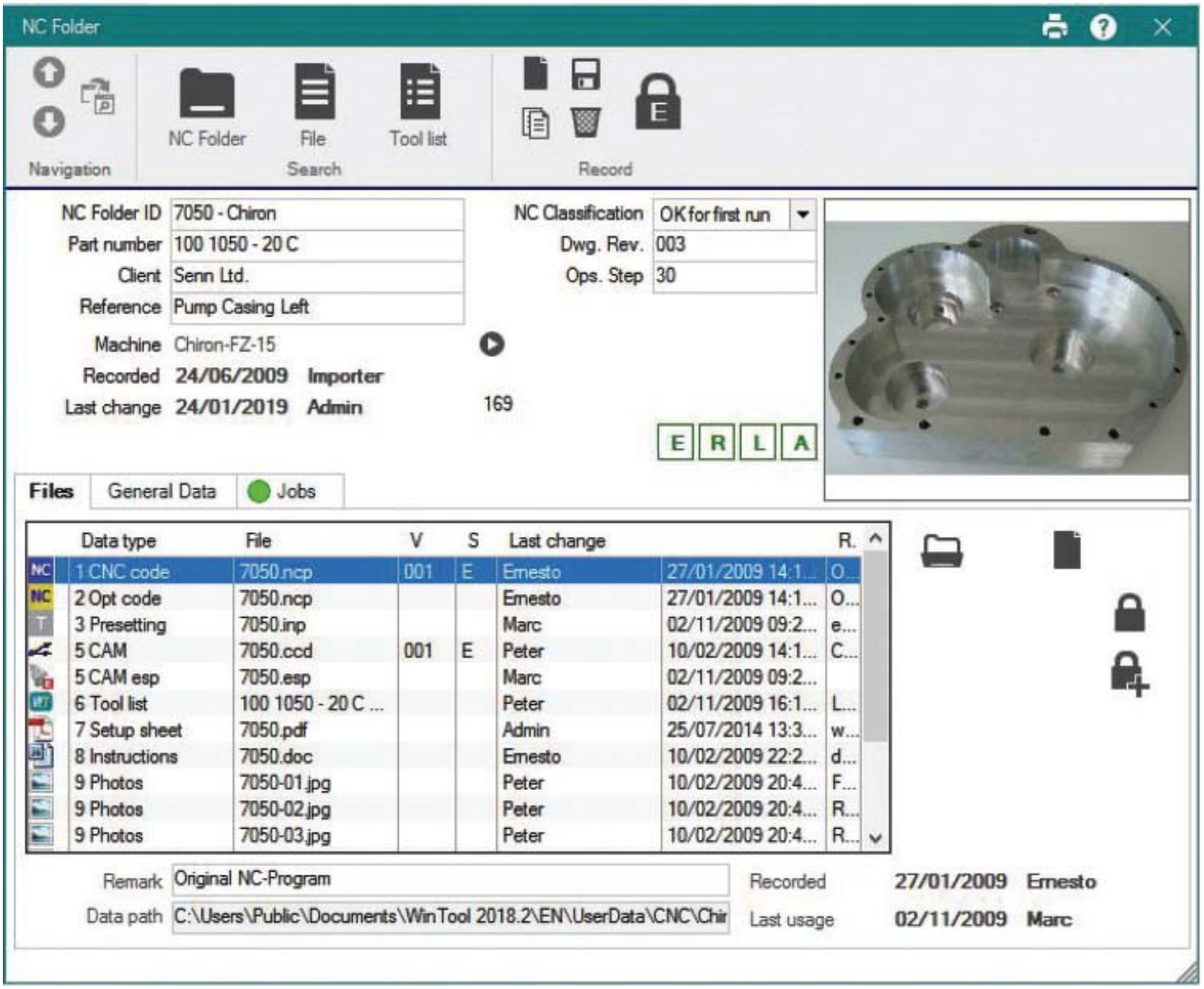


FIGURE 20.11 NC folder containing hard copies of all documents needed for a CNC operation.

CAP (Computer-Aided Programming)

The CAP system generates the processing commands (NC program) for CNC machines. Geometry, designation, and cutting data of the complete tools are taken directly from tool management. This ensures that all tools used are documented and conform to the situation in the shop.

The tool data must be uniform and complete for secure data transfer from tool management to the CAM system. After completion

of the NC program, the tool list is handed over to tool management

TOOL PRESETTING

The CNC machine needs input of the exact tool dimensions, meaning the position of the cutting edge relative to the zero position. In this way, the CNC machine knows where the cutting edge of the tool actually is positioned in relation to the spindle. In principle, the tool diameter and length can also be measured on the CNC machine. During this time, however, the machine would stand still and not be productive. For this reason, CNC machines are designed so that the cutting position can also be determined on the outside of the machine or set to a given dimension. On loading the tool from the magazine, the pertinent cutting values are also retrieved automatically.

There are user-friendly presetting devices that are given target values, designations, and tolerances from tool management and pass the actual measured values directly to the CNC machine. The integration of tool management with presetting devices takes place in the exchange format of the respective device manufacturer and can also include graphics and information on the measuring method

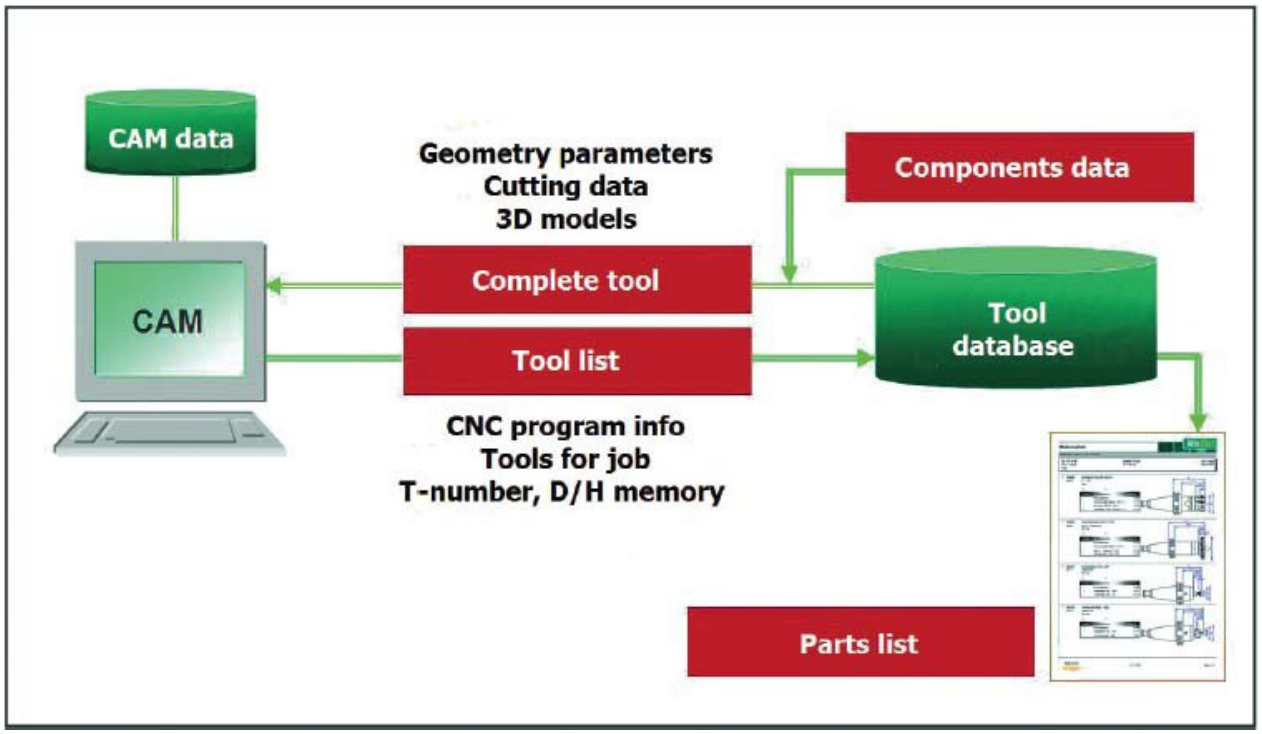


FIGURE 20.12 Integration with the CAM system.

FIGURE 20.13 Modern tool presetting device for tool measuring, presetting, and mounting.

To enable a measurement on the presetting device, it must have the same holder as the spindle in the CNC machine. More advanced

presetting devices find the cutting edge independently and take over the measured values automatically. Entry-level models use manual operations to perform an optical measurement; the result is stored in the software, displayed, or simply copied by hand.

If a company has a central tool prep station, it often has a more sophisticated tool setter because of heavy use; the time saved usually justifies the expense. Decentralized and less frequent use justifies the simpler model. The device should not have more features than actually needed; otherwise, the work becomes unnecessarily complicated. Thus it is not advisable, for instance, to integrate the tool-setting device with warehouse management, for it would make matters more complex because another entity, such as the company IT system, would become involved. For tools with a given geometry, the exact values of the cutting edge are determined. For adjustable tools, the default values must first be set and are then checked with the presetter. The target data (e.g., length, diameter, and corner radius) are noted in the tool sheet. The actual data are determined by measuring and are transferred to the CNC machine with identification, designation, etc. This can be done via a printed label, an automatically writable radio-frequency identification (RFID) chip or a digital file

TOOL LOGISTICS

Logistics deals with inventories, storage locations, and procurement of tools. Within logistics, a distinction is made between individual tool components and complete assembled tools. The components are differentiated between in-house tools those procured from outside suppliers.

Warehousing of the Components

The logistics of the components includes inventory management, demand planning, and monitoring of minimum inventory. When a minimum stock level is reached, tool management initiates a procurement process; this is done by the purchasing department with the enterprise resource planning (ERP) system. The logistics of tool management is set up to serve the tool user; it is also connected to the storage system and other equipment for production.

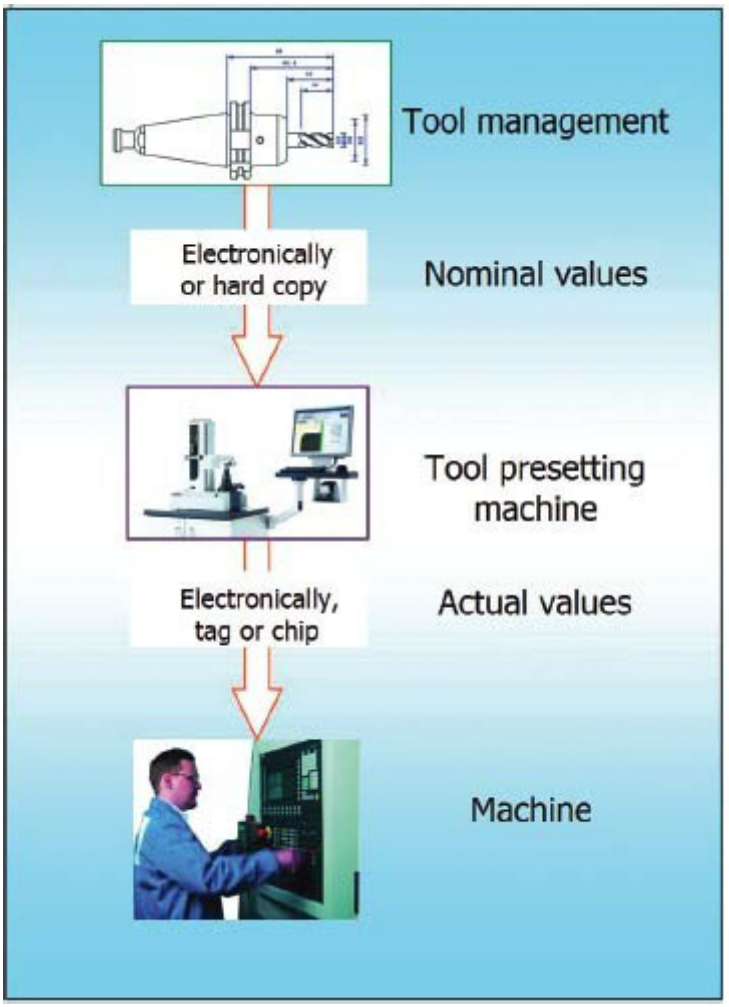


FIGURE 20.14 Data flow from tool administration and presetter to the CNC machine.

When a component is retrieved, a booking is made that reduces the stock accordingly and logs in the purpose and place of use (cost center). After use, the component is registered as returned to stock. Worn components are disposed of or logged in for redressing.

If the stock reaches the defined minimum quantity, the article will be included in the order proposal. All proposed articles are

ordered periodically after prior confirmation by the authorized employee. Instead of entering the article number via the keyboard, barcodes can be used to simplify the process of tool retrieval and return. All items of a pick list can be ordered with a push of a button; to avoid clutter, only wear parts are managed in logistics.

Based on the warehouse bookings, evaluations are made periodically to analyze changes in consumption and costs. The figures are used to optimize the minimum stocks, to negotiate delivery quantities with suppliers, and to assess tool life.

Use of the Components

Internal logistics mainly needs to know where a particular item is located and which cost center has to pay for it. Only cutting tools are actually consumed; the remaining components, such as body and clamping device, are merely cycling back and forth in the shop. The appropriate cost center is charged when the tool is retrieved/returned. Once a production order has been released, tools and consumables are ordered; the order makes a reference to the tool list in the core company data.

ERP System (Purchasing)

The ERP system controls and supports all business processes of the company, such as materials management, production, accounting, provision of raw materials, consumables, tools, and more. Tool management handles detailed planning and inventory control of the individual tools. If necessary, tool management puts out a purchase order (PO) to the ERP system that executes the actual order. The prerequisite is that the articles in both systems are registered with the same number.

Logistics of Complete Tools

Complete tools are built from components and usually are disassembled after use. Several of the same complete tools can be assembled as needed if a sufficient number of components are at hand. The logistics of complete tools relates to location and condition of the assembled units.

When scheduling a production run, the complete tools required for the operation are known from the associated tool list. Likewise, it is known which complete tools are already loaded on the CNC machine intended for processing. The tools that are not yet loaded in the tool magazine of the machine are printed out in a net loading list. They must either be reassembled or retrieved from tool storage. Coordinated logistics of complete tools reduces the time and effort required to deliver the tools and load them on the machine.

Storage Systems

The machine operator has access to conventional tool cabinets or a central tool dispensing system. The connection between the article number and the storage location is stored in the tool management system. Once a tool is requested from the logistics area of tool management, the storage system automatically picks the tool. Multistory storage systems evidently store more items on the same footprint than conventional storage cabinets

Matters are different with tool dispensing systems; these provide replacement inserts in real time. Tools are dispensed upon

user identification and entering the desired article number via keyboard or barcode. These systems are directly connected to tool management or the supplier, the available inventory of each article is always known, and the refilling can be arranged automatically. This precludes machine idle time due to a missing tool component.

ELECTRONIC TOOL IDENTIFICATION

The prerequisite for consistent, seamless tool data management is a closed data cycle. For this purpose, all tool data are automatically recorded, continuously updated, stored in the tool computer, and, if needed, transferred to the CNC machine. For this, RFID systems are the systems of choice. Monitoring of the tools in the work area of the machine is handled by special laser systems.

Introduction

The important task of tool management is to reliably identify the tools themselves and to make the propriety data of each tool unmistakably available. Depending on the performance of the CNC machine, these are some of the tool data that must be entered:

- Tool type
- Tool number
- Substitute tool
- Magazine location
- Standard/series/custom tool
- Drilling head/surfacing head
- Tool weight

- Maximum feed rate and torque
- Tool life/remaining tool life
- Notice of end of tool life
- Tool condition: broken/defective
- Fixed location/variable location
- Tool radius
- Cutting radius
- Collision radius
- Tool length
- Collision length
- Special tool code (customer specific)
- Wear compensation
- “Tool out of commission” flag
- Error code (cause of tool quarantine)

- Machine assignment

- Most recent use in machine

FIGURE 20.15 Tool storage system. Kardex Remstar Shuttle.)

The desire for further identification data may increase with the efficiency of the CNC machines. But it is evident from this list that:

- The system must allow for automatic data input and output. Manual input is not acceptable because it is error prone and takes an undue amount of time.

- Simple, mechanical methods of tool encoding (e.g., encoding rings) are not adequate.

- The tool data must be stored unmistakably and permanently.

■ Data input, output, and processing must be possible at multiple locations within the company.

■ Data management must start the first time a tool has been entered in the CNC system in order to save time.

■ The identification system must be applicable to different types of tools.

These conditions are currently satisfied most effectively by electronic tool identification systems. The most important component of these systems is the electronic data-storage chip, which is affixed to the tool and can be read with a special read head

Function/Principle

Tool data in earlier systems were exchanged between the data-storage chip and the electronics by means of contacts. Contact wear and contamination occasionally caused read errors. Today, inductive devices are used that work touchless and with much higher accuracy.

FIGURE 20.16 Two stationary and one rotating tool with integrated data carrier.

These devices employ two different principles:

- A read-only system
- A read/write system

The read-only system employs data-storage media with a preassigned eight-digit identification number. The read heads in the tool crib, the tool presetting device, and the machine itself work in conjunction with a central tool computer that stores and manages all tool data in a database. The code-storage medium merely supplies the identification number to the tool computer. The tool computer then assigns previously entered tool-related data to the fixed identification numbers. All data are displayed in a clearly arranged form on the computer screen. When the tool is placed in the tool magazine, the read head determines the identification number, and the tool data are supplied automatically to the CNC machine.

The read/write system uses data-storage media with greater storage capacities and can store up to 511 bytes of tool data. This capacity is sufficient to store the most important data, such as tool number, tool type, length, diameter, tool life, weight class, and so on. These data can be updated, modified, and read by the read/write head at any time. In other words, the tool carries its own data with it at all times. When it is inserted into a CNC machine, there is no need for a connection to the tool computer. When the tool is removed from the machine, the data contained in its data-storage

medium, such as remaining tool life and wear compensation, are updated automatically. If the CNC system is connected to a direct numerical control (DNC) computer, the data can also be passed across this connection to the tool computer if necessary for management-related purposes.

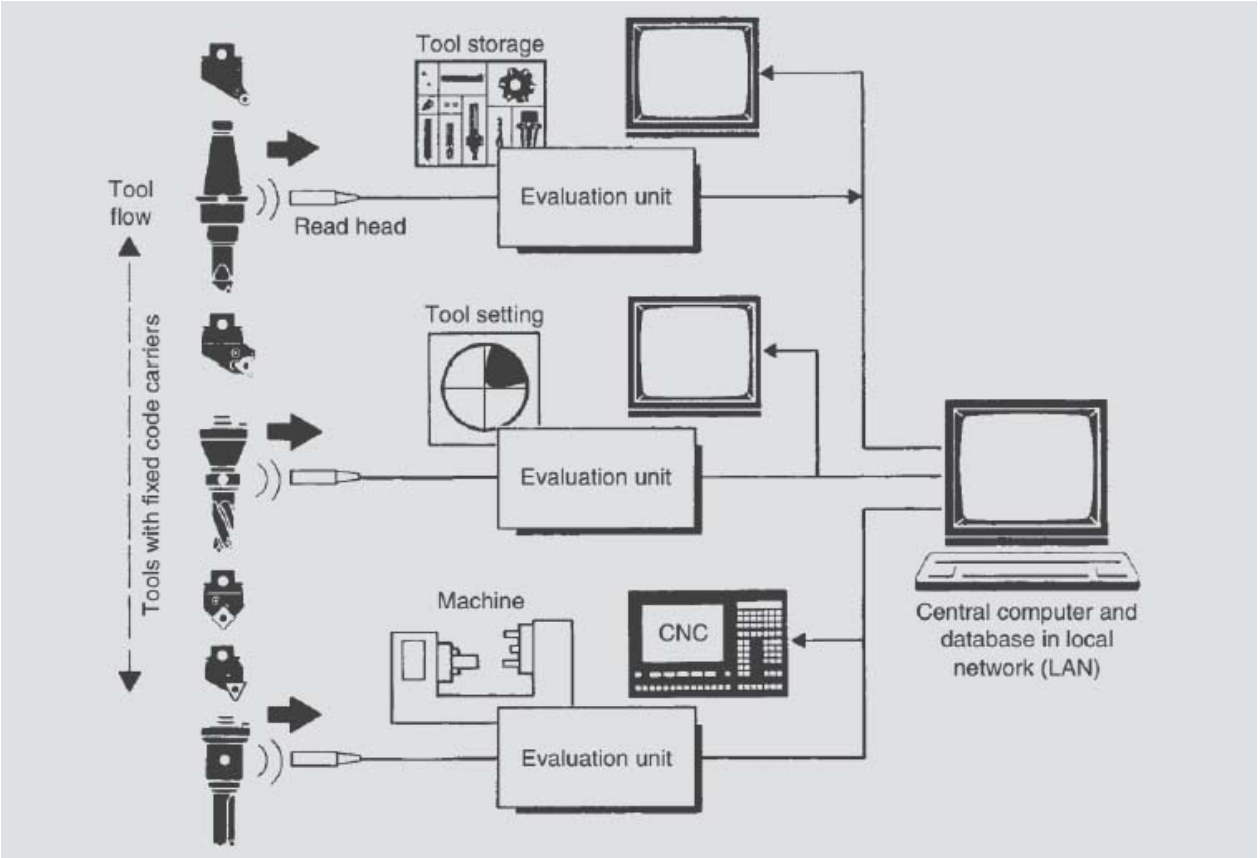


FIGURE 20.17 In a read-only system, the data carrier has a fixed number, and all data assigned to each tool are stored in the central computer under this number and can be called up from there.

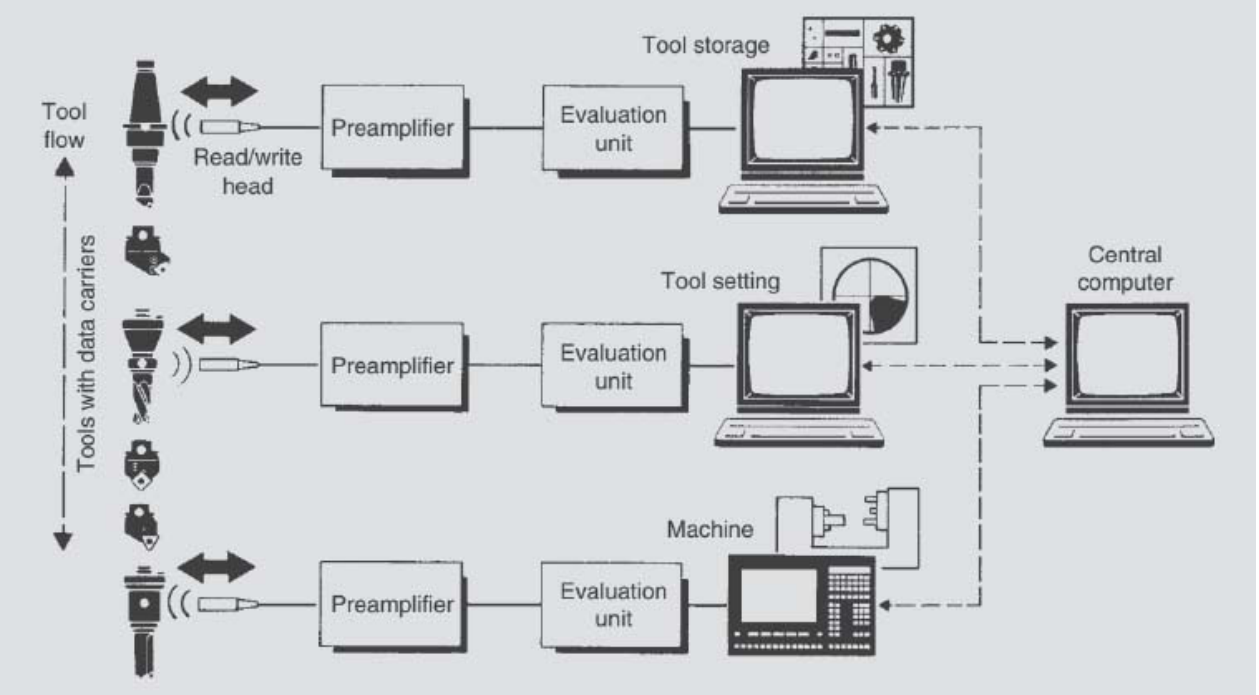


FIGURE 20.18 In a read/write system, the tool number and all the associated tool data are programmed in the data carrier and can be read directly.

Components of a Tool Identification System

An electronic tool identification system, as described earlier, consists of the following components:

■ A code-storage device, or chip, with fixed or modifiable coding

■ Read heads or read/write heads with preamplifiers

■ A reading station, connected with the read/write heads and computer or CNC system

■ A signal processor for read/write systems, with rs232, v24 outputs that are suitable for connection to a PC or a CNC system

■ A tool computer for storing and managing the tool data

■ Appropriate software for data storage, data management, data exchange, and clearly understandable displays on the screen

Technical data pertaining to the scanning distance, read time, programming time, write cycles, power supply, and so on can be obtained from the manufacturers of these systems.

Organizational Advantages of Electronic Tool Identification Systems

In view of the amounts of data required by sophisticated tool management systems used with highly automated CNC machines, electronic systems offer tremendous advantages, such as:

■ Automatic data flow between the tool presetting device, tool, tool computer, CNC system, and user

■ Increased integrity of data exchange because input errors are avoided and additional monitoring of random read and write errors

■ Shorter setup times on the machine

■ Better tool life

■ Increased efficiency in tool storage and tool presetting

■ Elimination of hard copies of tool data sheets in the shop

■ Improvement and automation of tool statistics

■ Support for operators involved in assembly, measurement, and inspection of tools

■ Improved tool management capabilities

Tool Identification and Data Management with RFID

What Does RFID Mean?

The abbreviation *RFID* stands for "radio frequency identification device." This is an automatic electronic identification technology that is increasingly used for noncontact identification, flow, and tracking of objects, goods, persons, and animals, as well as for in-process and access control systems and many other areas. A number of different types of data carriers and read heads are available for this purpose.

The flows of materials and information in computer-supported manufacturing are inseparably linked. This applies to pallets, clamping fixtures, and workpieces, but especially to tools that are used often in different locations with different data. Therefore, mechanical coding systems and barcodes have proven to be unusable for automatic tool data management; RFID is used instead. This principle and the associated components are rugged, insensitive to harsh working conditions, and reliable.

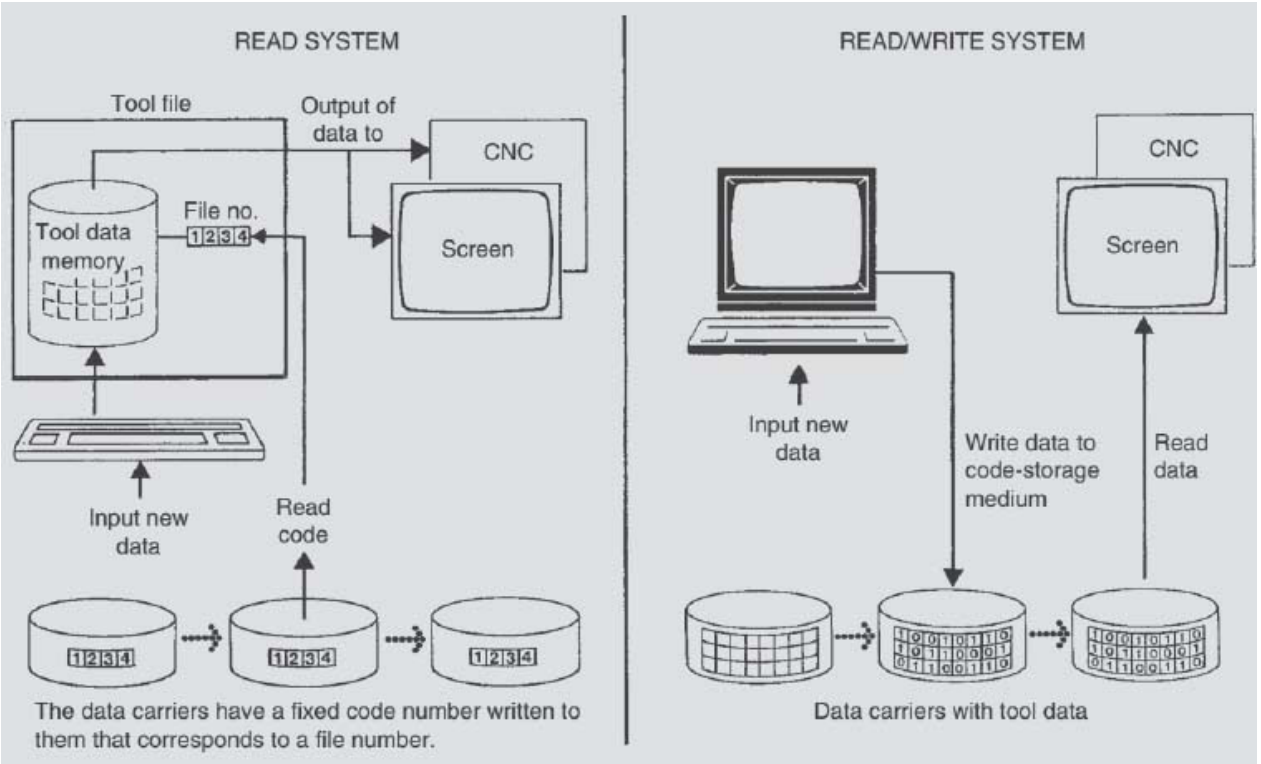


FIGURE 20.19 Functional principles of the read-only and read/write systems.

The use of RFID for tool identification has multiple advantages: the physical location of a tool is always known, machine damage caused by the wrong tool or tool data is prevented, and the tool can be used for its entire service life without repeated measurements. These advantages apply during tool use in the machine, transport, and in tool storage; a closed circuit of tool management thus exists.

When a tool with a RFID chip is loaded into the magazine, the tool data are automatically read, transmitted to CNC memory, and assigned sequentially to the current magazine location during operation. No further read operations are necessary during subsequent automatic tool changes from the magazine to the spindle and back. This leads to shorter changing times.

An RFID system contains the following components:

■ The transponder as the data carrier; also called an *RFID* and *radio tag*

■ The send/receive unit for communication with the transponder; also called *reader* or *read/write head*

■ The signal processor that controls the bidirectional data transfer between the read/write head and the transponder and buffers the data. It is connected to:

■ The computer system for processing and managing the data

It is possible for various fields of application to use special transponders that can be written to or read from in the high- or low-frequency range depending on the range that is required. The data exchange is noncontact by means of an inductive, that is, electromagnetic, read/write system. Depending on the range required, transponders can function either without their own power supply, called *passive* or with their own power supply provided by a battery, called *active*

Transponders are available in various designs, for example, as an adhesive label, button, chip card, pin, screw, or plaque. The electronic element is encased; thus it is hermetically sealed, extremely rugged, and resistant to impact, vibration, pressure, chemicals, and extreme temperatures. For use on a tool, the transponder is inserted in a borehole in the tool holder, bonded in place, and sealed. The dimension and position of the borehole in the holders are

standardized (ISO 14443, ISO 18000-4, ISO 10536, ISO 15693, etc.; Figure

Read-only memory (ROM) transponders can be written to only once. Recordable electrically erasable programmable read-only memory (EEPROM) chips allow the stored information to be overwritten more than 1 million times, which is more than adequate because tool information generally must not be edited very often. The number of read cycles is unlimited.

FIGURE 20.20 Transponders, or data carriers, for industrial use in tools. Protection classification: IP 67; capacity: 511 bytes or 2,047 bytes; type: EEPROM, read and write. Balluff.)

Data carriers can be used in any type of tool holder, even in modern holders for shrink-fit tools. The larger variants shown in Figure 20.20 were mostly used before standardization. The threaded design had the advantage of a nondestructive exchange. The modern data carrier is bonded in place. In this way, it can no longer be exchanged without destroying it, but this is typically not necessary because both tool and data chip remain associated with each other for their entire service life.

Another area of application for these data carriers is in assembly technology. The chips are always necessary when a number of small

tool segments are used in a fully automated assembly line. Many applications take advantage of the fact that data are not optically acquired by way of scanner systems, hand scanners, and so on but rather are transmitted to the read/write system by means of radio waves, which only takes a fraction of a second.

Functional Principle of RFID

Data transmission between the transponder and reader/receiver unit takes place by means of electromagnetic waves. At low frequencies, this occurs inductively via a near field and, at higher frequencies, via a far field. The read distance varies between a few centimeters and more than a kilometer depending on its design (passive/active), use of frequency band, transmission power, and environmental influences.

The reader generates an electromagnetic field that is received by the antenna of the RFID transponder. An induced current is generated as soon as the antenna coil comes near the electromagnetic field. This current activates the microchip in the RFID tag. In passive tags, the induced current also charges a capacitor that supplies power to the chip for a short period. In active tags, this is done by the built-in battery. Once the microchip is activated, it can receive commands from the reader. It transmits its serial number and other data being scanned by the reader to the signal processor by modulating a response to the field transmitted by the reader

Example: The passive transponders manufactured by Balluff for tool identification (type BIS M) are first scanned in the low-frequency (LF) range at 70 kHz to provide the power supply; next, data transmission takes place at 455 kHz. Recordable transponders have a memory capacity of 511 bytes or, in rare cases, up to 2,047 bytes. According

to current experience, 511 bytes are sufficient to store the tool data for 95% of all applications. DIN 69873 defines the dimensions of the data carriers: 10 mm in diameter and 4.5 mm high.

Memory Allocation

The data carrier memory can be subdivided internally into block sizes of 32 and 64 bytes, also called the *size of a page*

FIGURE 20.21 Evaluation unit, interface with the CNC. Interface: Choice of serial, parallel, InterBus, PROFIBUS, or DeviceNet.

Memory size up to 1,023 bytes = 32 bytes per block

Memory size up to 2,047 bytes = 64 bytes per block

TABLE 20.1 RFID Read Times In Dynamic Operation

Operation Operation Operation

Operation Operation Operation

Technical Advantages of RFID

The advantages of RFID compared with barcode systems include:

- Noncontact identification possible, even without line of sight
- Penetrates various materials, such as cardboard, wood, oils, etc.
- Unlimited reading and writing of the memory
- Identification and reading in less than a second
- Resistant to environmental influences
- Shape and size of the transponder can be adapted as needed.
- Transponders can be completely integrated into the item.
- High security thanks to copy protection and encryption

■ The RFID chip is a permanent data-storage medium that can be used to store all the product data. No redundant database is necessary to obtain initial information.

■ Objects equipped with RFID can be scanned more than 20 times more quickly than those with barcodes.

■ RFID tags can be read even when heavily contaminated.

■ Orientation of the object being scanned is much simpler than for objects with barcodes. It is sufficient for the object to be within the reading range of the scanner.

SUMMARY

Tools for CNC machines are integrated in the system of machine tool, workpiece, and CNC machine. They have to be manufactured so precisely that their interchangeability is guaranteed.
Furthermore, their optimal features, such as cutting values and service life, must be predictable. Finally, the process and wear-related tool change must be fast and precise. These features of a good CNC tooling system will only come into play when careful and systematic tool selection and preparation are ensured. It is a general requirement to catalog a new tool and perform the presetting outside the machine. In cases of doubt and lack of experience, advice from a well-reputed tool manufacturer or an experienced user should be solicited.

IMPORTANT POINTS TO REMEMBER

1. A well-organized, always up-to-date, and largely automated tool management system is one of the most important prerequisites for CNC production without wait times.

2. The tool management system has the task of ensuring an error-free and efficient order flow.

3. The tool management system organizes, updates, and manages all information for each tool in a database.

4. All data must be available at the workstations and when the tool is inserted into the CNC machine at any time.

5. Identification numbers are used to uniquely identify the tools.

6. The classification of a tool indicates what it is used for, such as drilling, roughing, face milling, etc.

7. Tools are classified in a system that fits the specific company so that they are easy to find.

8. The tool list reflects all complete tools required for the processing of part(s) in the machine.

9. The identification is a unique company-specific number for a tool. The components and the complete tools are numbered independently.

10. Tool management is divided into documentation, such as identification, classification, etc., and logistics, such as number, storage locations, and transport of tools.

11. Adjustable tools allow the setting of the diameter within a range so that fewer tools have to be kept.

12. Tool information is needed in several areas of a business. It is therefore important that tool data are managed centrally and consistently.

13. Modern CNC machines have software for tool management within the machine, including the output of updates. These include:

a. Management of replacement or twin tools in the magazine

b. Correction value memory for length, diameter, wear, and service life

c. Management of tool and location number in the magazine

d. Oversized tools and empty slots to the left and right

14. The previously used mechanical coding rings or barcode labels do not meet the requirements of digital manufacturing.

15. New tools are delivered as components with basic data, such as geometry, cutting data, tool life, etc.; these are provided by catalog or digitally.

16. After collecting the components, they are assembled to complete tools the way they are used in the various CNC machines.

17. The assembly results in new characteristic values that describe the complete tool.

18. The data of the complete tools are stored in the tool computer and can be transferred to a memory chip that can be located in the tool holder.

19. This memory chip and a matching reader form the RFID system.

20. When removing a tool from the machine, the possibly changed correction values and the remaining service life are automatically transferred to the data chip and are updated.

21. Said closed data cycle can also be used with a “read-only system” except that the data chip contains only the tool number. The updated tool data are transferred via DNC to the external tool computer.

22. Tool monitoring in the machine does not replace the external measurement or adjustment of the tools.

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INTRODUCTION

Many approaches to realize manufacturing optimization mainly attempt to shorten production and nonproductive times through the machining process as much as possible. It is better, however, to produce as many good parts with the least effort. For this, the negative impact of environmental and process-related fluctuations must be eliminated. These include, for example, temperature-related geometry changes of workpiece or machine, workpiece position in the workspace, deviation of the tool from the desired geometry, material inhomogeneity, and so on. At the current state of development of machine tools and controls, further improvement of the processing result by reducing individual errors can only be achieved with considerable technological or organizational effort. Higher precision and increased production reliability can be achieved when geometric variations of machine, tool, and workpiece are measured and compensated through control measures. The term *process control* is used to express the feedback of the processing result into the CNC machine to effect corrective action. A stylus in the machine spindle can capture deviations between spindle and workpiece so that the CNC system can make immediate corrections.

STARTING POINTS FOR PROCESS CONTROL

Any additional operation, such as reworking a workpiece, increases the cost of production. Therefore, one should always strive to capture geometric deviations and correct their systematic share within the scope of the required manufacturing tolerances. Examples include:

■ Readjustment of the machine geometry (tracking) by capturing temperature-based geometry deviations or the position-dependent residual error of complex machine kinematics

■ Recording workpiece position and orientation, setting the zero points for the NC program

■ Measuring excess stock and automatic adaptation of the NC program via parameters

■ Detection of tool displacement after rough machining and compensation by adjusting tool parameters

In terms of the successful production result, it is the objective to capture the workpiece geometry without taking the workpiece out of the machine. In this context, it must be clarified how precise these measurements must be and whether this can be achieved reliably. Because the measurement result is used for the adaptation of program or machine parameters, the measurement accuracy needs only to be as precise as the smallest possible

correction increment that can still be achieved for dimension change on the part.

A typical approach based on this principle could be the following example: assume that a series of five parts on a machine needs to be processed and a measurement of the first part indicates a dimensional adjustment needs to be made. The second part will be measured to verify that the adjustment has been processed correctly. If the measurement is within tolerances, the remainder of the series can be machined. The last part is then checked to ensure that the entire series conforms with a very high probability to the quality criteria.

Only a few actual parts need to be measured outside the machine (e.g., with a coordinate measuring machine [CMM]), according to the quality requirements of mass production, to confirm that the process control works. This measurement validates the controlled production process, not the individual part. This procedure allows detecting unacceptably large uncompensated geometric fluctuations of workpiece geometry. This check is not a quality control measure such as a first piece inspection check, but it reveals whether the production accuracy is in line with the repeat accuracy of the machine and manufacturing process. In the end, it is assured that the highest quality the machine is capable of providing translates to consistently high quality of the processed workpieces.

AREAS OF APPLICATION OF WORKPIECE AND TOOL MEASURING SYSTEMS

An important criterion for the selection of a measuring system for integration into machine and CNC system is the time when the system is supposed to be used. Four phases have been established in practice:

- Preprocess measurement
- In-process measurement
- Near-process measurement
- Postprocess measurement

The most commonly used method for checking and measurement correction of the machine geometry or detecting the actual workpiece position is the preprocess measurement. It is evident that the exact geometric parameterization of the rotary axes in the kinematic chain of a multiaxis machine is a prerequisite for high-quality production. Depending on the required manufacturing accuracy, it is recommended to test the actual position of the involved machine axes with measurement probes and a CNC testing program before production commences and to compensate possible deviations if necessary For this procedure, the NC program provides measurement and correction cycles

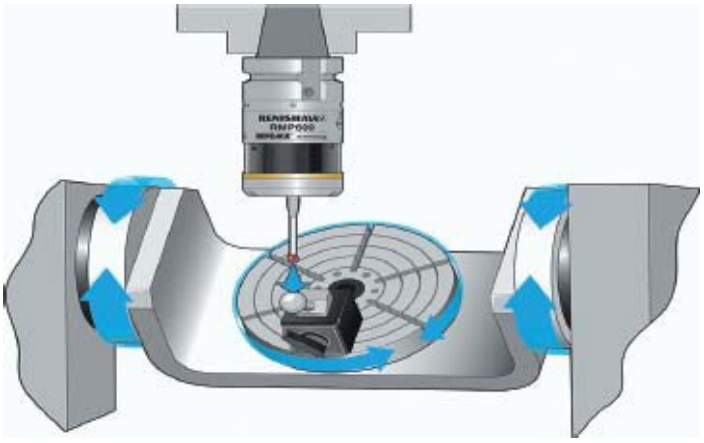

FIGURE 21.1 Measurement setup to determine the rotary axis geometry with a reference sphere and probe.

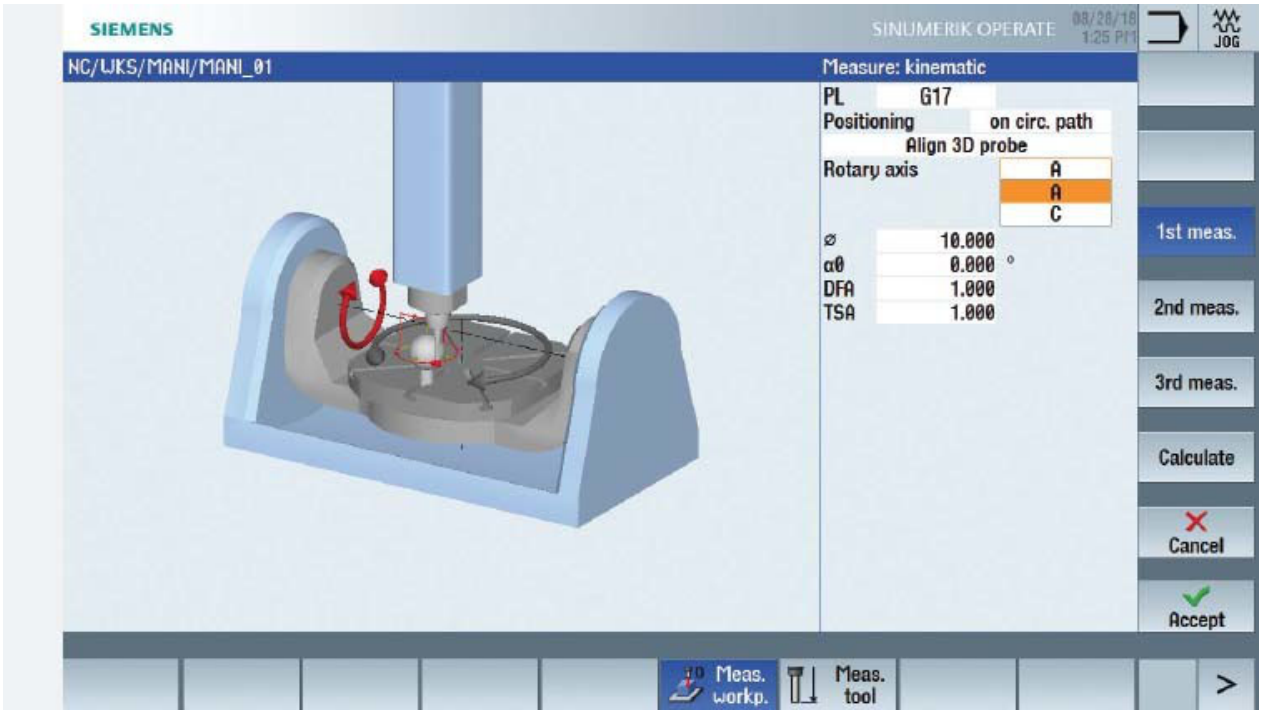

FIGURE 21.2 Control-specific measurement cycle for recording the rotary axis geometry (example CYCLE996), CNC Sinumerik 840D sl.

Before starting an NC program, the workpiece must be exactly positioned at the programmed location. This must be done by

appropriately repeatable workpiece holders, or more flexible and more reliably, the actual workpiece zero point is detected by measurement relative to the programmed zero point and communicated to the CNC machine (e.g., as a zero-point offset; see Section 24.8). The probe is mounted in the spindle, and the test can be done with high accuracy both in setup and automatic modes 21.3 and

FIGURE 21.3 With a four-point measurement of a bore, the workpiece zero point is placed in the center of the blank.

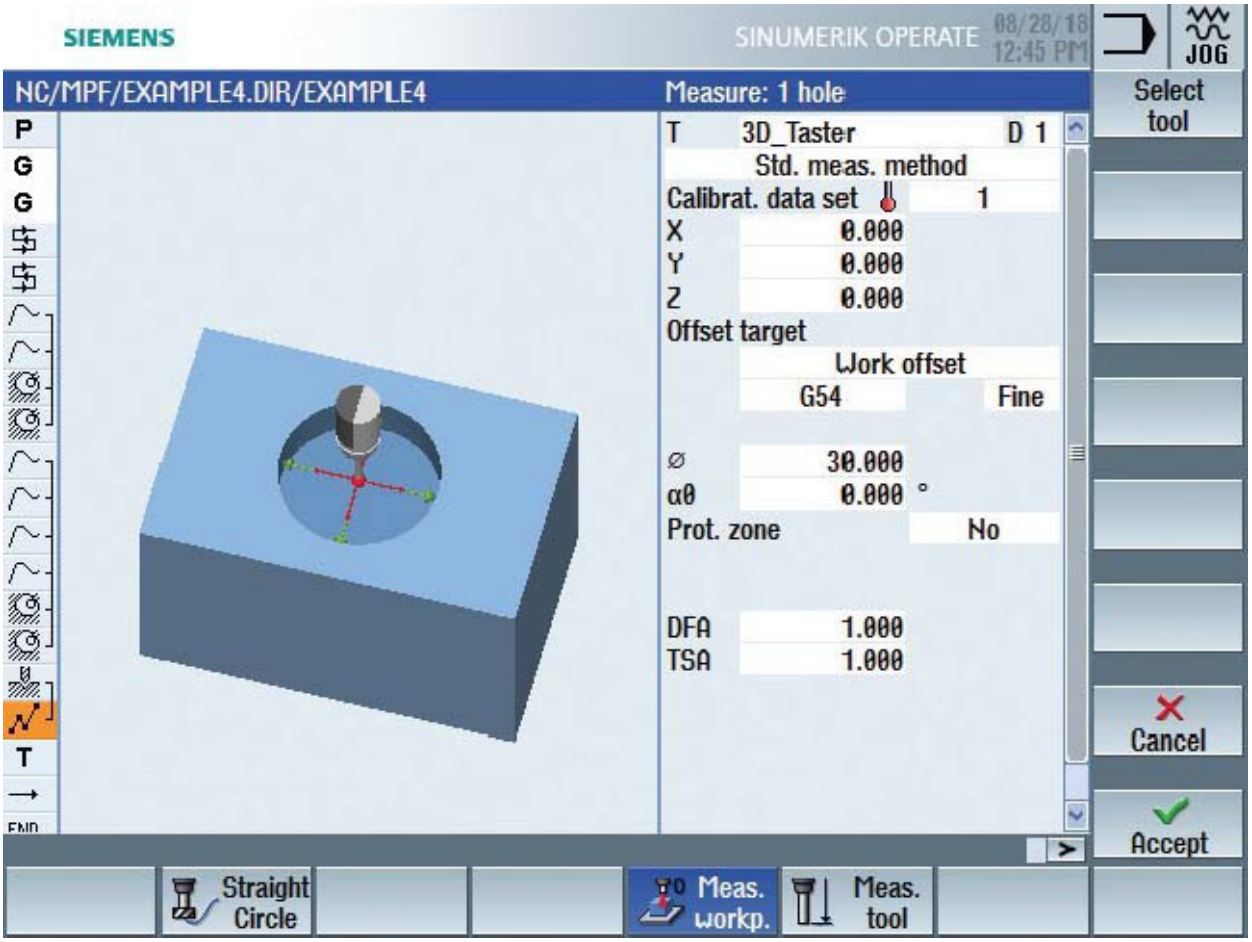

FIGURE 21.4 Example of a control-specific cycle for the measurement of a hole in automatic mode; deviations can be entered as a correction of the tool radius in the tool table or as a zero-point offset, CNC Sinumerik 840D sl.

The actual tool data, such as length, diameter, and cutting geometry, must be known to the CNC machine before starting a machining cycle. These data can be established outside the machine with a tool presetting device or directly in the machine. For this, tactile or contactless tool measuring systems in the working area of the machine can be used Control-specific cycles support the measuring process both in setup and in automatic mode

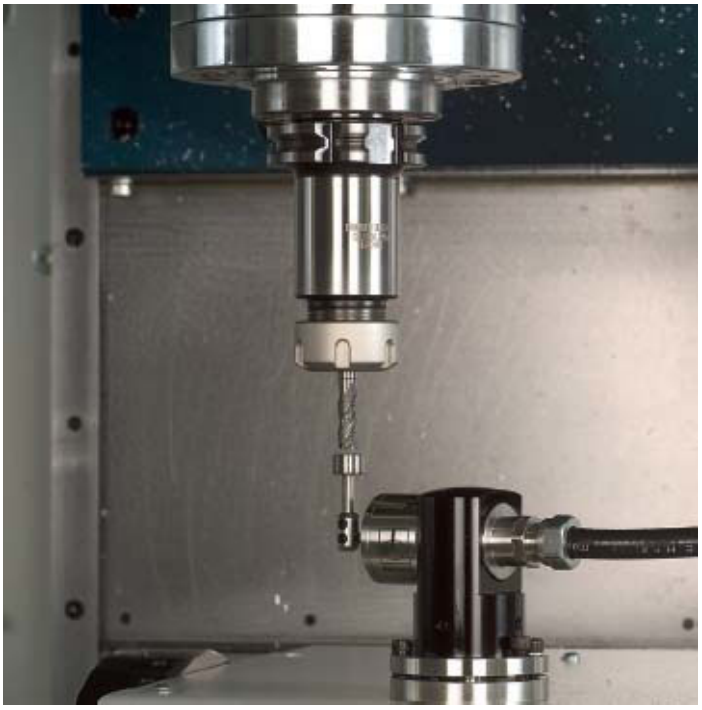

FIGURE 21.5 Capturing tool length with a tool probe in the work area of the machine.

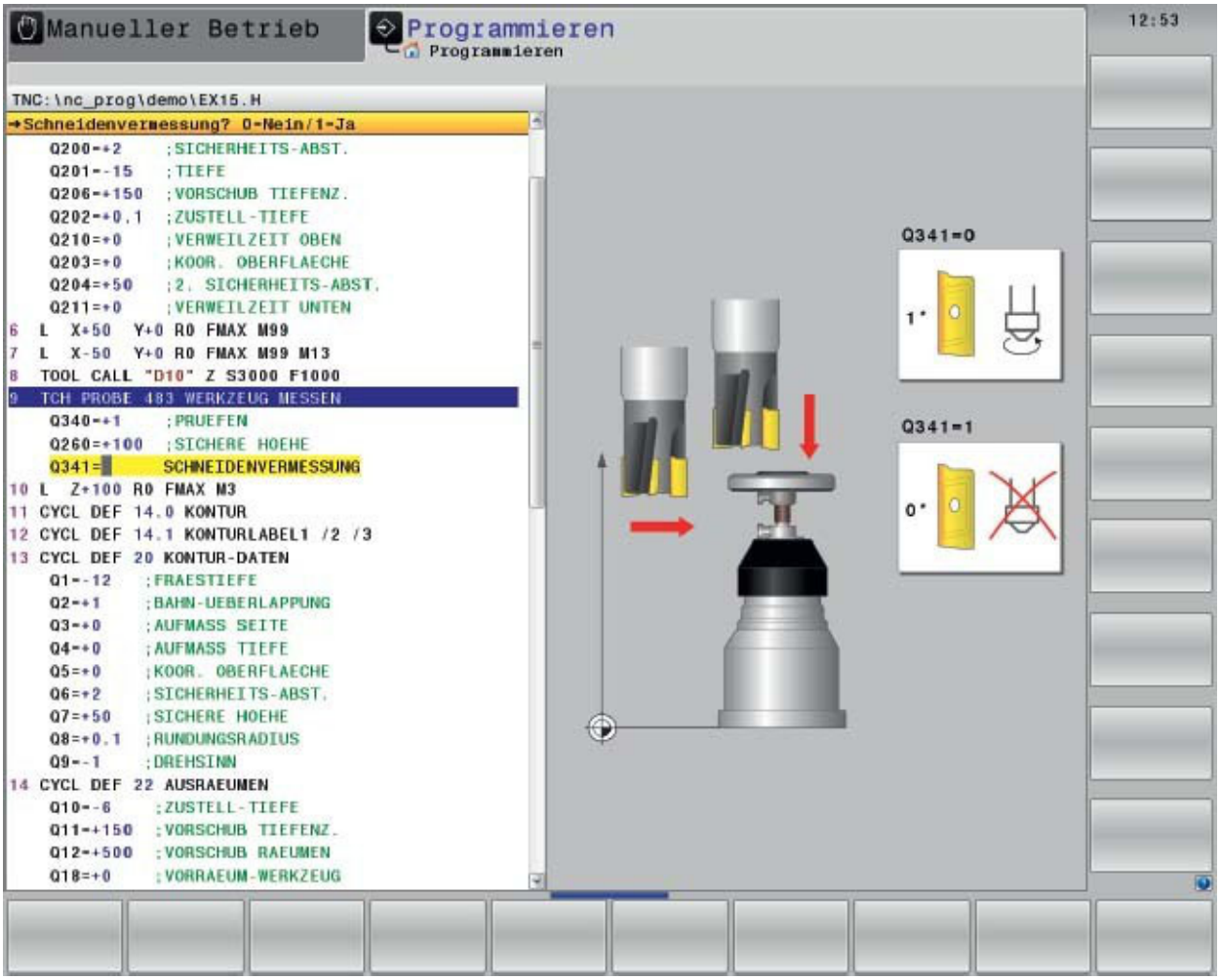

FIGURE 21.6 Example of a control-specific measuring cycle for programming an automatic tool measurement. The table touch system, TNC 640 with cycle TCH PROBE 483, is instructed to measure tool length and radius, and the CNC machine calculates deviations, based on the data of the tool table. The results of the comparison are automatically entered in the table as a tool offset. This feature allows high dimensional accuracy in the fabrication of components with tight manufacturing tolerances and fits. Even wear or tool breakage can be detected easily and quickly. HEIDENHAIN).

A true in-process measurement that captures workpiece geometry during the manufacturing process by means of permanently installed workpiece-specific sensors is particularly common in grinding

machines. Here the in-feed of the grinding wheel is regulated directly as a function of the measured value on the workpiece. Vibrations and other unfavorable environmental conditions can preclude the use of high-precision measurement technology; this is the case of milling with an interrupted cut.

A measurement between the individual machining operations captures and corrects geometry deviations automatically. The correction is reflected on the next part. Measuring or switching probes can be automatically inserted in the tool spindle, are very flexible, and deliver a highly accurate result. The adjustment of the probe relative to the workpiece and the probing cycle are programmed in the NC with special control-specific measuring cycles. The determined geometric deviations may be corrected in the next production cycle via CNC parameters such as tool length and diameter or zero offsets.

The CNC machine captures and processes the complete measurement results, stores them, and, if necessary, records them on a workpiece-related basis Thus, a complete machine-based quality documentation is realized.

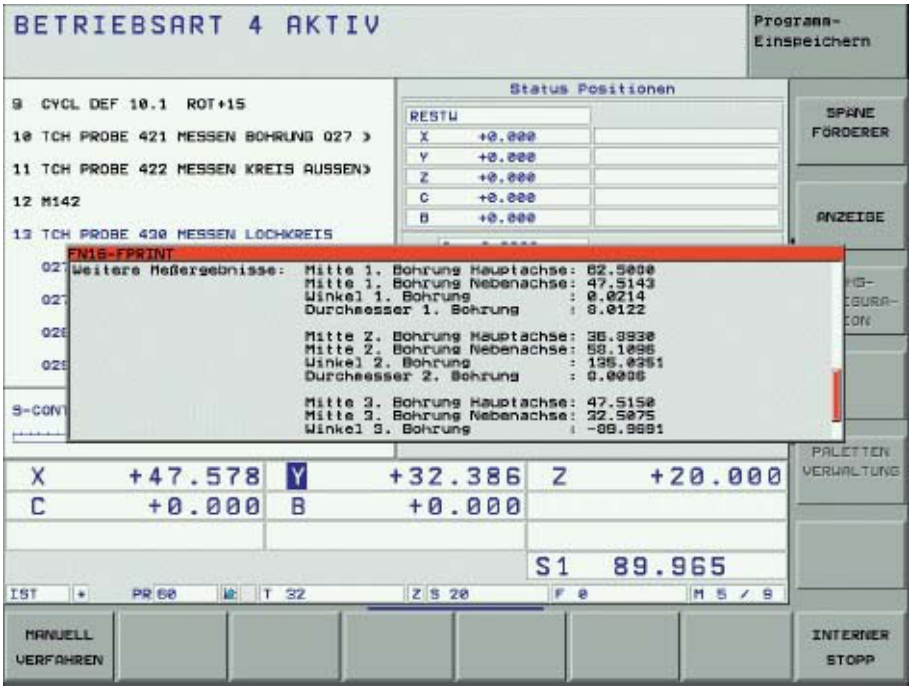

FIGURE 21.7 Example of a control-specific screen output a Heidenhain iTNC 530 with TCH PROBE 421 during the milling process. The programmed measuring cycle has been completed, and the control system displays the measurement results on the screen. The machine operator receives important information about the accuracy of the machining and decides whether the program must be canceled or can be continued. *(Source:* HEIDENHAIN.)

In case of short cycle times or extensive measurements, the postprocess measurement is used for testing and documentation of the finished workpiece. Here the part is completed and measured externally, and the result is fed back to the CNC machine. It is also used for complex measurements that cannot, or only with great difficulty, be performed during the run time of the NC program.

WORKPIECE MEASUREMENT SYSTEMS FOR MACHINE TOOLS

Requirements for the Accuracy of Workpiece Measurement Systems

As stated previously, the measuring accuracy of the CNC machine only needs to be as good as the smallest possible correction increment. Without regard for the respective processing, it stands to reason that the measuring accuracy of a machine is only as good as the positioning accuracy of the tool. Measuring systems that meet this requirement are sufficient for process control if the machine is basically accurate enough for reliable compliance with the required manufacturing tolerance. Should, however, the machine not satisfy this requirement, nonconforming parts should be anticipated, and a 100% inspection should be performed with more accurate external measuring instruments.

Switching Spindle Probes

The basic technical principle is a high-precision electromechanical switch that sends an electrical signal to the CNC machine when it comes into contact with the workpiece. The CNC machine stops the feed motion of all axes immediately and records their actual positions after registering the signal The actual measurement is therefore carried out by the position measuring systems of the machine and not by the probe.

Illustration of the phases of signal generation based on the kinematic resistance principle. The repeat accuracy of the retraction of the mechanics is important for reliable measurments.

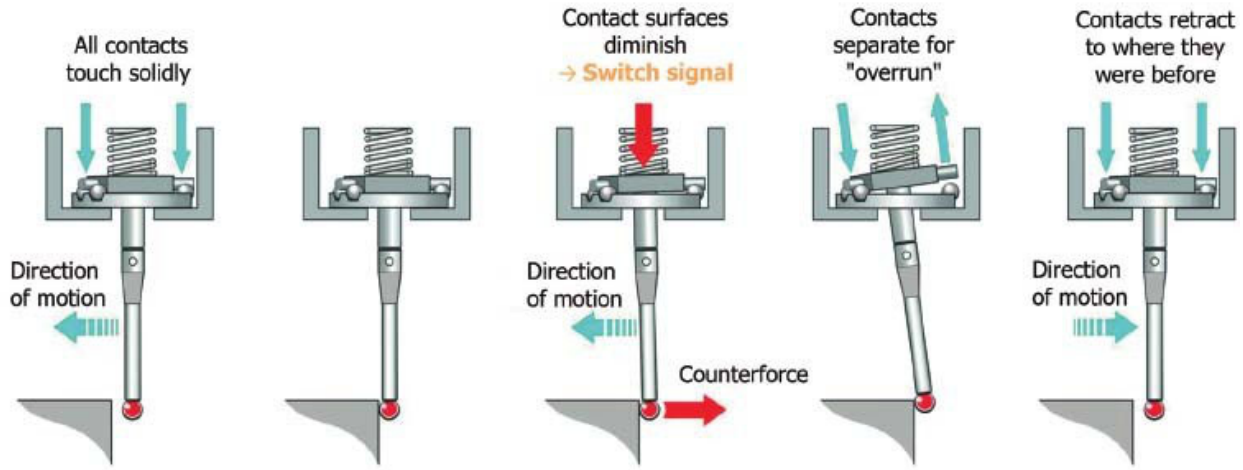

FIGURE 21.8 Procedure of probing with a switching stylus.

When a moving probe touches the workpiece, the immediate deceleration of the feed movement begins; therefore, a flexible suspension of the probing mechanism and a very high kinematic reproducibility are required to compensate for the so-called probe overrun without damaging the probe.

In structural design, a distinction is made between systems in which kinematic bearing and switching elements are identical and variants that use a separate switch. The systems suitable for process control achieve repeat accuracy of less than 1 µm. The actual achievable value, however, depends on probe length and rigidity. The probing uncertainty is rarely specified. Probing direction, calibration method, and manufacturing accuracy of the probe components have a great influence on the result

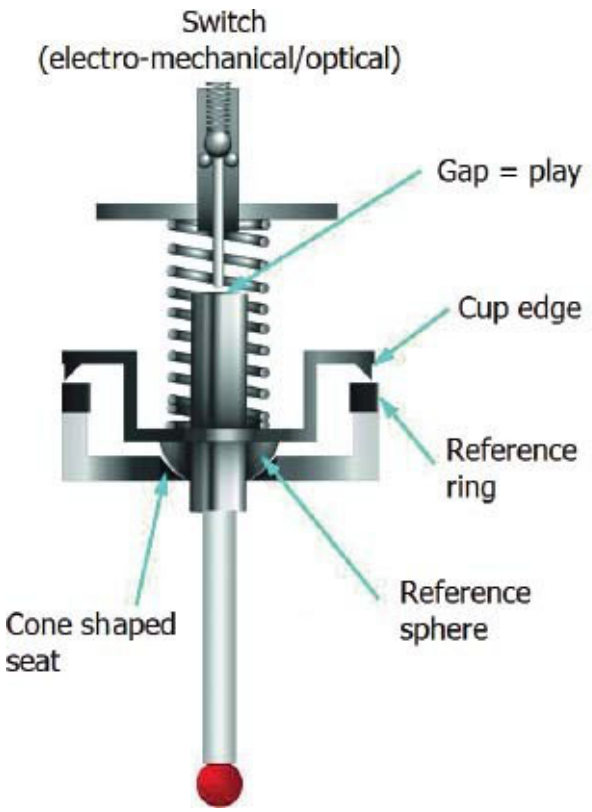

FIGURE 21.9 Example of a probe design with mechanical suspension and separate switching element.

The effective radius of the probe sphere and the position of the sphere center relative to the spindle are required for the CNC machine's internal calculation of the coordinates of the touched surface point. These values must be determined for each probe, before first use and after each change of probe insert or probing speed. There are control-specific cycles for the calibration. On machines with direct position measuring systems probes with a joint kinematic bearing and switching element, typically accuracies of better than ±10 µm in 2D are possible. An accuracy of up to ±2 µm can be achieved in the main axis directions in which the probe has been calibrated.

Renishaw developed a probing system with a systematic arrangement of stretch-measuring elements as contact sensors to improve the 3D touching accuracy. The switching signal is generated without mechanical movement by force measurement An appropriate design with very low switching forces can use very small probing spheres (e.g., diameter = 0.3 mm) and very long probes (e.g., 300 mm; Figure For a typical probe length of 50 mm, stretch-measuring elements provide very good 3D scanning uncertainties of ±1 μm and a ±0.25 μm repeat accuracy.

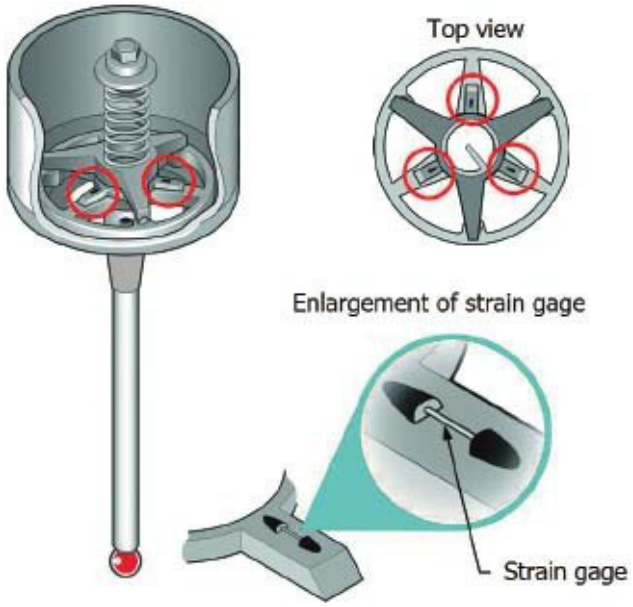

FIGURE 21.10 Operational principle of measuring probe with Rengage stretch-measuring technology.

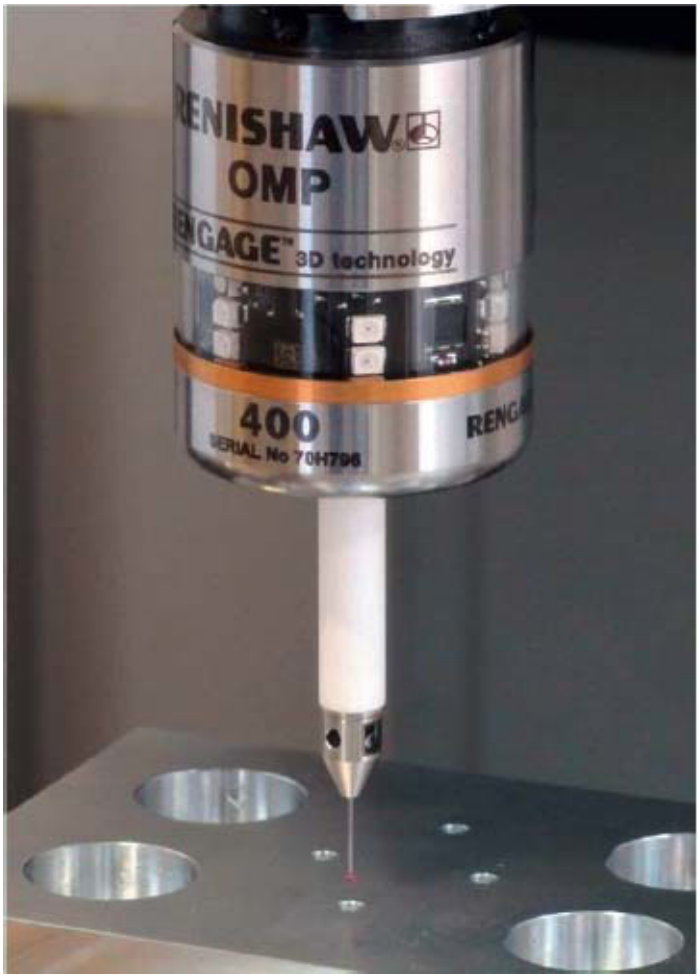

FIGURE 21.11 The smallest geometries can be measured with stretch-strip technology (the probe sphere in the figure has a diameter of 0.3 mm).

Measuring Spindle Probes

Typical applications for measuring probes are:

1. Capture, or digitize, unknown workpiece geometries.

2. Directly measure a certain geometric feature (e.g., a bore or shaft diameter).

3. Flexible measurement of a profile deviation (2D) or position deviation (3D).

Case 1

For tactile digitizing, sensors with a large 3D measuring range, typically greater than ±2 mm, are used. The format of the position signals of the probe usually corresponds to that of the linear encoder because the CNC machine treats these as such. Because these systems actively intervene in the position control of the machine tool, special safety and control technology requirements must be met. This also applies to the various typical operating forms of such a machine:

■ Normal operation

■ The CNC machine moves the probe according to a defined sampling strategy across the part (e.g., in a meandering motion or with evasive movement in

■ The operator moves the probe across the part, and the CNC machine retraces the probe and the axes accordingly.

The actual measurement takes place in each case with the simultaneous recording of the machine and probe position. The resulting cloud of points must be evaluated downstream with a computer program. Typical system accuracies for the measurements are in the range of less than 1/100 mm.

Case 2

Systems are used that directly measure the feature in question. These could include measuring heads for bore or shaft diameters that determine diameter, shape, and location of the workpiece at two or more points at the same time. The lack of flexibility of the measuring heads, because they are only suitable for the respective nominal diameter, is augmented by the machine-independent accuracy of often below 1 µm. A higher accuracy than that of the machine, however, only makes sense if the cutting tool itself can achieve this accuracy independent of the machine, for instance, a programmable boring tool. No further communication with the CNC machine is required while the measuring takes place, except data recording.

Case 3

These applications are for suitable systems that are moved along a predefined path without feedback of their measured values. Therefore, they use a much smaller measuring range. For this purpose, a sensor with a higher resolution can be used. The actual reading of the position of the probe sphere results from the synchronized recording of machine and probe position. For example, a Renishaw system uses wireless infrared signal transmission and captures the complete of the probing sphere with a 0.1 µm resolution with up to 1 kHz. In order to achieve this data transmission rate and evaluate the data during the run time of the NC program, direct connection to a CNC machine with an open architecture, such as a Siemens 840D sl, is required. The measurement accuracy for single points with high-quality tactile measuring systems is about the same with the switching probes (±1 µm). The high point density, however, yields a much higher accuracy in feature definition through single-point measurement, for example, in finding radii and the centers of small circle segments. Thanks to the system architecture, the measured values for process-oriented control are available directly in the CNC machine. As a result, highly accurate adaptive machining can be

performed without taking the workpiece out of the machine and conducting the measurement on a stand-alone coordinate measuring machine (CMM).

Variants of Signal Transmission for Spindle Probes

Touch probes integrated in the machine tool can measure workpieces as well as tools in the work area of the machine. For the measuring signals to be processed in the CNC machine they must be transferred by one of these methods:

- Optical
- Radio
- Inductive
- Wired

FIGURE 21.12 Requirements and data flow for an analog measuring probe.

Given the great installation effort, it is recommended to ask the machine manufacturer to install the probe assembly when placing the machine order. Various system manufacturers such as Renishaw, Blum, M&H Inprocess, Marpos, and so on also offer systems and services for retrofitting. Which signal transmission is used depends on the choice of the supplier and on the state of the machine and application.

Optical signal transmission takes place in the infrared part of the spectrum and always requires a free line of sight between transmitter (e.g., the spindle) and receiver. Therefore, optical transmission cannot be used in large machines where line of sight is not available. Infrared transmission is cheap, widely used, has many touch probe variants, and allows existing machines to be easily retrofitted.

Radio transmission can only be safely used if the system is shielded from the influence of outside systems, such as frequency shift transmission. Unlike for optical transmission, there is no need for visual contact. Nor do obstructing contours between transmitter and receiver influence the transmission reliability of the system. The integration effort is comparable to that of optical systems.

Inductive signal transmission via opposing coils also provides a robust interference-proof transmission. Because of the required machine-specific design adjustments, however, the installation effort is high. For this reason, retrofitting is typically not advisable.

Wired transmission guarantees a trouble-free signal and energy transfer. A wired probe can only be used in the tool spindle as an external tool while the spindle is arrested with a coded plug. Table probes, for instance, load cells, require the appropriate protection of the cables in the work area.

Programming of Measurements

The geometry of a part can be checked with control-specific measuring cycles. These are cycles that, after appropriate parameterization, perform all necessary positioning and measuring movements. The CNC machine calculates the geometric dimensions of tool or workpiece based on the recorded values. For process control, it is important that the measurements can be used directly for corrections. Therefore, the cycles must be able to use the measurements to overwrite the available influencing parameters such as zero offset, zero-point rotation, tool corrections, or program parameters.

Several aids are available to assist in the programming of combined machining and measuring programs:

■ Direct NC programming:

● *Program* The cycles must be entered and parameterized manually.

● *Control graphical user interface* The parameter definition of the cycles is supported by a graphical representation on the CNC machine, and the input values are compared with limit values for plausibility.

■ Interactive programming on CAD model:

● *CAM programming system for result documentation* (same as with a CMM). All required points are first measured individually by the machine and recorded. After completing the program, the file is read back into the CAM system and evaluated. Direct feedback is not possible.

● *CAM programming system for process*

The measuring sequences are integrated directly into the machining program. Because the measuring points are already evaluated in the program, tool data, parameters, and zero points can be corrected with the use of the results The necessary logical decisions and value assignments can be defined in a neutral way. Only the postprocessor generates the control and machine-specific NC code.

Potential for Improvement for Process Control

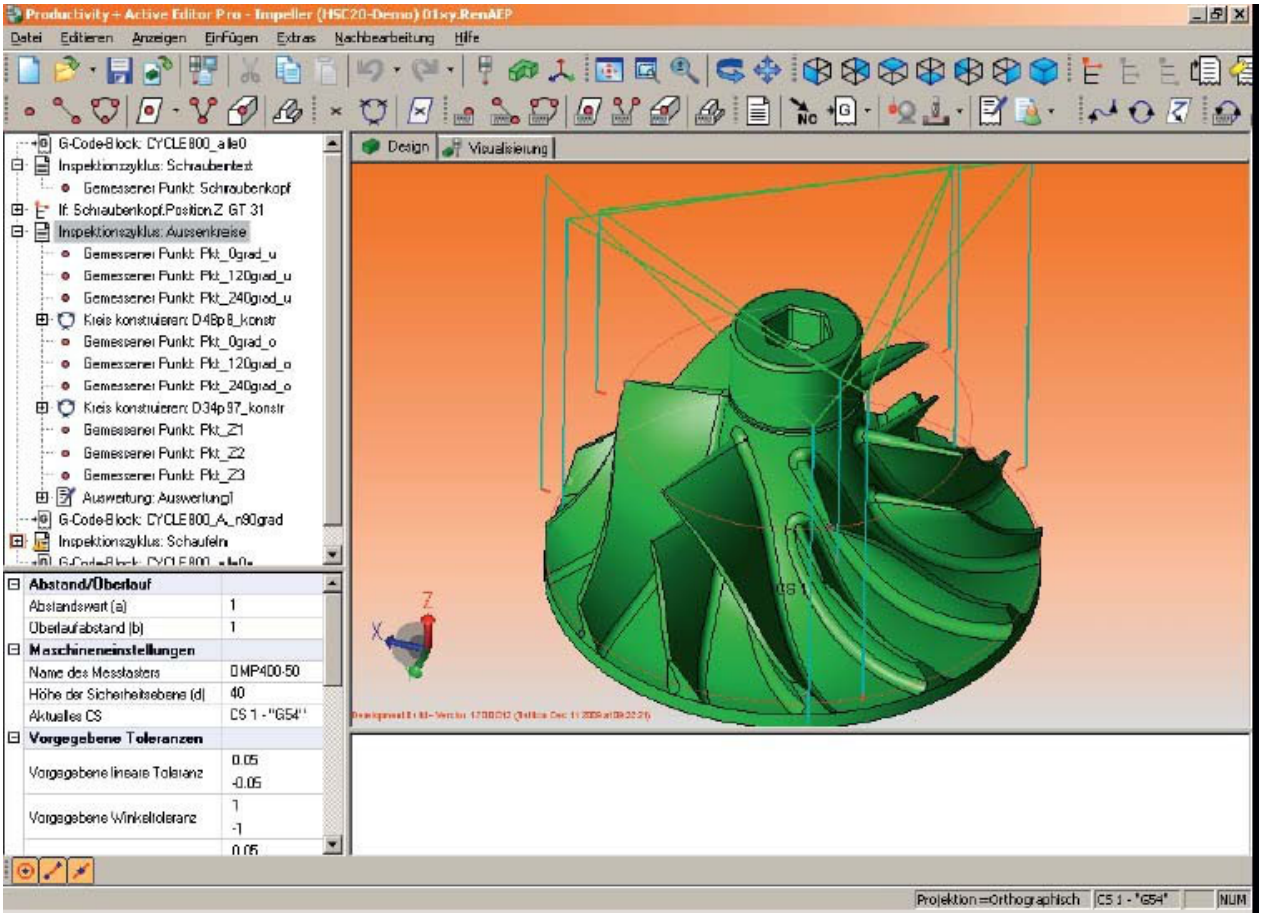

FIGURE 21.13 Interactive programming of measurements and parameter corrections in a CAM system.

The positive effects of using process control are evident in the results of a practical capability study with different process monitoring methods For this purpose, the workpiece *rotary encoder rings* with a tolerance of ±0.02 mm were manufactured with three different methods:

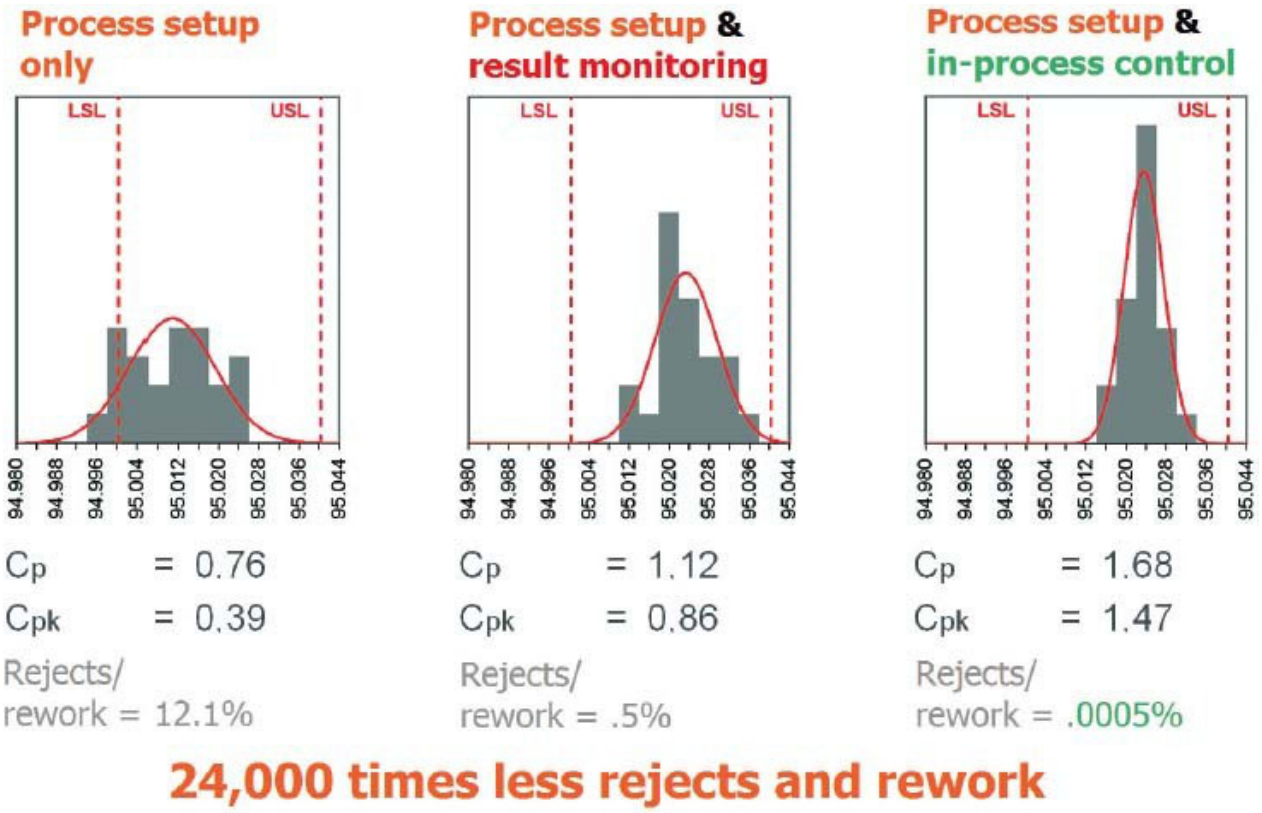

FIGURE 21.14 Reduction of rejects through in-process checking and in-process compensation.

1. Process setup only:
Method: The workpiece is clamped; the repeat accuracy is the same as the precision of the chuck. The tool parameters are not corrected in the process.
Result: The number of rejects is unacceptable; the parts do not satisfy the roundness tolerance.

2. Result monitoring on a CMM and result feedback:
Method: The finished workpiece is measured on a CMM. The measured deviation from the reference geometry is entered as a tool correction before the next part is processed.
Result: The correction effects an improvement in the next workpiece and reduces the differences between workpieces. Nevertheless, this

approach has a quality signature that is below the acceptable level of a reliable manufacturing process for most companies.

3. Intelligent in-process control with feedback
Method: After prefinishing, the tool parameters are corrected with 75% of the measured deviation from the desired geometry before finishing.
Result: Process reliability reaches a high level; extended operating times without personnel can be realized.

Measuring the finished part and making appropriate adjustments result in an improvement by compensation of tool wear. In the investigated case, there are large fluctuations due to upstream processes. The external measurement of the previous part is therefore not adequate for predicting the deviations for the next part. Because this is standard for many manufacturing processes, process-oriented measurement with direct control is by far the most effective solution.

IMPORTANT POINTS TO REMEMBER

1. Given the current state of machine tools and CNC machines, further process improvements can be achieved only with considerable design or organizational effort. Yet additional operations, such as the rework of parts, increase the cost of production. Therefore, it is mandatory to maintain the desired quality level through suitable measuring procedures inside and outside the machine.

2. The measuring accuracy only needs to be as good as the smallest possible correction increment that can still be made on the workpiece.

3. An important criterion for the selection of the measuring system and the integration into the machine and CNC is the time of measurement within the process. A distinction is made between these four phases: pre-process measurement, in-process measurement, process-related measurement and postprocess measurement.

4. The pre-process measurement is used to check and correct the machine geometry or to capture the actual position of the workpiece.

5. The in-process measurement is operation-parallel recording of the workpiece geometry by means of permanently installed

workpiece-specific sensors; it is used mainly at grinding machines.

6. Process-related measurements between individual machining operations can record quality-relevant fluctuations of the workpiece and correct the process in the next step. Switching or measuring probes that can be automatically exchanged into the tool spindle achieve the required accuracy with high measurement flexibility.

7. Tool data, such as length, diameter, and cutting geometry, can be determined either on external tool setting devices or directly in the machine. For this, tactile or noncontact tool-measuring systems can be used in the work area of the machine.

8. The actual measurement of a switching probe is made by the position-measuring systems of the machine and not by the probe.

9. For measuring workpieces and tools in the machine, most CNC machine brands offer appropriate cycles for measuring in setup or in automatic mode. For this purpose, the CNC machine describes parameters such as zero-point offsets and tool lengths. The measurement results can be logged both within the CNC and externally.

10. In order for the measurements to be processed, they must be transferred from the work area to the CNC machine optically, via radio frequencies, inductively, or by data cable. Probes can also be retrofitted on the production floor. The better option, however, is to have measuring hardware installed by the machine manufacturer during commissioning.

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INTRODUCTION

A look at technical drawings reveals that there is hardly any dimension that cannot be measured during processing in the machine. Therefore, probes for workpiece measurement have become standard. In mass production, however, even higher goals are set: for a 100% quality rate, closed process chains are needed. For this (dimensional) form, positional and surface roughness data must be captured and applied to the production process in real time and with high precision. The solution lies in machine-integrated measurement instruments for continuous process-integrated measurements.

Depending on the requirements, integration of the measurements at different positions in the machining process is possible. Preprocess measurement captures, among others, the position of the workpiece before processing. This is of great importance, for example, for the chained processing of cast blanks because the dimensions of casts vary to some degree. To ensure the closed process chain, the measured correction values for the CNC program are transferred to machine control. Process-related measurements are performed between the individual processing steps. In this way, correction values for the NC program are automatically calculated and applied to the next processing step. In the best case, this will eliminate complete processing steps, such as prefinishing with allowance and subsequent finishing to final size. In highly productive mass production, this means a great savings in time and money and thus unit costs. The

postprocess measurement takes place after machining and ensures that all quality-relevant characteristics comply with the specifications. Rejects are sorted out automatically, and the entire linked production process continues during nights and weekends with great reliability and without human assistance.

BORE-MEASURING HEADS FOR SHORTEST MEASURING TIMES IN BORE PRODUCTION

In the highly productive area of bore production, machining processes are optimized in the range of tenths of a second. Bore-measuring heads with a probing time of well under 0.5 second are superior to any conventional measuring probes. The measuring systems are placed in the tool magazine and are loaded into the spindle to measure holes and fits with narrow tolerances They are mainly used in the mass production of parts with the same bore diameters, for example, engine parts such as cylinder heads and blocks, piston rods, valves, and hydraulic components Their operation is based on a floating measuring mechanism that does not depend on the exact spindle position and the actual axis positions of the machine. This is in contrast to other near-process measuring systems. The independent analog measuring unit measures the bore diameter with true objectivity and maximum precision with a resolution of 12 bits/0.15 µm. In addition, as an optoelectronic measurement system, it does not have wearing parts and therefore offers maximum reliability.

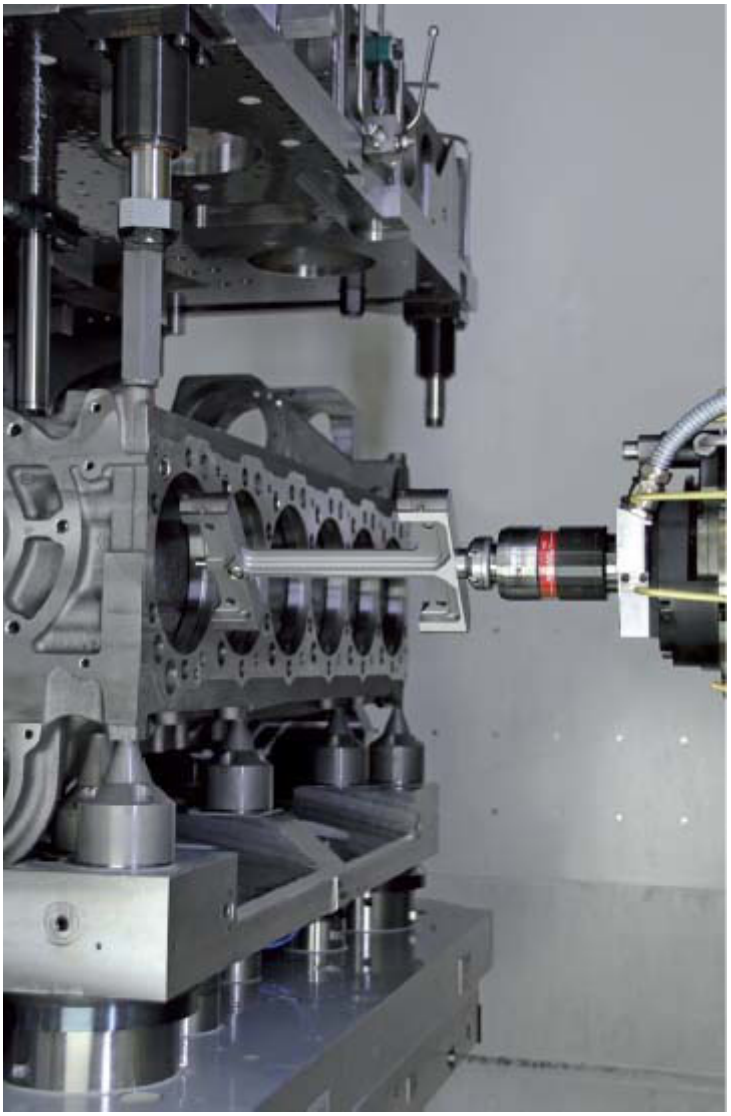

FIGURE 22.1 Bore-measuring head BG61 at the diameter measurement of cylinder bores before the cylinder liner is pressed in. Blum-Novotest.)

FIGURE 22.2 Diameter-specific bore sensors are used predominantly in the mass production of workpieces with the same bore diameters. Blum-Novotest.)

Another device variant is equipped with up to eight individual measuring elements and thus able to measure diameter, shape, and position The diameter-specific bore measuring heads have a measuring range of up to 0.4 mm. The analog measured value is sent to the receiver wirelessly and transmitted to the control unit, which takes over the analysis of the measured values.

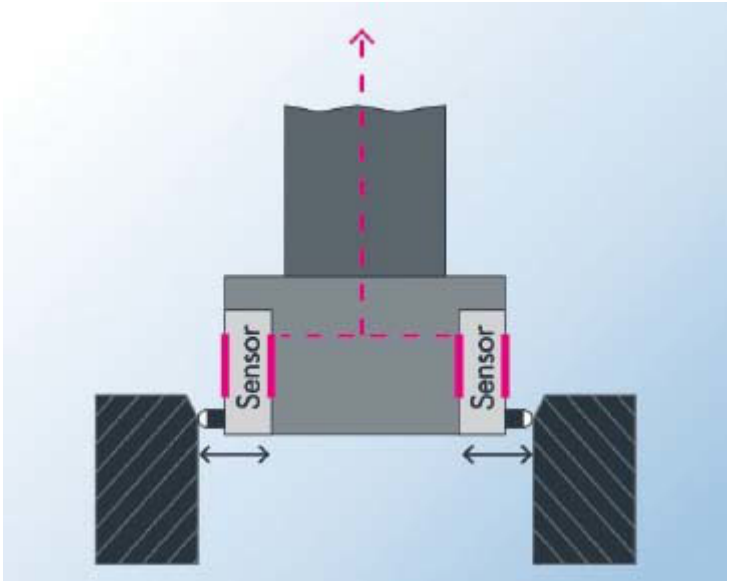

FIGURE 22.3 Measuring head with two individual measuring elements. Blum-Novotest.)

The objective of many companies in the field of series production is the realization of a closed process chain. If a measurement deviates from the target value, the control unit automatically makes a correction toward the center of the tolerance. In the programming, the tolerance limits must be set for all dimensions that are automatically measured. If a trend is evident within consecutive measurements, possibly caused by temperature elevation or tool wear, the computer will cause a correction in the process. In case the measured value lies outside the tolerance, the machine will automatically stop.

ROUGHNESS-MEASURING DEVICES FOR THE AUTOMATED SURFACE TEST

Given the harsh conditions prevailing in machine tools, until recently, the automated machine-integrated recording of the feature's "surface quality" was considered not technically feasible. Until then, surface inspection on the clamped workpiece could only be realized with a manual operation or a subsequent control step outside the machine. Both approaches do not support mass production because they are time consuming and unreliable. Using machine-integrated roughness-measuring instruments, the process chain is now closed, and out-of-spec surfaces can be automatically detected in the original clamping

FIGURE 22.4 Roughness tester TC63RG at the high-precision and automated testing of a workpiece surface in the machine tool. Blum-Novotest.)

Standard surfaces from milling, turning, and grinding operations can be checked within seconds in the micron range, and the

following roughness values will be evaluated:

- Arithmetic mean roughness
- Root mean square roughness
- Roughness
- Averaged roughness
- Maximum single roughness
- Wave depth

Roughness values measured with the analog surface probe can be recorded for later use, put out as a status value, or displayed on the screen. By using a very small measuring force, a standard cone-shaped probe with a very small tip radius can be used, whereby very precise measurements of a mean roughness of 2 µm are possible. Very short measurement times coupled with the highest reliability and precision stand out especially in the highly productive serial production of gearboxes, aviation components, and engine parts such as compressor wheels or connecting rods. In addition to the perfect surface quality, surfaces such as cylinder bores, for example, are also “functional surfaces” that must comply with exactly defined roughness values. In the case of a combustion engine wall, the specified surface also has the task of lubrication storage and dispensing; if the surface deviates from the requirements, the function is no longer assured.

A number of devices are available for machine-integrated surface quality monitoring. They differ in design and are tailored to the requirements of the respective measuring task. The roughness gauge TC63-RG Single employs a newly developed single measuring element. A similar device has been used for decades in BLUM bore-measuring heads Because of the modular design of the device, the system can be easily adapted to the measuring requirements; this can be particularly helpful in cases of very large workpieces or hard-to-reach surfaces.

FIGURE 22.5 The roughness meter TC63-RG Single with single measuring element for high-precision roughness measurements on straight surfaces. Blum-Novotest.)

DIGILOG PROBE FOR DIGITAL AND ANALOG DATA ACQUISITION

The functional principle of the digital probe can be derived from its name: as soon as the probe tip touches the workpiece surface, a switching signal is generated. The workpiece surface is thus recorded point by point. The more points recorded, the more information about the workpiece surface is included in the evaluation. The probing of individual points, however, requires considerable, usually unacceptably long measuring times. Therefore, analog probes are used to scan workpiece surfaces. Yet these are usually very large and not suitable for use in CNC machines.

The Digilog probe combines digital and analog data capturing in a handy device and is designed for the harsh environment of a machine tool. It is stored in the tool magazine and automatically inserted into the tool spindle for the measurement A typical application in series production is the inspection of valve seats in combustion engine cylinder heads. The valve seat tool is a shaping tool, so precision and integrity of the tool are decisive for the surface quality. Unfortunately, these tools have a tendency toward untimely microbreakouts, so regular replacement of the tool does not provide a remedy. The solution is scanning of the newly created contour of each valve seat immediately after the reaming operation with a Digilog probe. The defect caused by a worn tool is often only a few tenths of a millimeter broad with an elevation of a few microns. This makes detection by digital scanning nearly impossible because the number of measuring

points would have to be extremely high. The Digilog probe very reliably "senses" the deviation through the analog measurement so that the machining center can be stopped immediately and the valve seat tool can be changed

FIGURE 22.6 Analog measurement via scanning of the workpiece surface. Blum-Novotest.)

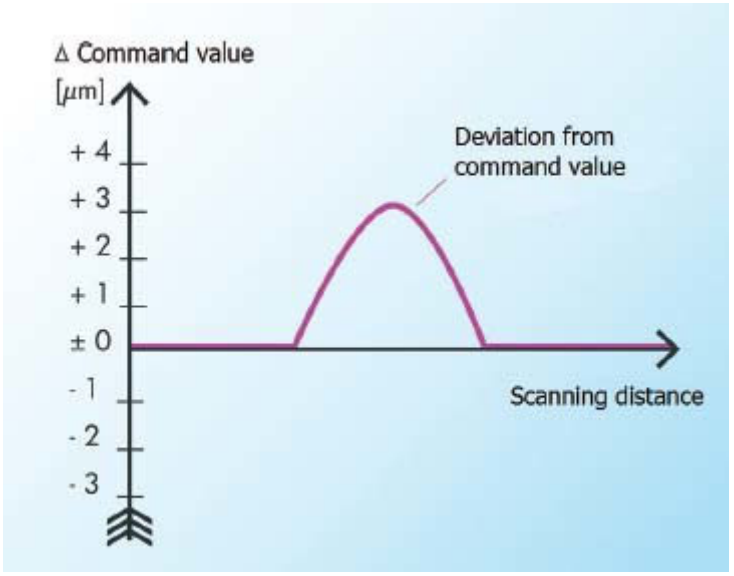

FIGURE 22.7 Deviation of nominal contour is detected within seconds. Blum-Novotest.)

In addition to the optimization of standard machining operations, flexibility in production is becoming ever more important. Often the increasing individualization of products leads to reduced lot sizes. The more often a machining center is converted, the more important setup time becomes. Automatic retooling and measuring of fixtures, workpieces, and tools can save a lot of time. A Digilog measuring system, employed directly in the machine tool, also has the following advantages:

- Automatic workpiece zero-point detection

- Temperature drift detection of the machine

- Verifying blank dimensions before processing

- Detecting inaccuracies when clamping complex or very large components

In the case of very large parts, for example, gears for wind turbines, 100% quality control after production on a CMM is often impossible because machines of that magnitude are not available. With a Digilog probe, a very large number of measuring samples can be performed in a short time while the part is still in the original clamping on the machine In short, the reliability of the result increases due to the large number of measuring points. For this reason, analog scanning is becoming ever more important.

FIGURE 22.8 Processing errors can be detected with the workpiece probe TC64-Digilog while the part is still in the machine tool. Blum-Novotest.)

HIGHEST PRODUCTIVITY WITH SIMULTANEOUS MEASUREMENT

In serial production, every second counts. Twin-spindle machines significantly reduce the cycle times via simultaneous machining. With the TWIN technology, measurement can also be carried out simultaneously while the parts are in the original clamping. Both two-workpiece probes and two-tool probes can be used for simultaneous measurement via radio control The simultaneous use of touch probes enables cycle time reductions of up to 50% without compromising quality. Other capabilities of the system include:

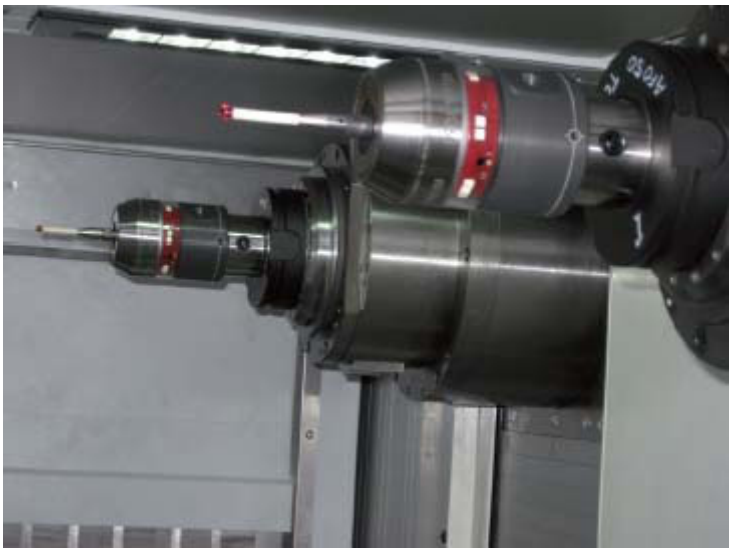

FIGURE 22.9 Cycle time reduction of up to 50% with TWIN technology on twin-spindle machines. Blum-Novotest.)

- Quick self-examination

- Temperature compensation of the machine tool

- Quick self-check of the machine (e.g., for hardware integrity)

SUMMARY

Given cost and time pressures, modern semiautomated and fully automated series production is showing a clear trend toward process-oriented measuring in the machine while the part is still clamped. For this, machine tools use measuring systems and corresponding measuring software. The CNC machine uses prepared measuring cycles that compare the actual and target conditions. Based on the results, it is automatically checked whether the measured value lies within tolerance and machining can resume, whether tool offset values need to be manipulated, or whether an unrelated error message was put out.

Highly productive mass-production installations in particular, using chained production lines, are pioneering the use of process-related measuring technology. Interruptions in the nature of external measuring operations would impact and delay the entire downstream production process. It is also increasingly used in situations where postprocess measurement with subsequent finishing for accuracy and cost-effectiveness reasons does not seem to be worthwhile at first glance. Here the industry prefers the machine-integrated measuring technology with bore-measuring heads, Digilog probes or roughness gauges, and the associated measuring software.

However, measuring in the machine is not a substitute for stand-alone high-precision CMMs in the quality assurance department. This is for the purpose of providing quality

documentation for each workpiece or a particular batch or due to accuracy requirements.

IMPORTANT POINTS TO REMEMBER

1. Bore-measuring heads are used for the high-precision process-related measurement in series production.

a. Fast automatic measurements of bore diameters

b. Process control by determining compensation values

c. Fully automated production in closed process chains

d. Machine-independent measuring system with a floating measuring mechanism

e. Single-measurement elements allow fast and automatic measurement of diameter, position, cylindricity, roundness, and concentricity.

2. Digilog probes detect processing errors by quick scanning.

a. Digilog = digital measurement with high precision and analog scanning with lightning speed

b. Workpiece measurement in CNC lathes and milling and grinding machines

3. Roughness-measuring devices are used for machine-integrated quality monitoring of surfaces.

a. Evaluation of the surface roughness in the original clamping

b. Automated roughness measurement in CNC lathes and milling and grinding machines

c. Higher productivity and process reliability because of the elimination of manual and downstream testing

d. Minimize scrap through immediate correction

4. TWIN technology enables simultaneous use of touch probes on double-spindle machines.

a. Automated workpiece measurement with two simultaneously operated touch probes

b. Temperature compensation of the CNC machine

c. Significant increase in productivity and cycle time reduction of up to 50%

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INTRODUCTION

CNC machining centers often operate in automatic multishift operation without constant monitoring by an operator. Scrap, resulting from worn, broken, or incorrectly measured tools, is therefore recognized very late, possibly only in quality control. Laser systems for machine-integrated tool measurement and monitoring contribute to avoid these and other problems and to produce a maximum number of good parts.

In simple terms, a laser measuring system for tools is a high-precision light barrier. If a tool interrupts the laser beam, at a certain percentage of shading, a switching signal is generated and transmitted to the CNC machine to record the axis positions. Software integrated into the control system uses the measured value and a reference value for calculation of the tool dimensions.

The optical system must be designed to function reliably in the harsh environment of a machining center. Therefore, the optics of a laser transmitter and receiver are protected from coolant and chips through a pneumatically operated shutter and an air curtain. Thanks to additional plausibility checks by the integrated electronics and special measuring strategies, the presence of airborne coolant does not affect the measurement. Special nozzles blow compressed air at the tool to prevent falsification of the measurement.

With the cooperation of the CNC machine, focused laser measurement systems can capture tool dimensions from a diameter of 0.01 mm in length and radius or monitor for fractures, cutting-edge outbreaks, and rotation accuracy. Tool measurement in the workspace and at the rated speed also can detect clamping errors. Additionally, the effective dynamic length and radius change can be compensated for

FIGURE 23.1 Precise monitoring of a drill bit while coolant is on with LaserControl NT. Blum-Novotest.)

TOOL BREAKAGE MONITORING

The functional principle of a laser measuring system is based on a light barrier. It must be installed in the working area of the machine so that it is within reach of all CNC axes. It is beneficial if the laser measuring system uses visible laser light.

A classic method of tool fracture monitoring is the control of the tool geometry. Here the predefined tool length is checked by the laser measuring system. Tool breakage monitoring thus represents pure length control, working both when the tool stands still and when it is in operation. This has the advantage that length and radius changes can be detected at high tool speeds. If, however, the tool length is outside a specified tolerance, an error message is displayed.

Laser measuring systems can measure and check 90% of the common cutting tools:

- Centric tools such as drills, taps, or reamers in operation
- Tools with internal cooling, end mills, or styli
- Tools in 90-degree-angle heads or swivel heads
- Custom tools such as grinding wheels, form tools, and saw blades

Rapid tool failure control can prevent serious mistakes and associated high costs. A noncontact tool integrity check between two processing steps will ensure that no consequential damage will occur in case of a compromised tool. For example, when a drill bit breaks during predrilling, in the worst case, all following tools will also break. The costs for this accident must not be neglected because the possible ensuing collision could jeopardize the integrity of the spindle. This again can result in further great expenses.

SINGLE-CUTTING-EDGE CONTROL

The laser measuring system can detect, apart from tool length, the smallest cutting defects up to wear dimensions in the micron range. Single-edge monitoring will check whether every single cutting edge is within a given tolerance Because of the high sampling rate of the system, this control can be performed almost at nominal speed. With this method, four different errors can be captured:

FIGURE 23.2 Every single cutting edge of the milling tool is checked with the laser measuring system very quickly for integrity and wear at a speed depending on the number of cutting edges. Blum-Novotest.)

1. Cutting-edge damage

2. Tool wear

3. Buildup on an edge

4. Clamping errors

Because of the high repeat accuracy of the switching point, a tool setting accuracy of up to 1 µm can be achieved. Unlike external measurements, the measurement takes place in the actual work conditions at nominal speed. The requested measurements, for instance tool length and diameter, are automatically recorded under the correct tool number in the tool offset memory, which precludes manual input errors.

MEASUREMENT OF HSC TOOLS

High-speed cutting (HSC) is characterized by high spindle speeds and highly dynamic drives. Spindle speeds of up to 60,000 rpm require, in addition to balanced tool holders, perfectly inserted tools. Clamping errors cause unbalanced tools with the following consequences:

1. The circular path described by the longest cutting edge increases its radius and consequently also the effective diameter of the tool.

2. The other cutting edges are not or are only partially engaged because the protruding edge does most of the work, which drastically increases uneven tool wear.

3. The centrifugal forces caused by an unbalanced tool can damage the tool and the spindle bearing.

Special measuring cycles for time-optimized laser measuring systems enable detection of the longest cutting edge at nominal speed and thus determination of the effective length and radius compensations. In addition, the eccentricity can be checked for compliance with a programmable tolerance value.

Additional Options

The laser measurement method also offers further options, such as determination of radius and center point for ball end mills or

control of radius and bevel in form cutters For ball end mills, even an angle-dependent radius correction is possible at up to 50 points. All the functions described assume that the CNC machine is equipped with the necessary software.

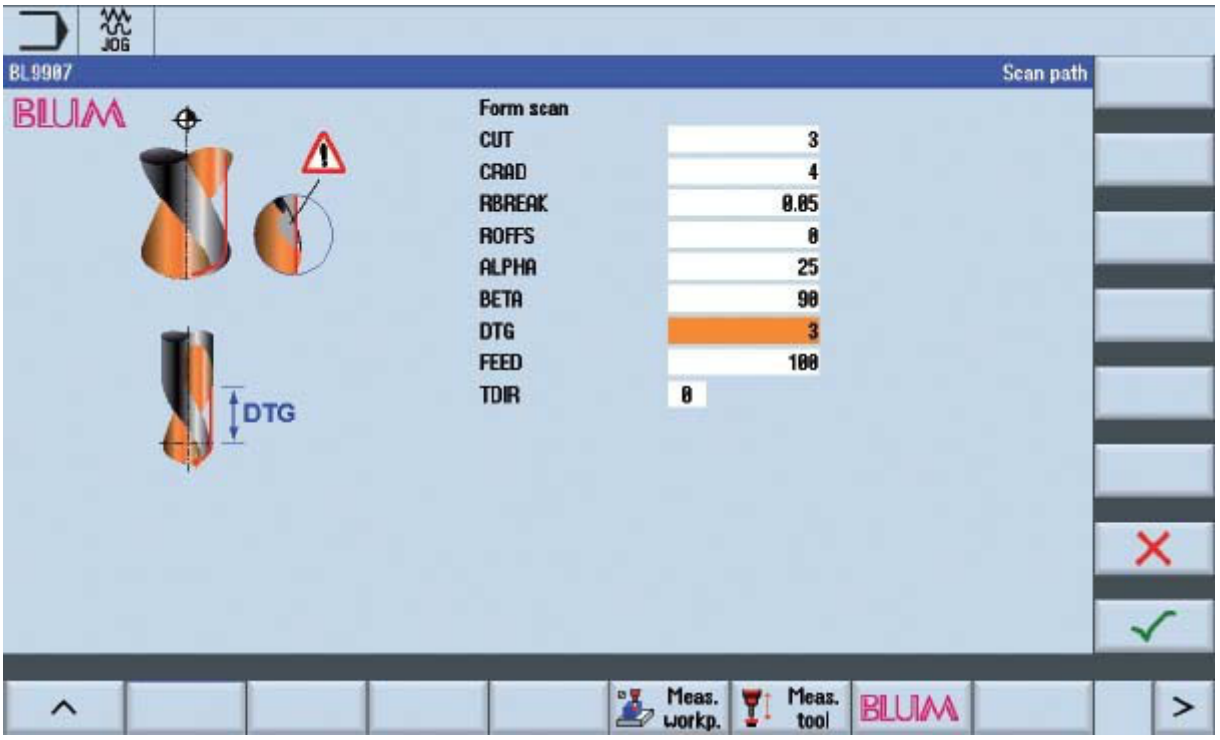

FIGURE 23.3 Input menu for form control of milling tools with a rounded cutting edge; example of a Siemens 840D. Blum-Novotest.)

COMBINED LASER MEASUREMENT SYSTEMS

CNC multitasking machines, such as turn-milling and mill-turn centers, are used increasingly in modern fabrication. The measurement and monitoring of rotating tools on these machines can be carried out easily and quickly with laser measurement systems. Lathe functions on multitasking machines, however, place additional demands on the measuring system. The laser measurement of nonrotating tools is extremely precise, yet it requires a time-consuming multipoint search that defines the cutting edge. In addition, the presence of coolant on the cutting edge affects process safety more than on rotating tools. For this reason, hybrid measuring systems are available in which the laser measuring system is supplemented by a probe When using a tactile probe, the presence of coolant does not pose a problem, and it takes a significantly shorter time. In addition, with the laser measuring system, all features and benefits of an optical system continue to be available.

FIGURE 23.4 Measurement of a lathe tool with the Blum-Novotest hybrid measuring system LaserControl NT-H 3D.

SUMMARY

A laser measuring system in the machine tool is a high-precision light barrier. When the laser beam is interrupted by a tool, a switching signal for acquisition of the measured value is generated from the axis positions and transferred to the CNC machine. The challenges in tool measurement are growing steadily; this can be the result of technical developments, such as the touch-sensitive tools, or the significantly improvement performance of modern machine tools. Only the safe monitoring and adjustment of the tools allow operators to take advantage of the power of modern machine tools, namely, operation with little human help and maximal production quality.

Laser-based measuring systems are used in the work area of the CNC machine for timely wear and breakage detection. Using special techniques, systematic interference can be avoided in real time via an algorithm. The method of “pulling” measurements eliminates coolant interference and allows safe and fast tool setting.

IMPORTANT POINTS TO REMEMBER

in productivity: nonproductive times are reduced to a minimum; operation with little human help or unmanned and fully automated processing becomes possible.

2. Quality improvement: consequential damage resulting from undetected tool breakage is eliminated, and the reject rate is reduced.

measuring systems are used for the accurate measurement and control of tools:

length and tool radius

form

monitoring

breakage

cutting-edge monitoring

monitoring

with touch tool probes, laser measuring systems have the following advantages:

are measured in the real clamping system at the rated speed.

tool length and radius change at high speeds is compensated.

with spindle and tool holder are detected.

accurate, and automatic measurements of the smallest and touch-sensitive tools are possible.

cutting-relevant features of a tool can be monitored.

24 The CNC Program

25 Programming CNC Machines

26 NC Programming Systems

27 Manufacturing Simulations

Simulations Simulations Simulations

Simulations Simulations Simulations

DEFINITIONS

Program

Generally, a *program* consists of a sequence of instructions that cause a computer to perform a specific machining task. The structure of a these programs can be very different and depends on the job at hand and the computer that is programmed.

NC Program

An NC program is also called a *part* it controls the process and sequence of operations for a distinct workpiece on a CNC machine. For this it contains the entirety of data and control information necessary for the machining. These data must be in the correct syntax so that they can be recognized and processed by the CNC machine.

Data Transmission and Input

A numerically controlled machine does not do anything by itself; only the NC program sets it in motion. This program must first be created, checked, and then entered into the NC or CNC machine. Initially, mechanical data carriers in the form of perforated strips were used. These early NC programs were written manually with a teletype typewriter and simultaneously recorded by punching holes in a paper tape with a tape puncher. By means of a punched-tape reader, the NC program was then read sentence by sentence into the NC machine. This process suffered several disadvantages. Paper was unsuitable for the workshop, whereas

plastic and laminate damaged the tape punchers over time and caused frequent read errors. Reading and rewinding speed was very slow; tapes could not be corrected, and the storage of tapes was difficult. The availability of mobile electronic storage media has significantly reduced these problems. But only the advent of data transmission with direct numerical control (DNC) via a local data network directly from a central computer into the CNC machines has contributed to today's accuracy in data transmission. Ethernet, for example, has largely established itself as the de facto industry standard. The program is stored completely in the CNC machine; only programs of excessive length are reloaded.

NC Programming

NC programming is performed with computer-based programming systems in the process engineering office or directly on the machine with *shop-floor programming* (SFP). Manual programming with the calculation of individual moves of the CNC machine axes has been superseded by machine-specific or computer-based universal programming systems. It is characteristic of these systems that the workpiece geometry is programmed instead of individual machine motions.

After programming, the resulting machining process can be displayed as a graphic-dynamic simulation. Simple parts can be programmed on the CNC machine with integrated, very powerful machine-specific and dialog-based programming systems. The result can also be displayed in a graphical simulation.

STRUCTURE OF THE NC PROGRAM

The program consists of a discretionary number of blocks that describe the entire workflow of the machine step by step Each block corresponds to one line in the NC program and consists of the address with numerical values. The individual blocks are numbered, which makes it easy to find a particular block, and the numbers can serve as markers.

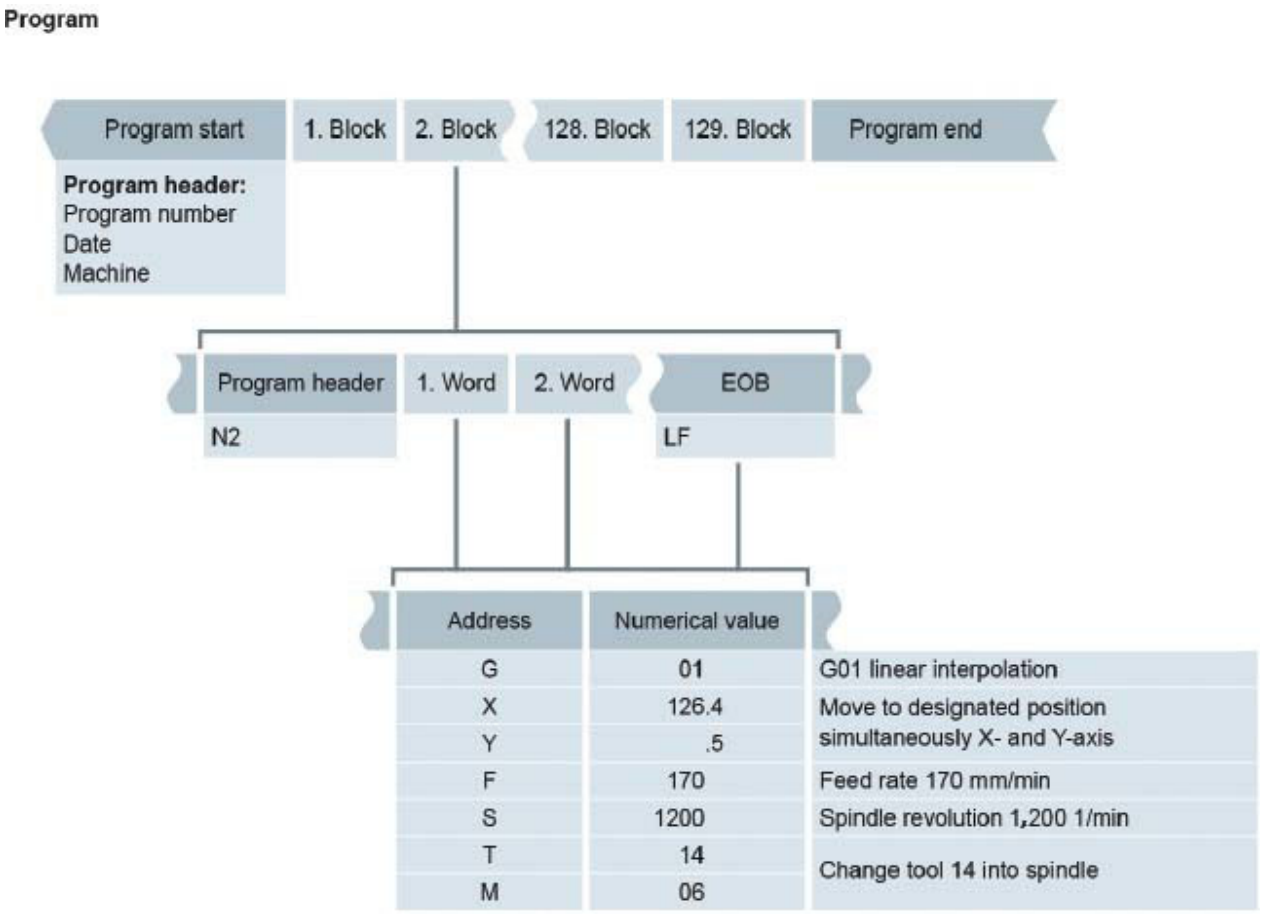

FIGURE 24.1 Basic structure of an NC program in address format.

The address determines which functional group of the CNC machine is involved. Therefore, an address may only appear once in

a block, but there are exceptions. G- and M-commands can be used more than once in a block.

TABLE 24.1 Address Designation per DIN 66025/ISO 6938

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A block can include different instructions. The following differences are possible:

■ *Position* Used to control the relative movements between tool and workpiece (addresses are *X, Y, Z, A, B, C, W,* ...).

■ *Technological* They define the feed rate spindle speed and tools

■ *Switching* Used for selecting the tools switching table positions coolant on/off (M), and more

■ *Move* They determine the type of movement (G), such as rapid traverse, linear interpolation, circular interpolation, and plane selection.

■ *Correction commands* e.g., for tool length correction, cutter diameter and tool tip radius compensation, and zero-point offsets

■ *Cycle or subroutine* Used for frequently recurring program sections

The numerical values of the position information define the position that is approached and should be entered in decimal notation, without leading or trailing zeros.

Lastly, one differentiates between main and subordinate blocks:

■ Main or reference blocks are characterized by the fact that all addresses with the current numerical values are available. This simplifies resumption of program execution of a long program after an interruption. According to ISO 8963, the fist character in a reference block is the alignment function character ":" or all blocks preceded by even 100 or 1,000 numbers are programmed as reference blocks.

■ Subblocks contain only information whose value changes over the previous entry.

Meanings of the Commands

The meanings of the basic commands, their syntax, and the program structure are defined by DIN 66025/ISO 6938. In addition, nonstandard specific commands in their own syntax can be programmed. The spectrum of these additional functions ranges from functions for program sequence, such as calculations and loops; branches to special functions, such as working area limits; reference programming; and configuration commands In general, the scope and options of these specific commands are significantly greater than those of the DIN standard. The programming instructions of the CNC manufacturers provide pertinent information.

TABLE 24.2 Examples of Addresses for Axes with Additional Instructions (Some of These Also Appear on the Display of the CNC Machine)

1000 ZOTSEL (GT300-NPV.zot) ;selection and path for NPV-Table

;--------------------Processing with right spindle ----------

N1010 MainSp(S2) ; feed rate for spindle 2

N1020 SMX(S2=3000) ; max. rpm at G96 spindle 2

N1030 G8(SHAPE80)

;----------Position chuck in starting position (necessary for SPS)

N1040 S2CLOSE=66 ; close chuck S2, 66 == Inside – outside – clamping

;---

; Zero point G59 1 mm to the right of left face

N1060 G0 G90 DIA G18(X,Z) G53 G48 G90 X = 260 Z = 300 Z2 = 1 M205

1070 IF TARTTYPE$ = “GUSSTEIL” THEN

N1070 (MSG T3 roughing tool right)

N1080 M6 T3 ; tool change

N1090 G0 G47 G96 G59 X100 Z-10 Z2 = 1 S2 = 200 M204 ED1

N1100 (MSG facing on spindle 2)

N1110 G0 X45 Z0 M8

N1120 G1 X10 F.17

N1130 X8 Z.2 F.1

N1140 X-.5

N1150 G0 X45 Z-10

N1160 G0 G53 G48 X = 260 Z = 300 ; go to safe change position

1180 ENDIF

;---

N1170 (MSG T4 fining tool right)

N1180 M6 T4 ; tool change

N1190 G0 G47 G59 G96 X = 45 Z = -10 Z2 = 1 S2 = 220 M204 ED1 M8

N1200 (MSG process side 1 on spindle 2) ; contouring with standard cycle

N1210 G171 (P DameKontur, CD2, LD1, CR0.5, CA0, CES1, UCV0)

N1220 G0 G53 G48 X = 260 Z = 300 Z2 = 1 M9

N1230 M30

PROGRAM STRUCTURE, SYNTAX, AND SEMANTICS

Syntax is a formal rule that determines the structure of statements in a programming language without referring to the meaning of the words. The meaning of words is called Both make for the program structure consisting of characters, words, and blocks, as well as the arrangement of this information on the data medium.

A typical NC program structure for three-axis position control, according to EIA RS 274 B, could be

N4, G2, X ± 4.3, Y ± 4.3, Z ± 4.3, I4.3,
J4.3, K4.3, F7, S4, T8, M2, H2, L2, $

This means:

N4: 1 to 4 digit block number. Each program can be divided in a maximum of 9,999 blocks.
G2: Two-digit preparatory functions, determining, for instance, type of interpolation, machining cycle, direction of the tool radius compensation, or the distance to go input (absolute or incremental).

X ± 4.3, Y ± 4.3, and Z ± 4.3

Positional data input with four digits in front and three digits after the decimal point, for example, the maximum programmable length is 9999.999 mm (decimal point programming).

I4.3, J4.3, and K4.3

Auxiliary parameters of the circle center in circular interpolation, where in one block only one IJ or JK or IK corresponding to the interpolation level XY, YZ, or XZ may occur.

F7

F6.1 G94 = feed rate in mm/min

F4.3 G95 = feed rate in mm/revolution

F5.2 G04 = dwell time in seconds

F7 G104 = dwell time in revolutions

S4: Four-digit spindle speed in rpm

T8: Eight-digit tool number, with or without the corresponding correction number. It is also possible to use five or six-digit tool numbers.

M2: Two-digit number (00 to 99) for auxiliary functions; switching commands such as coolant on or off, tool change, or spindle orientation

H2 and L2: Used to call up tool compensation values. The compensation values are stored in the compensation value table.

$: Symbol for end of the block.

MISCELLANEOUS (M) FUNCTIONS

There are no buttons to press on the machine for turning machine functions on and off. Everything must be programmed with switching commands with the following addresses:

TABLE 24.3 Switching Functions According to DIN 66025/ISO 6938, Sheet 2

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Note: All not mentioned M-functions are not designated or freely available

S: spindle speed (rpm)

T: tool number

M: auxiliary (miscellaneous) functions

F: feed rate

Blocks with such switching commands are, for instance:

N 10 S 1460 M 13 $

Step 10: Spindle speed 1,460 rpm

Clockwise rotation of the spindle and coolant ON.

N 60 G 95 F 0.15 $

$ $ $ $ $ $

N 140 T 17 M 06 $

$ $ $ $ $ $ $ $

N 320 M 00 $

$ $ $ $ $ $ $

N 410 M 30 $

$ $ $ $ $ $ $ $ $ $

Switching commands remain active as if they had been turned on with an actual switch. They can be changed or turned off or be overwritten in the program. If appropriate, several switching commands can appear in one block.

When an M-command is given, it should be noted that some M-commands are executed immediately, meaning at the beginning of a block; others become active later, at the end of an executed block. The definitions of the M-commands can be found in the programming manual of each machine.

POSITIONING DATA

Positioning data have three meanings for the machine:

1. The value determines the command position that has to be approached.

2. The plus (+) or minus (-) sign indicates the direction of travel or defines the quadrant.

3. The order determines the sequence of movements.

The positioning data include the axis addresses or

Axis addresses with several characters can also be assigned. In this case, the position information is programmed with an equals (=) sign. This has the advantage that programs on machines with many axes are much easier to read; for example: X1 = 123,000 X2 = 234,500 X3 = ...

Position information can be expressed in drawings as absolute dimensions and/or as relative dimensions Both types of dimensions therefore should be permitted in an NC program so that print dimensions can be used directly for programming.

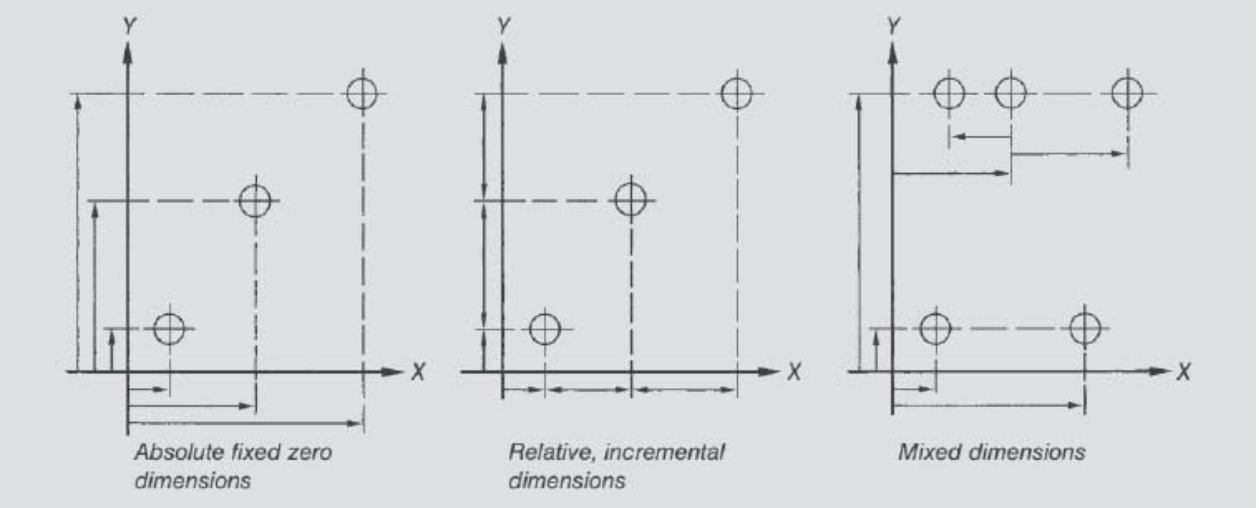

FIGURE 24.2 Dimensions in drawings as absolute and relative dimensions.

The absolute dimension indicates the distance of a position to the program zero point; the relative dimension defines the position difference from the previous position. With G90/G91, it is possible to switch between absolute and relative value input without losing the program zero point.

If a tool must access the seven positions indicated in Figure 24.3 in succession and return to the zero point, this results in different types of data entries depending on how the pattern is dimensioned in the part drawing Absolute programming has the advantage that a subsequent change of a position does not affect all other dimensions. In the case of relative dimension programming, the programming of the following position must also be corrected. Also, the reentry into an interrupted program is easier accomplished with absolute programming.

TABLE 24.4 Position Dimension Table for the Hole Pattern in Figure 24.3 for Absolute and Relative Dimension Programming

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PREPARATORY (G) FUNCTIONS

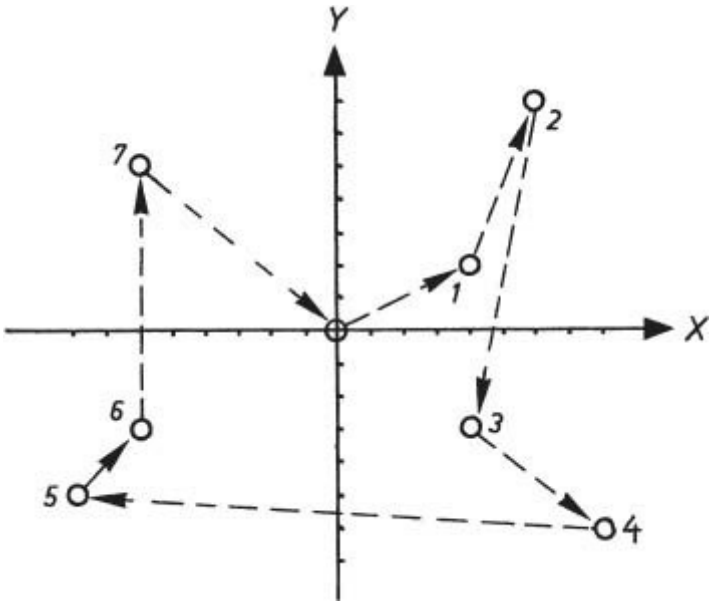

FIGURE 24.3 Sketch of a hole pattern.

Advantages of Relative Dimension Programming

1. The sum of all programmed and the sum of all programmed must be zero after returning to the starting position. This allows an easy control for programming errors. However, with mixed absolute/relative programming, this control option is not possible.

2. Subroutines such as drilling patterns, recesses, undercuts, and milling cycles can be very easily copied and transferred to other positions.

The two-digit preparatory functions (G = go) and the position information ...) belong together. The G-functions determine which computer program is used to process the subsequent position information in the CNC machine. The position data instruct where to go; the G-functions instruct how to go. In most cases, even more G-functions are needed to prepare the NC for the input of position information. Therefore, the term *preparatory position conditions* is used. For this, it is necessary to save several G-functions and to keep them active. Depending on the CNC machine, the programming of these G-functions must be either successively in several blocks, or all G-functions can be combined in one block.

TABLE 24.5 G-Functions According to DIN 66025/ISO 6938, Sheet 2

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* All not mentioned G-functions are not designated and are freely available.

For the sake of clarity, all G-commands therefore are divided into three kinds and several groups. Only G-commands from the same group can overwrite each other or, in other words, only one G-command is effective for each group. There are three kinds of position conditions. The underlined letters indicate the switch-on state and do not need to be additionally programmed, depending on the CNC:

■ Modal, meaning G-functions that remain in effect over several blocks for the type of interpolation G01, G02, G03, G06:

- Selection of planes G18, G19
- Tool offset G41, G42, G43, G44
- Zero offset G92,
- Positioning characteristics G08, G09, G60, G61, G62

- Work cycle

- Dimensions G91

- Feed rate setting G93, G95

- Spindle speed input G96, G97

■ Position conditions, active in only one block:

- Dwell time G04 (in conjunction with *F* for the time)

- Speed increase and decrease G08, G09

- Tapping G63

- Reference-point offset G92

Function of the G-Conditions

Example

There are several paths to get from starting point S to the end point *E* The selection is made by the G-function:

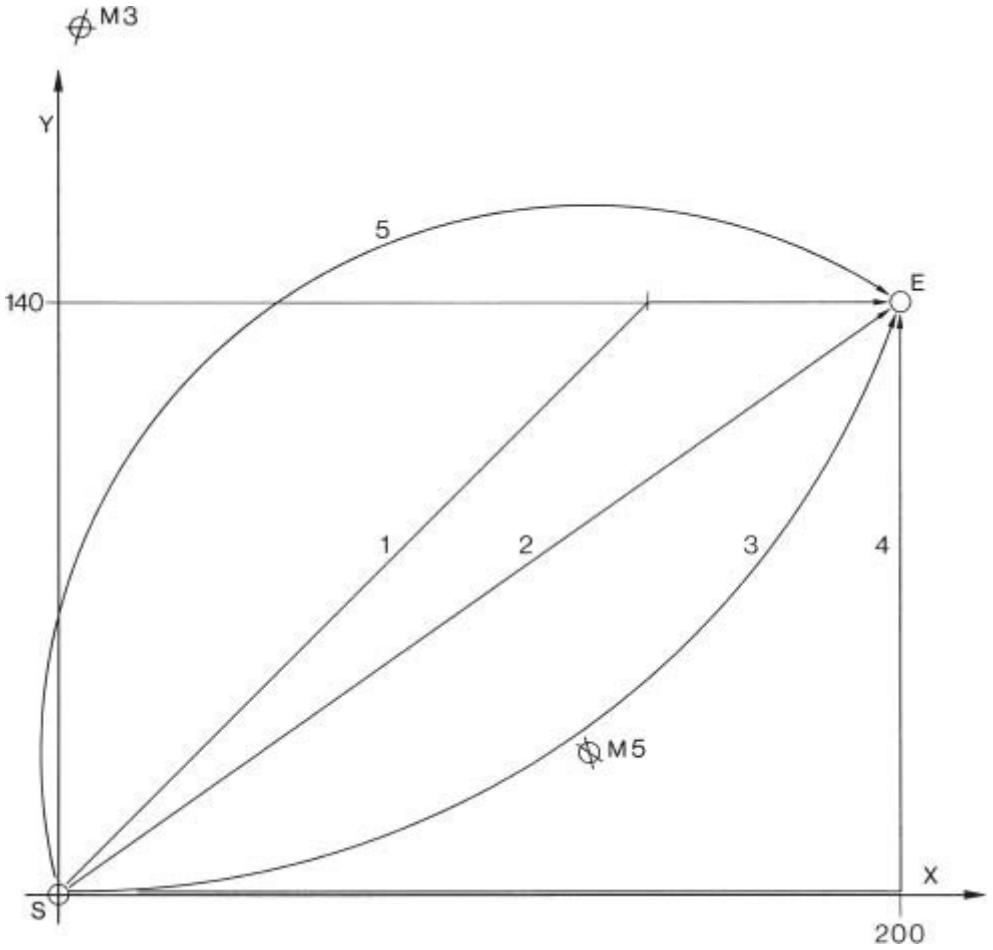

FIGURE 24.4 Using various G-functions on various paths to move from starting point *S* to end point

First option:

N100 G00 X200 Y140 $

From *S* to *E* in rapid traverse, 140 mm at an angle of 45 degrees, the remaining path parallel to the

Second option:

N200 G01 X200 Y140 F400 $

In a straight line (linear interpolation) with a feed rate of 400 mm/min.

Third option:

N300 G03 G17 X200 Y140 R205 F120 $

Motion in a counterclockwise circular path at radius R205 from the arc center M3.

Fourth option:

N 400 G00 X200 $

N 401 Y140 $

Motion by in-feed at rapid traverse speed, first parallel to the then parallel to the

Fifth option:

N500 G02 X200 Y140 R-130 $

Motion in a clockwise circular path around center M5 with radius of R130.

The meaning of the G-functions is specified in DIN 66025/ISO 6938, sheet 2, and should be the same for all NC brands.

Examples

N 10 G81 $

From step 10 on drilling cycle G81 active, meaning that all are relative dimensions, motion in *X* and *Y* takes place at rapid traverse speed, and the drilling feed rate is specified in mm/min.

N 40 G02 G17 X460 Y125 I116 J–84 $

Block 40: clockwise circular motion until end point X460 Y125 is reached.

N70 G04 F10 $

Block 70: dwell time 10 seconds; that is, the spindle continues to turn while the feed motion of the axis is suspended for 10 seconds.

N 100 G17 G41 H11 T11 $

From block 100 on: the compensation value that was entered at memory location H11 and is now retrieved from there takes effect in the The offset is to the left when viewed in the direction of motion.

N 160 G54 $

Block 160: the first group of zero-point offsets for all axes is called up.

MACHINING CYCLES

Most CNC systems contain a special type of subroutine with preprogrammed fixed cycles to perform processes that recur frequently. Cycles are intended to help simplify programming and reduce program size by allowing each recurring sequence to be called up only once and then supplied with the necessary parameter values each time it runs. However, there is a distinction between the following types of cycles.

Drilling Cycles

For drilling, reaming, countersinking, and tapping per DIN 66025/ISO 6938 (G80– G89) 24.6 and Figure an example is provided in Figure Only the are programmed for an unchanged drilling cycle. At each position, the drilling cycle is activated automatically until it is canceled with the command G80 or overwritten with another G-cycle.

TABLE 24.6 Drilling Cycles G80–G89 According to DIN 66025/ISO 6938, Sheet 2

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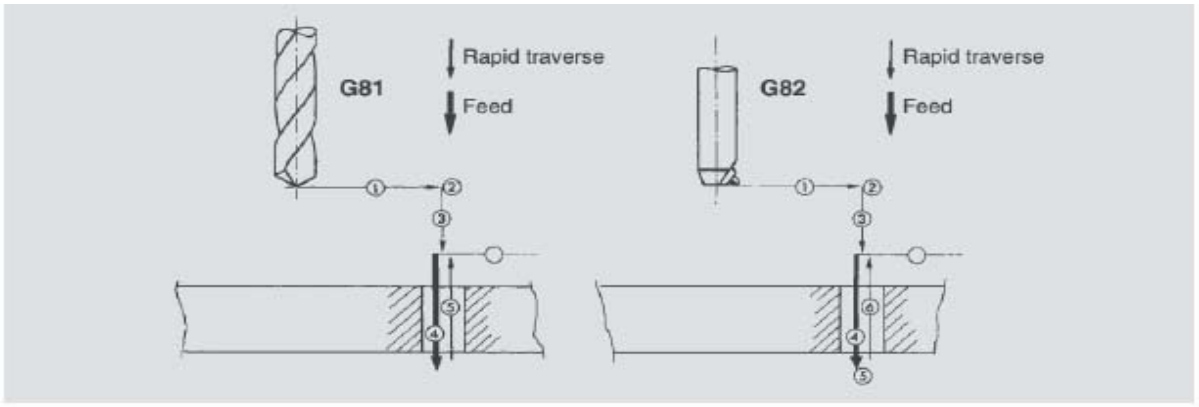
2 2


G81
Rapid traverse
Feed
G82
Rapid traverse
Feed

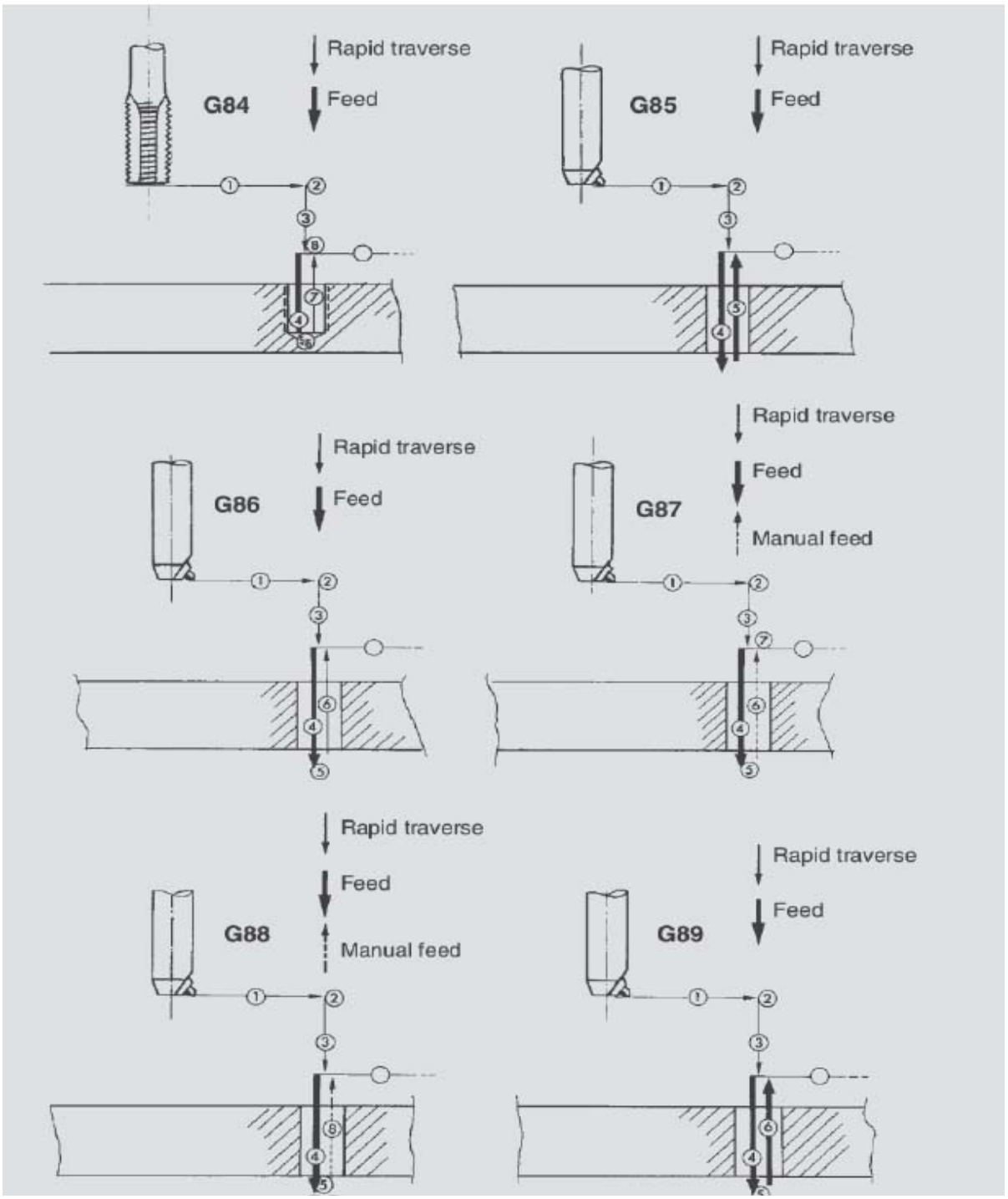

G84
Rapid traverse
Feed
G85
Rapid traverse
Feed
G86
Rapid traverse
Feed
G87
Rapid traverse
Feed
Manual feed
G88
Rapid traverse
Feed
Manual feed
G89
Rapid traverse
Feed

FIGURE 24.5 Drilling cycle according to DIN 66025/ISO 6938, sheet 2.

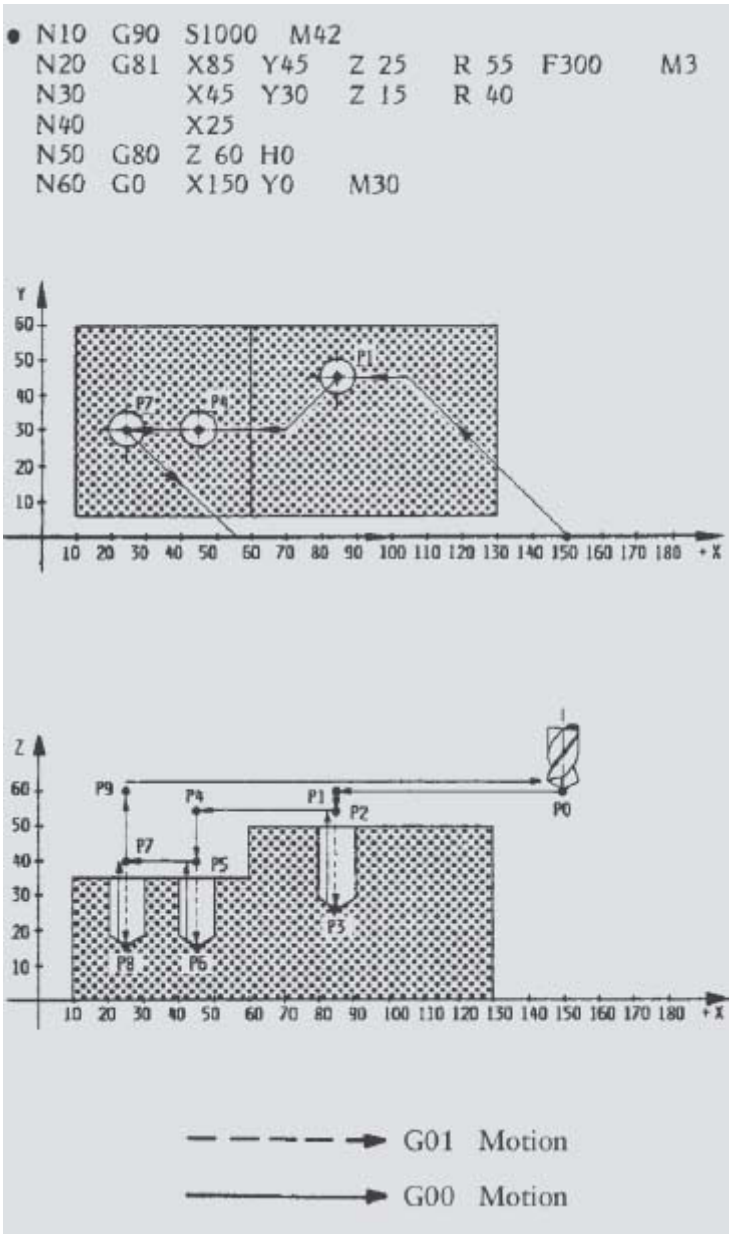


FIGURE 24.6 Example G81: drilling cycle.

Milling Cycles

For slot milling, pocket milling, hole milling, thread milling, trunnion milling, and so on; the cycles are not standardized but designed individually for each CNC brand.

Turning Cycles

For longitudinal cutting and facing, thread cutting parallel or conical with automatic feed, as well as cycles for undercuts and recesses with automatic cut division Also, turning cycles are not standardized and depend on the CNC brand.

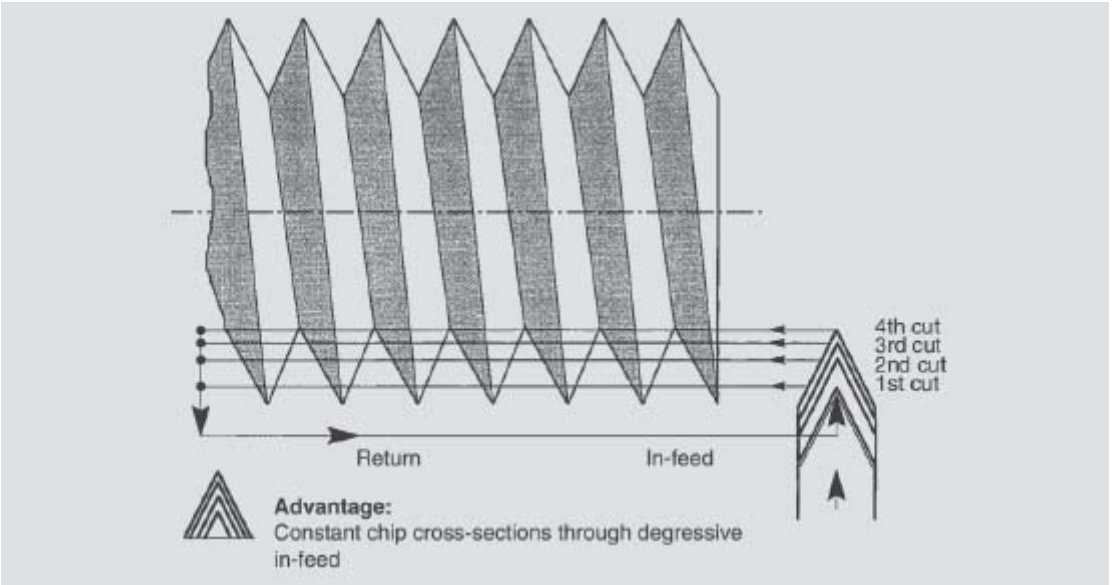


FIGURE 24.7 Thread cutting with degressive feed-in in order to keep the chip cross section constant or smaller with each cut.

Free Cycles

Also referred to as *subroutines* and specially designed for each type of machine, such as tool change cycle (M06) or geometric cycles

for bolt circles, rows of holes, deep hole drilling, circular segment milling, pocket milling, and so on.

ZERO POINTS AND REFERENCE POINTS

A CNC program to automatically process a workpiece requires an exact definition of various zero and reference points in the machine tool. For this, the machine manufacturer and user must define appropriate points in the machine and on the workpiece 24.8 and

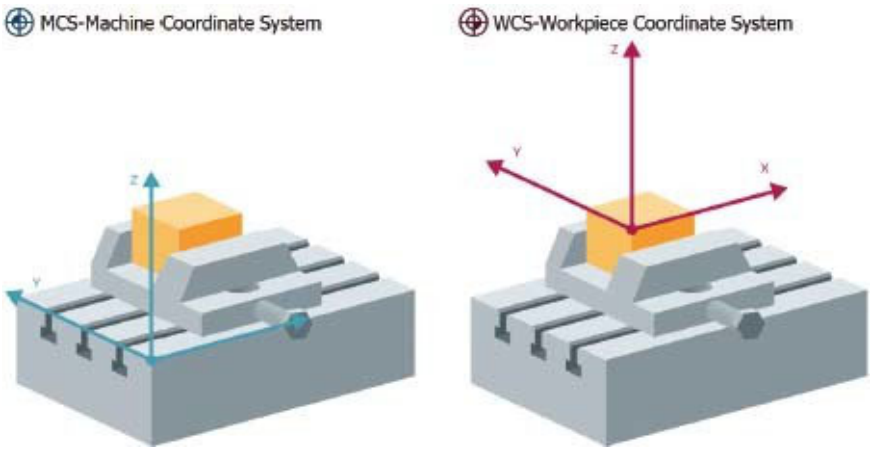


FIGURE 24.8 The machine coordinate system (MCS) is set by the manufacturer and cannot be changed. The workpiece coordinate system (WCS) is set by the programmer or machine user.

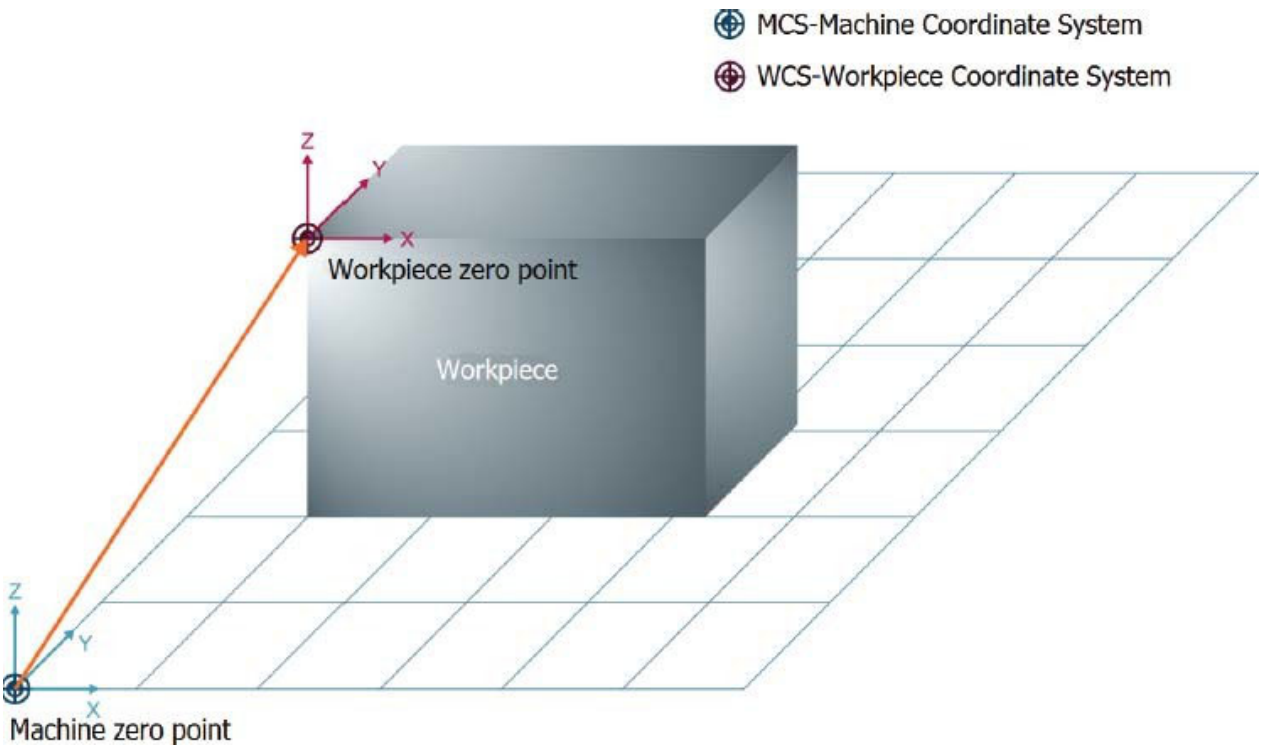


FIGURE 24.9 The zero-point offset defines the displacement of the reference point from the machine coordinate system to the workpiece coordinate system.

Machine Zero Point *M*

The machine manufacturer absolutely determines the zero point *M* for each axis.

It defines the origin of the machine coordinate system and cannot be moved. The encoders of all axes are adjusted according to these points and their values entered into the CNC machine.

On lathes, the machine zero point is typically located in the center of the spindle flange on the stop surface. On milling machines, it lies usually at the edge of the travel range or in the middle of the machine table.

Machine Reference Point *R*

The reference point *R* is defined in the work area of a machine and is used to determine the exact start position before beginning a work program. The coordinates of the reference point *R* are determined by the machine manufacturer and always have the same value relative to the machine zero point. These values cannot be changed by the machine operator. When referencing the machine at the beginning of a shift, the positional values of the axes are typically set to zero.

Referencing of NC axes with no absolute measuring system is carried out with a three-phase reference point process:

1. Move the axis on the reference cam.

2. Synchronize with the encoder zero mark.

3. Move the axis to the reference point.

This procedure must be set up by the machine manufacturer during commissioning; that is, the parameters must be set for the approach speed, direction, delay time, and so on.

The approach of the reference point can take place for all axes simultaneously or successively. The machine operator must pay attention to possible collisions with the workpiece or clamping devices. Automatic CNC machining cannot be started without first referencing the machine.

If the axes of the machine are equipped with an absolute measuring system, no referencing of the axes is required. The CNC

machine recognizes the correct axis position immediately after it has been turned on.

Workpiece Zero Point *W*

The workpiece zero point *W* is the origin of the workpiece coordinate system. It can be freely chosen by the operator or programmer and is best determined in such a way that all dimensions of the drawing refer to this point or can be easily calculated. It is also important that this point, after the workpiece has been clamped, can be approached and picked up quickly. In the case of a lathe, the workpiece zero is often the intersection of the rotary axis with the reference edge of the linear encoder. On a milling machine, the workpiece zero point is often placed on a corner or center of the workpiece. Axis designations and directions must conform to the machine coordinate system and depend on the machine used.

Next, the axes will be set to zero relative to the workpiece coordinate system; that is, the zero point is moved from the machine zero point to the workpiece zero point. The workpiece zero point must be determined by the operator by touching off the tool or by probing.

Coordinate values related to the machine zero, however, should not be used for programming. This is because in multiaxis machines these values do not match with the position of the workpiece, and the programmed workpiece cannot be transferred to another machine or clamping method.

When touching off with the help of an already determined and measured part, a very small chip is removed, thus creating the zero point. On a milling machine, this step can also be performed using

an edge finder or test indicator. In this case, the machine axis is moved in jog mode or with a hand wheel. The values thus determined must then be entered in the CNC machine.

A more precise way to determine the zero point is by means of an automatic measuring probe. However, this necessitates the installation of dedicated hardware and software. Many CNC machines support the use of switching probes through appropriate measuring cycles or the manufacturers of these probes offer software packages for the use of their product in conjunction with the various CNC types.

Zero-Point Offset

The parameterization and activation of the zero offset affects the adjustment of the coordinate system to the workpiece coordinates. The difference between machine zero point and workpiece zero point can be entered in the CNC machine in a zero-offset table. The use of zero offsets is very advantageous because it renders the CNC programming of a part independent of the machine coordinates 24.10 through

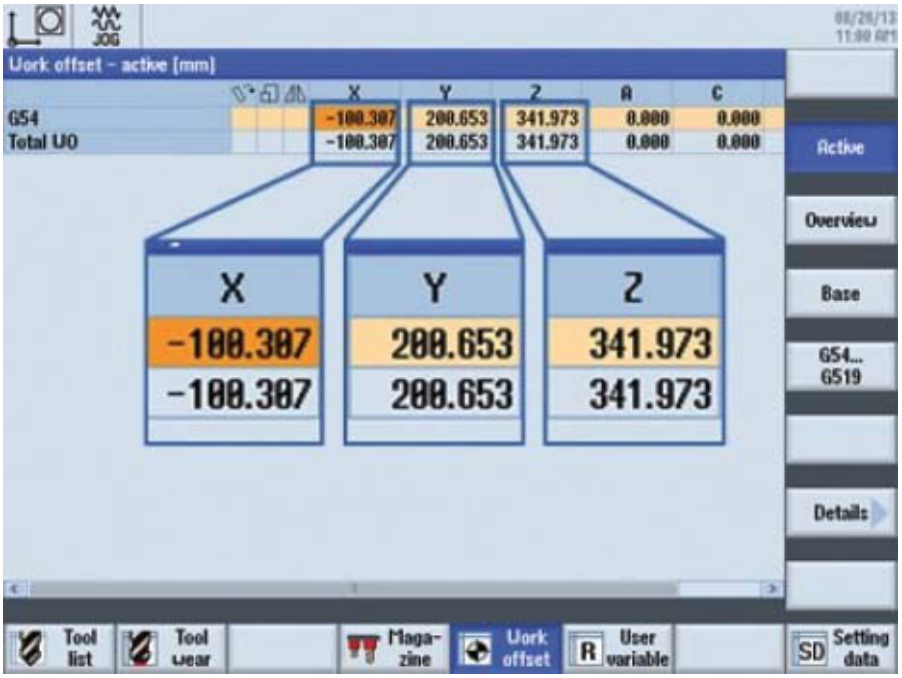


FIGURE 24.10 CNC entry of zero-point offset G54 on a Sinumerik 840oD sl. Siemens.)

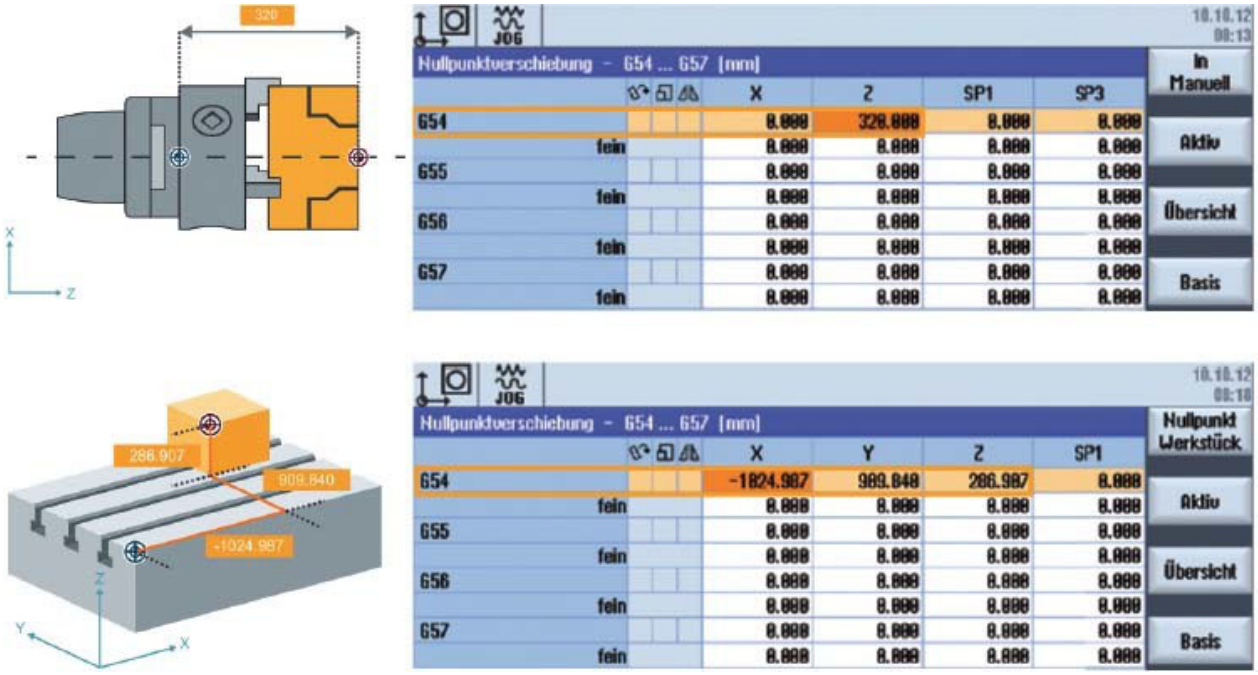


FIGURE 24.11 CNC entry of a zero-point offset on a lathe in a milling machine Sinumerik 840oD sl. Siemens.)

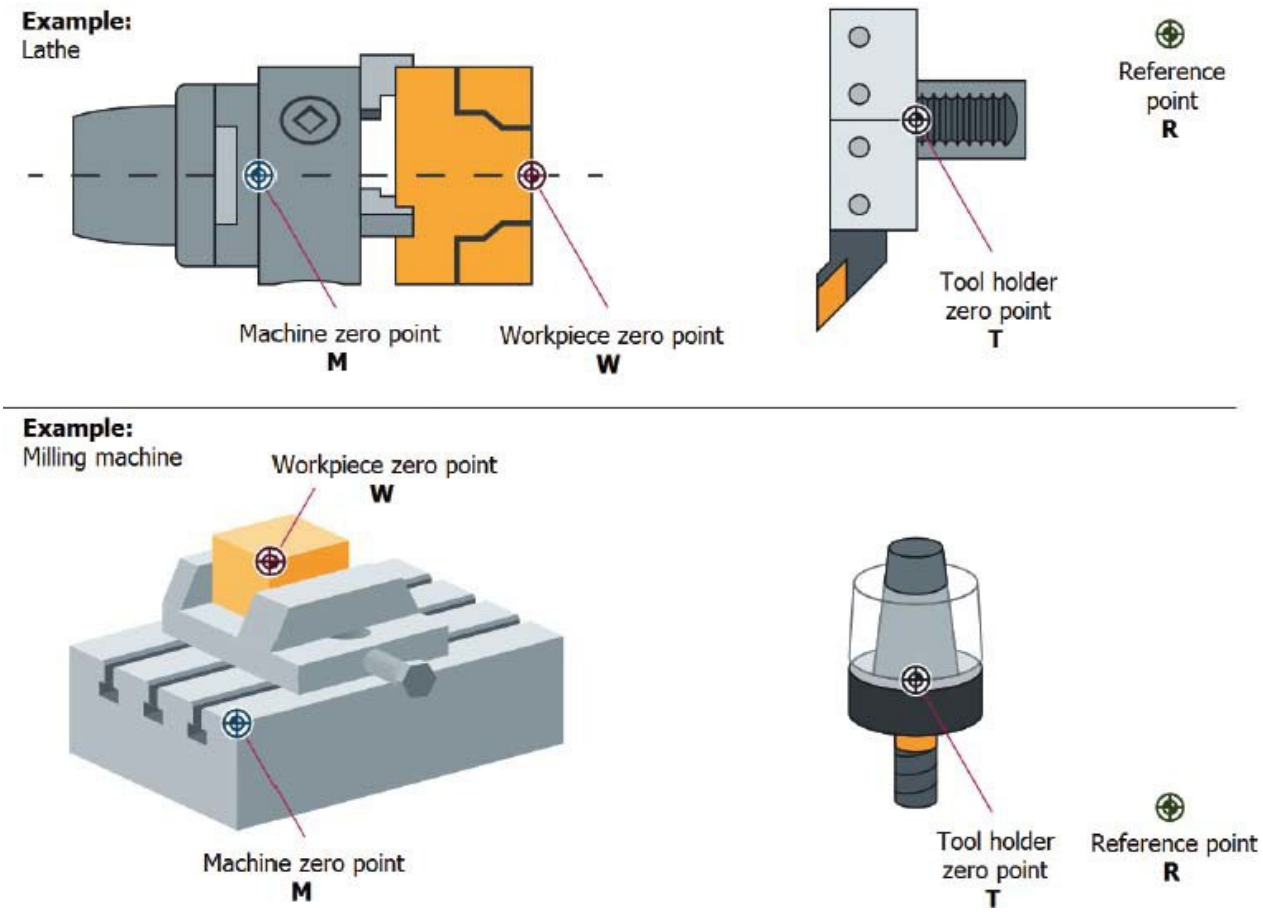


FIGURE 24.12 Principle representation of the zero points on a lathe and milling machine.

The CNC machine offers up to 99 memory locations for zero-point offsets. If a cycle is started and the beginning of the program reflects an offset, these values will be called up by the CNC machine and used for calculation of coordinate values. This means that subsequent coordinate values for the processing of the part will be reflect the difference between the offsets.

The zero-point offsets will be called up with the G-functions G54 to G57. It is up to the programmer to determine which G-function is used for a zero offset. The use of zero offsets makes the work for the programmer easier, particularly when the program zero point is

programmable and can be freely set. For instance, a hole pattern can be applied anywhere in the usable machine area and the initially calculated coordinate values will stay unchanged. For machine tools with pallet changes, clamping cubes, or clamping towers, the zero-point displacements are used in conjunction with a manually changeable correction value to define clamping coordinates. Setup times can be reduced by using several zero offsets particularly in single or small series production. For instance, for each clamping fixture an individual and unique stop can be set and written in the zero-offset table of the CNC machine, or a special workpiece zero point can be set for different workpieces. Next, relevant offsets in the program are activated according to the clamping device or the workpiece. If the same workpiece will be processed at a later date, the associated zero point is immediately available again under the same code. Once a zero offset has been defined, it will stay in the CNC machine until it is redefined under the same code.

Tool Changing Position

The tool changing position is the location within the workspace where the tool can be changed without danger of a collision with the machine. This point has been set by the machine manufacturer and cannot be changed by the machine operator under normal circumstances. However, it is the responsibility of the operator to prevent collisions between tool and workpiece, particularly in the case of long or large tools.

On lathes, the tool change is usually carried out by advancing the turret. Here the operator/programmer must either program a fixed retraction position after each tool use, or for each new tool, a collision-free tool change must be guaranteed through appropriate programming.

Tool Carrier Reference Point *T*

The tool carrier reference point *T* is relevant for setting up with preset tools. It is located on the tool holder. By entering the tool length, the CNC machine calculates the distance of the tool tip from the tool carrier reference point. In this way, the tool length correction compensates for the differences in length between tools. The tool length is the distance between the tool carrier reference point and the tool tip. This length can be measured with a tool setter and entered with predetermined wear values in the tool correction memory. With these values, the CNC machine calculates the correct traversing movements in the feed direction.

TRANSFORMATIONS

Coordinate Transformation

In a coordinate transformation, coordinates are transferred from one coordinate system to another This function is mainly used for simplifying the programming of spatial coordinates into the axis coordinates of a CNC machine with swivel or rotary axes or a robot with nonlinear kinematics.

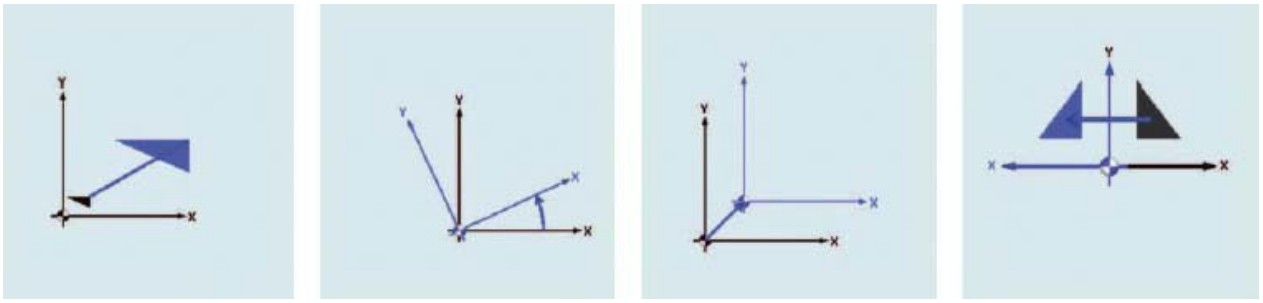


FIGURE 24.13 Typical transformations: shifting, rotation, scaling, mirroring.

Typical transformation processes include the following:

Shifting (Translation)

Movements can be programmed in the orientation of a given axis. This makes it possible to work with changing zero points, for instance at recurring machining operations on different workpiece positions.

Rotation

The workpiece coordinate system can be rotated in space. Rotation might be needed when processing axially parallel and inclined workpiece surfaces in one clamping.

Mirroring

With this function, workpieces can be mirrored on coordinate axes. All the movements that follow, for instance, those that are programmed in a subprogram, are mirrored.

Scaling

Scaling allows one to program axis scale factors so that a workpiece is smaller or larger in the orientation of a specified axis. This makes it possible to consider geometrically similar shapes or different shrinkage levels in the programming.

Kinematic Transformations

Kinematic transformations are used to program positions in a Cartesian coordinate system. The CNC machine transforms the programmed traversing movements of the Cartesian coordinate system to the traversing movements of the actual machine axes. Typical kinematic transformations are as follows:

Face Transformation (TRANSMIT)

Face transformation allows drilling and milling of contours, for example, square, hexagonal, eccentric circular grooves, wrench flats, etc., on the face end of a workpiece by means of axial tools This is done with an interpolation of the and rotary axes.

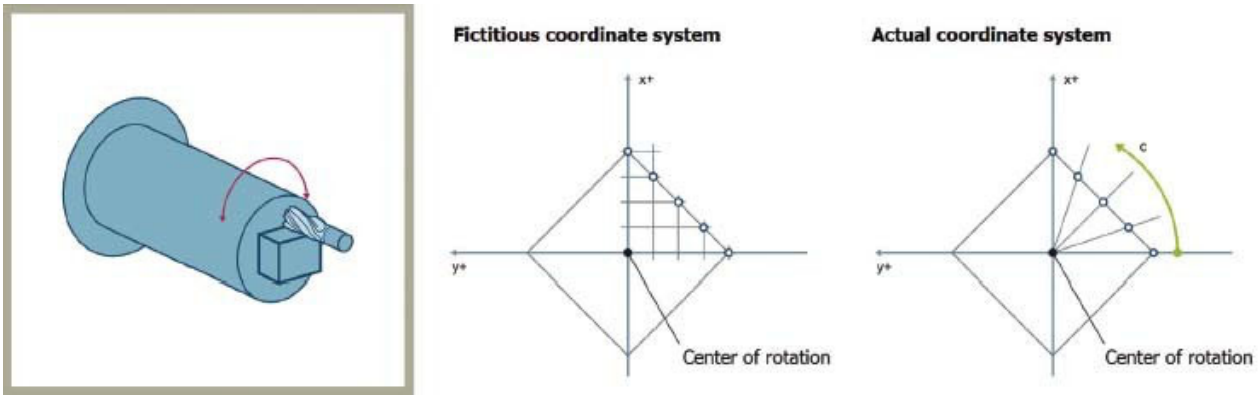


FIGURE 24.14 Face transformation allows machining of the face. The programming takes place in the fictitious coordinate system; the machining itself occurs in the actual machine coordinate system.

Face transformation is programmed in a fictitious (Cartesian) coordinate system and The machine movements themselves are carried out in the actual machine coordinate system. Face transformation is typically used on lathes. It allows compensating the limited travel of the and or also an absent On milling machines, face transformation is used if the mechanical construction of the machine does not allow reaching all

Cylinder Surface Transformation (TRACYL)

Cylinder surface transformation allows milling operations on the (curved) surface of a cylinder Both straight line and circular contours can be programmed. It uses an interpolation of the and the rotary axis. The cylinder surface transformation is programmed in a fictitious (Cartesian) coordinate system and The machine movements are carried out in the actual machine coordinate system. Programming necessitates an unrolling of the cylinder surface that will be milled. The unrolling refers to the actual diameter on the cylinder.

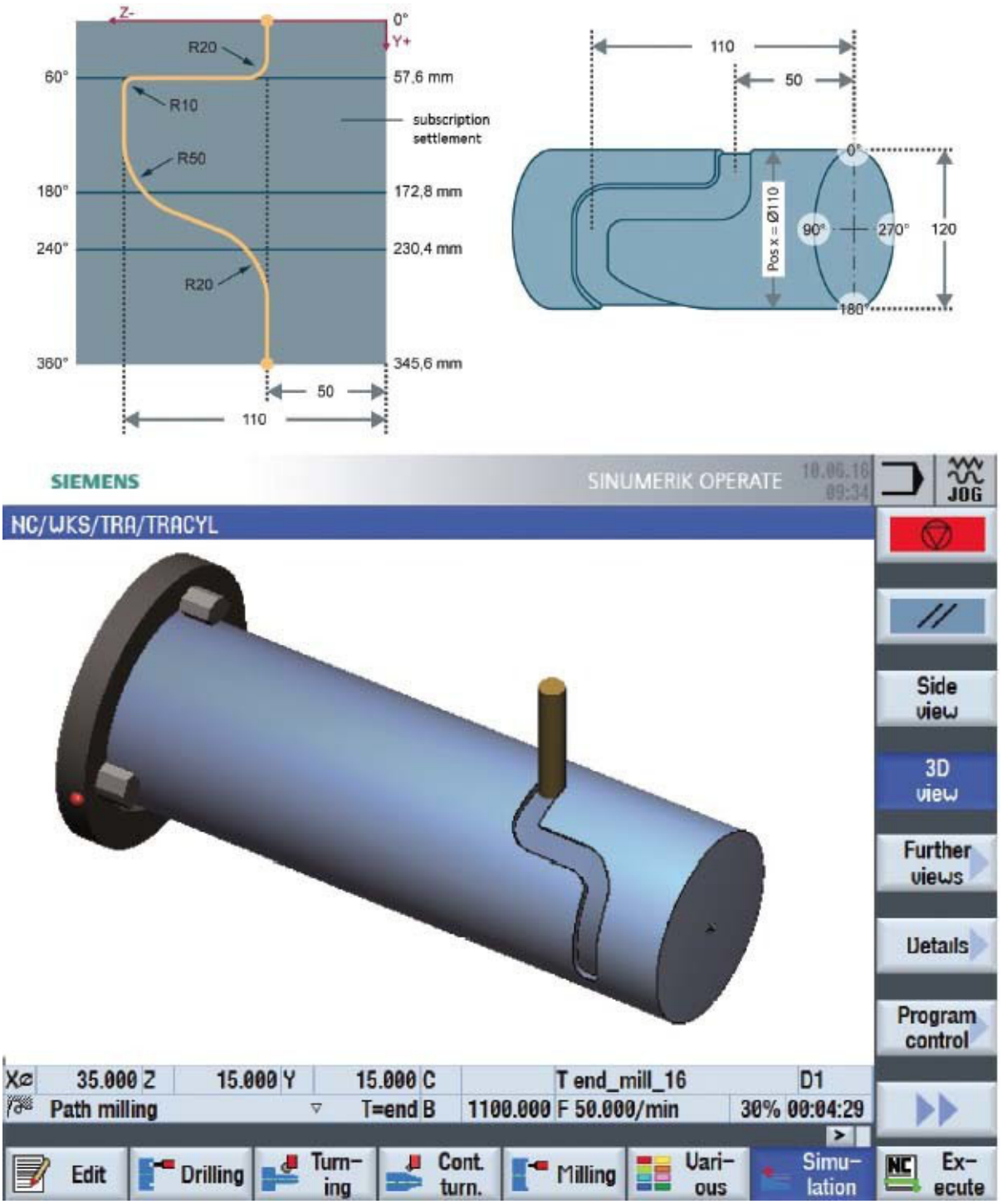


FIGURE 24.15 Cylinder transformation. Milling on the cylinder surface: the programming of the contour (groove) takes place in the fictitious rolled-off representation; the machining takes place in the actual machine coordinate system. Siemens.)

Skew Angle Transformation (TRAANG)

Skew angle transformation or *slanted axis* transformation enables programming in the right-angled workpiece coordinate system (WCS) on machines with obliquely arranged machine axes This is a typical axes arrangement of grinding machines and lathes with a

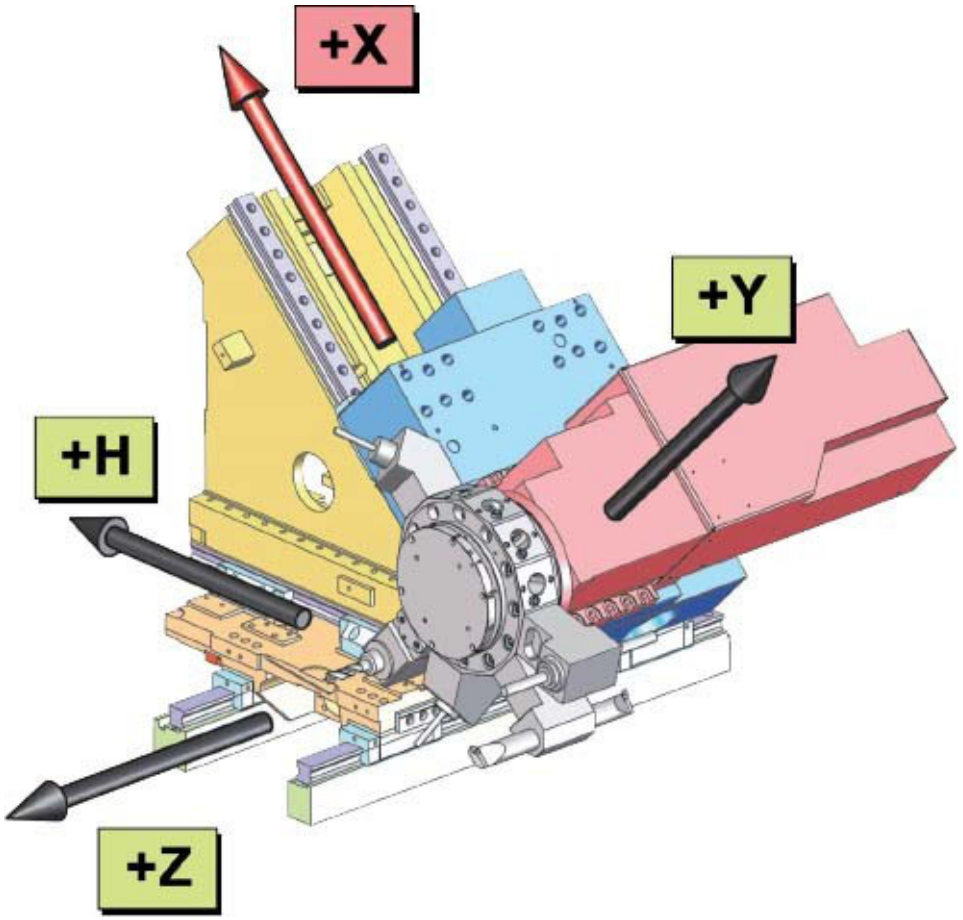


FIGURE 24.16 Typical design of a lathe with a EMCO Maier.)

Orientation Transformation

In the case of orientation transformation, the programmed position information always refers to the tip of the tool, which is traced orthogonally to the machining surface in the workspace. Virtual rotary axes describe the orientations of the tool in the workspace. A typical orientation transformation is the *Five-Axis Transformation (TRAORI)* as in Figure

Multiaxis transformations are intended for the processing of spatially curved surfaces, which, in addition to the linear axes, also have rotary axes. In the case of the five-axis transformation, there are three linear axes and two rotary axes 24.17 and In multiaxis transformations, a rotationally symmetric tool, such as a milling tool or laser beam, can be arbitrarily oriented to the workpiece in the workspace.

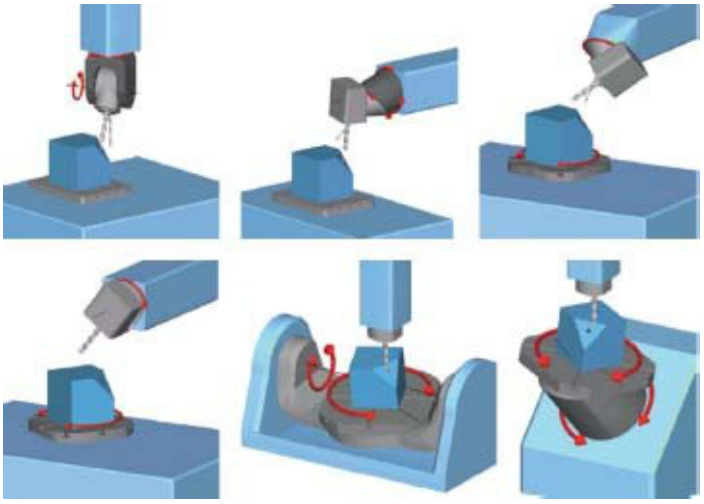


FIGURE 24.17 Examples of possible kinematics of a milling machine that necessitates different transformations.

FIGURE 24.18 A bladed disk, called a is a component that can only be machined with five-axis transformation.

TOOL CORRECTIONS

Workpiece dimensions are programmed directly, based on the drawing dimensions. Tool data such as cutter diameter, cutting position of the lathe tool (left-handed/right-handed lathe tools), and tool lengths therefore must not be taken into account when creating the program. When manufacturing a workpiece, the tool paths are controlled depending on the respective tool geometry so that the programmed contour can be established with each tool that is engaged.

The tool data must be entered into the tool correction memory so that the CNC machine can calculate the tool paths. The NC program merely calls up the required tool, by tool number or name, with the required correction data. The CNC machine retrieves the required tool correction data during the program processing and applies them for the various tools. The tool length correction compensates for the difference in length. The tool length is the distance from the tool carrier reference point to the tool tip.

Contour and tool path are not identical. The cutter or cutting center must be led on a contour parallel, called the to the contour of the part To do this, the CNC machine needs to “know” the tool shape from the tool offset memory. The path of the tool center is shifted during program processing, depending on the tool radius and the cutting direction, so that the cutting edge moves exactly along the desired contour.

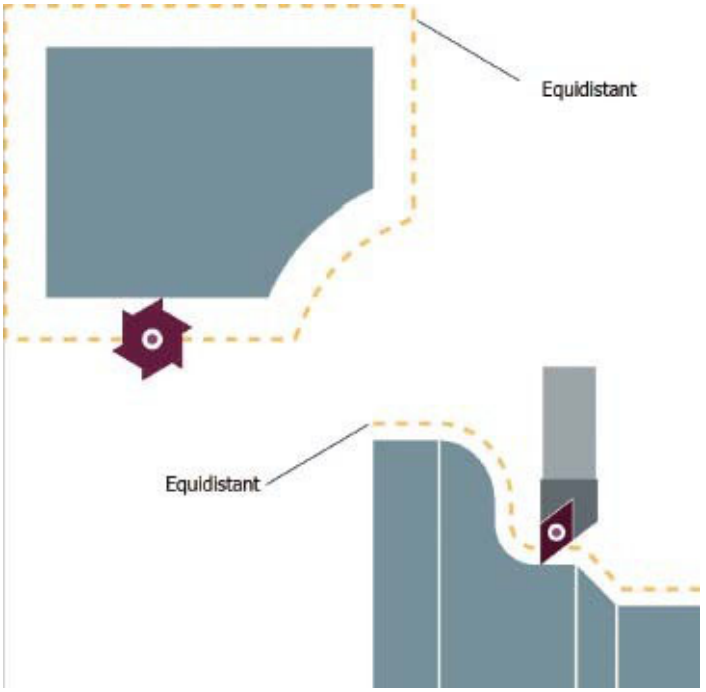


FIGURE 24.19 The tool radius compensation shifts the point of application of the tool exactly to the desired contour of the workpiece.

Even with perfect preparation of the parts programs, fixtures, and tools, additional corrections to the tool might have to be made in the CNC machine. These result from deviations of the tools themselves or tool wear. These deviations can be determined with control measurements on the workpiece or fully automatically with integrated tool measuring devices in the working area of the machine. These tool wear corrections are added to those in the tool offset memory. Depending on the CNC model, there are various programming instructions for these corrections.

Example

Tool length compensation allows reconciliation between the tool length assumed for programming and the actual tool length, say, after a tool has been dressed. The difference in the dimension or the

absolute tool length is entered in the correction value memory. In the program, this value is called up via the address *H* or together with the tool and the correction number. The same applies to the milling tool offset correction. The CNC machine makes the correction either via G41/G42 or via G43/G44 above), independent of the quadrant in which processing takes place.

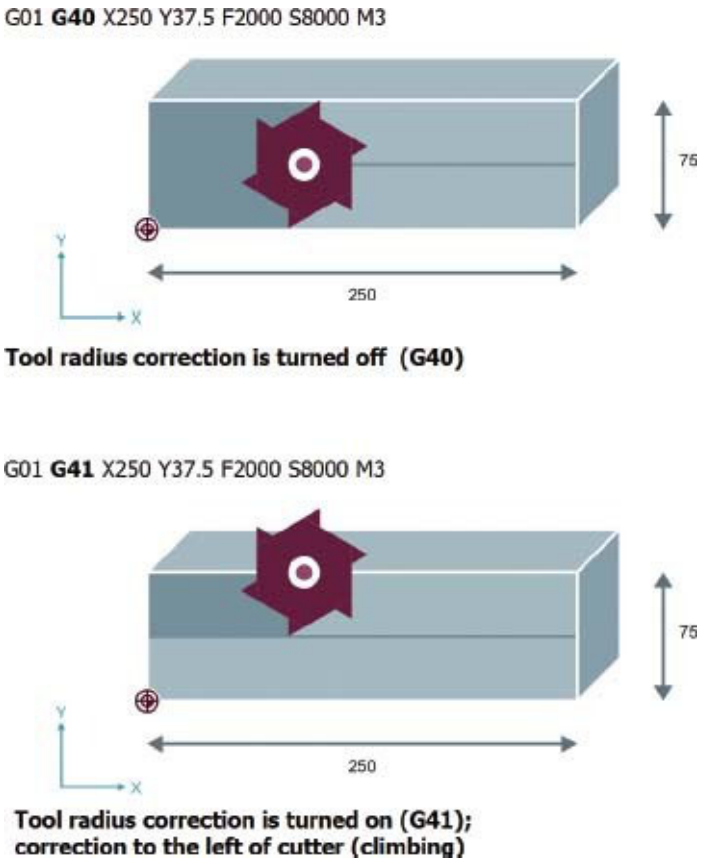


FIGURE 24.20 Tool length compensation for spiral drills.

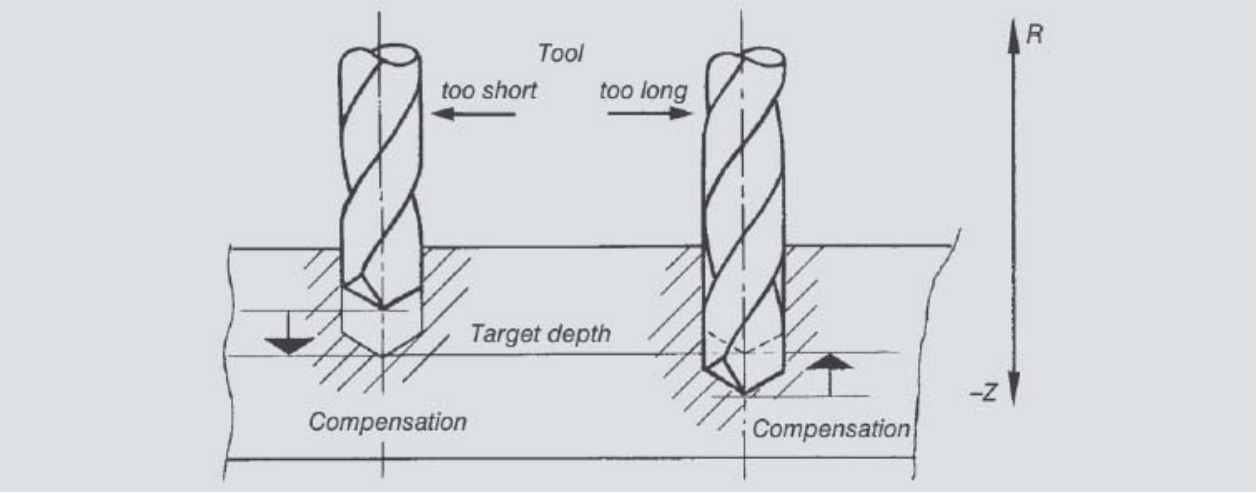


FIGURE 24.21 Effect of the milling tool radius compensation or equidistance correction on the point of impact of the tool.

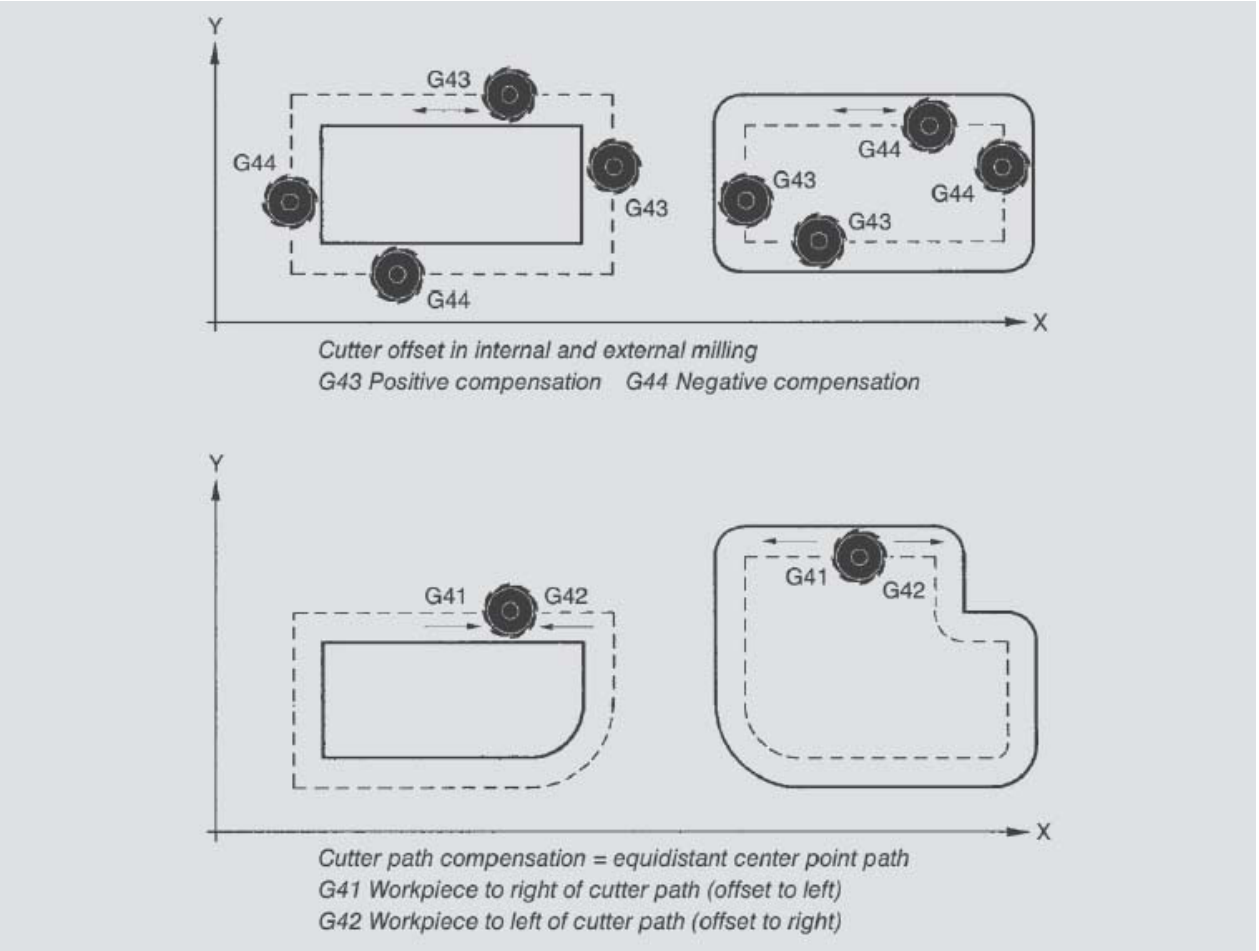


FIGURE 24.22 Milling tool offset and milling tool radius correction.

It is the purpose of the cutter radius compensation or cutter path correction to calculate the required equidistant tool center path for each programmed workpiece contour. This applies to both turning and milling 24.23 through

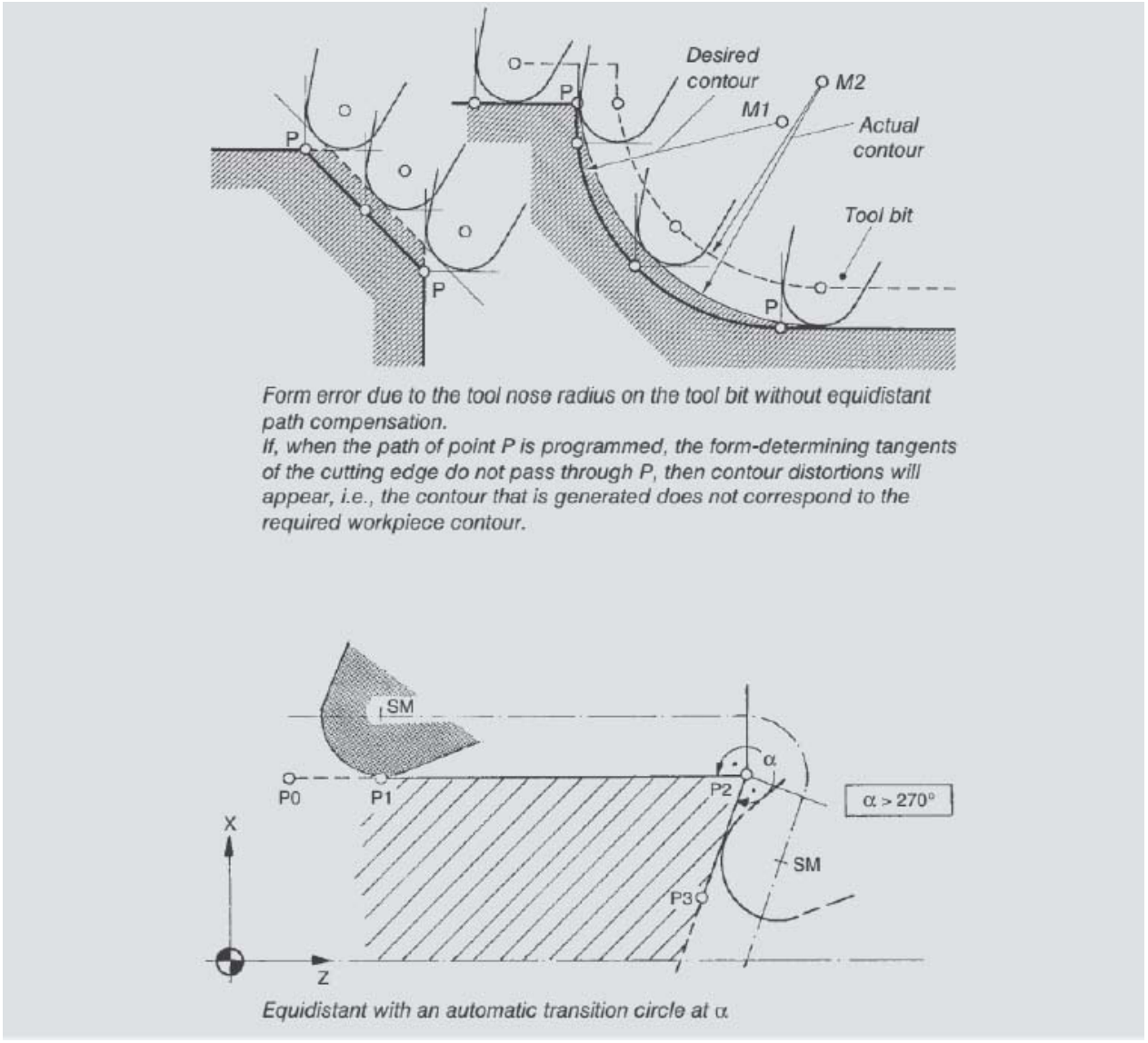


FIGURE 24.23 Cutting-edge correction on a lathe.

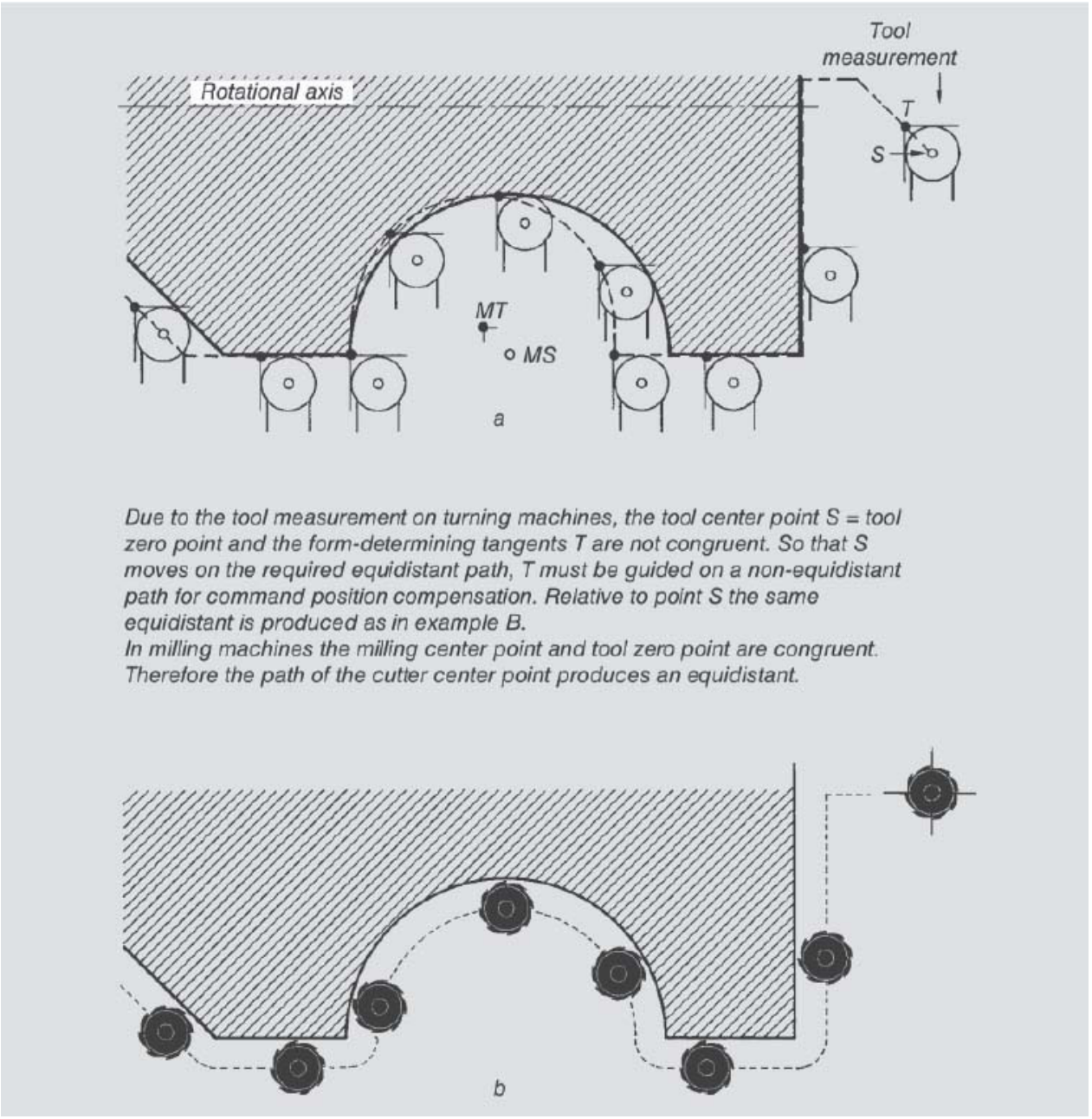


FIGURE 24.24 Difference between (a) cutting radius compensation on a lathe and (b) cutter radius correction on a milling machine. The workpiece contour must be programmed; the transition radii and equidistants are automatically generated by the CNC machine.

• N010	G17				
N020	G41	D2			
N030	G1	X125	Y50	F3000	→ P1
N040		X105	Y40		→ P2
N050		X90			→ P3
N060	G3	X75	Y25	J-15	→ P4
N070	G1	Y20			→ P5
N080		X25			→ P6
N090		Y60			→ P7
N100		X45	Y80		→ P8
N110		X70			→ P9
N120	G3	X100	I15		→ P10
N130	G1	X125	Y60		→ P11
N140		Y50			→ P1
N150		Y30			→ P12
N160	G40	Y20	M30		→ P13

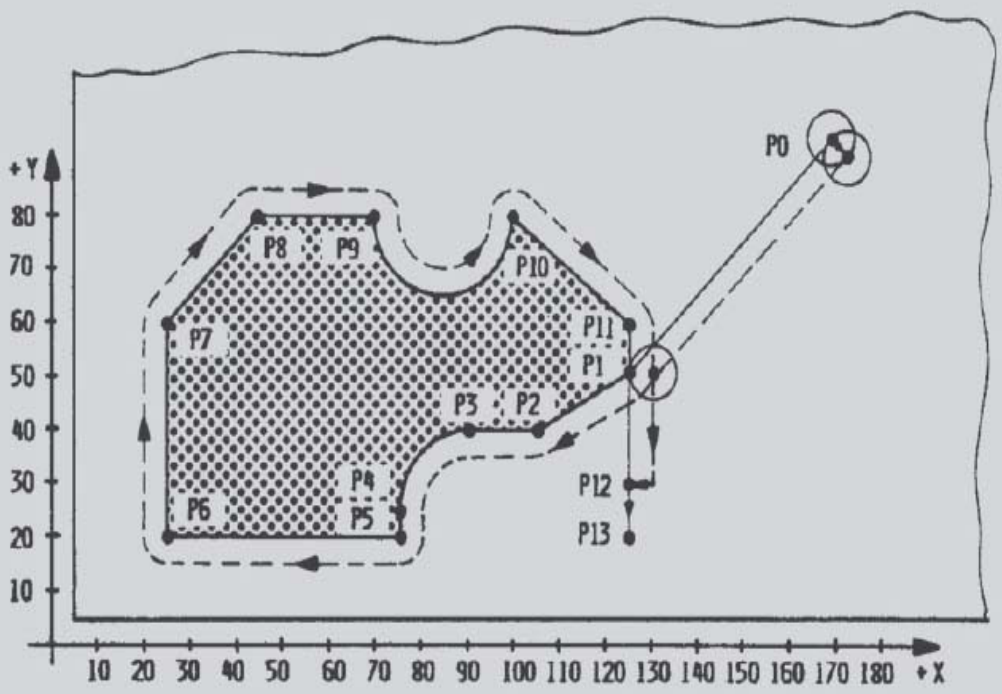


FIGURE 24.25 Programming example for G41: tool radius offset to the left.

For machines with pallet change, an axis-parallel offset of the individual workpieces must be taken into account. When swiveling the rotary table, deviations from the zero position result, and these must be corrected. Here it is advantageous if the CNC machine recognizes and applies the once-measured offset in the automatically.

DXF CONVERTER

Modern CNC machines can open DXF files directly and extract contours or machining positions. This saves the operator the effort of programming and test runs; the manufactured contour corresponds exactly to the specifications of the designer.

The definition of the workpiece reference point is done simply by moving the drawing zero point of the DXF file to a meaningful place, if it cannot be used directly as a workpiece reference point. The operator can hide superfluous layers of the DXF file in order to display only the necessary information on the contour that is processed on the screen. An easy-to-use DXF converter can detect a contour path and the desired orientation even if it is stored on different layers. It will initiate automatic contour recognition as soon as the operator has selected the second element of the contour The operator only selects subsequent contour elements when a contour is closed or branches out. In addition, machining positions from the DXF file can be selected and saved as a point file, in particular to transfer drilling positions or starting points for pocket machining.

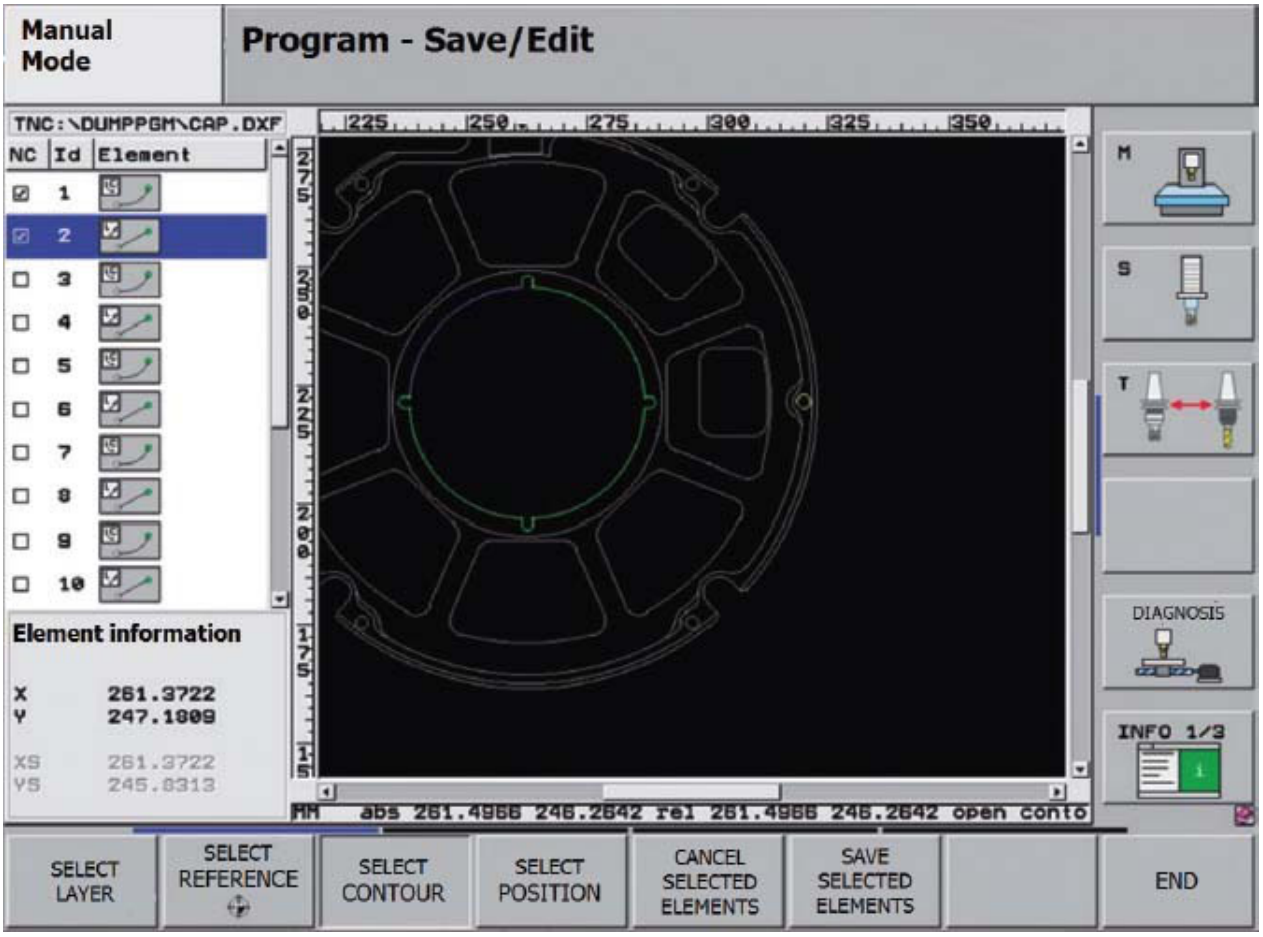


FIGURE 24.26 Contour selection in a DXF converter. Heidenhain.)

3D Graphics

Detailed 3D graphics on the CNC display help the operator to identify missing information or inconsistencies in the program without danger to the workpiece, tool, and machine by simulating the entire process. It can display the workpiece very vividly and detailed in any viewing angle.

For the simulation, the programmer first defines the blank. Next, the 3D simulation graphics display the machining program virtually. It presents the workpiece precisely and provides a meaningful preview of the actual machining process

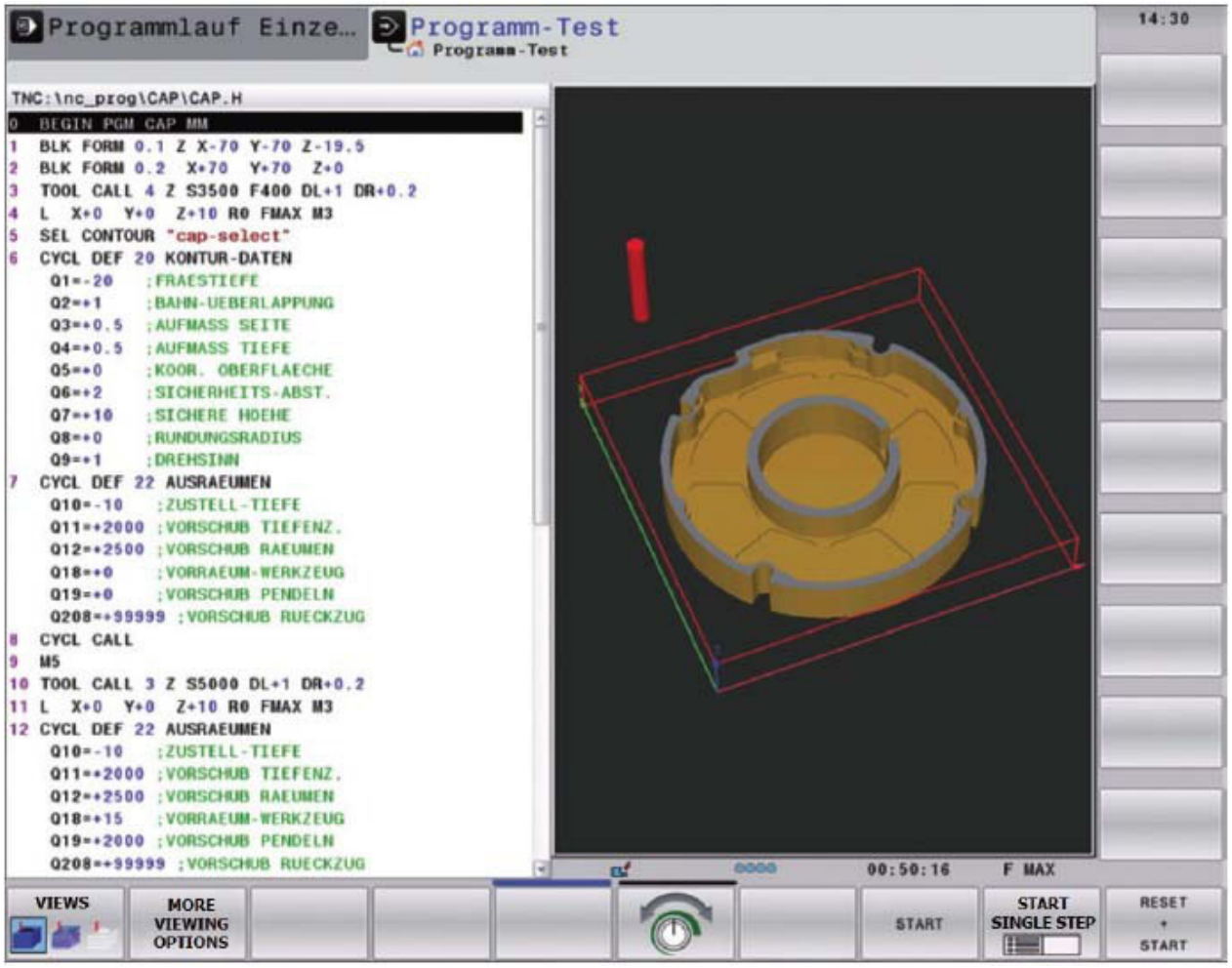


FIGURE 24.27 Processing program based on an imported DXF file. Heidenhain.).

Because the 3D simulation is done on the CNC machine, the operator can quickly run a program that has been created on the machine. This also applies for programs generated with CAD/CAM systems. It is a useful tool for the machine operator because the 3D simulation graphic takes into account the kinematics model stored in the CNC machine, which has been adapted to the actual geometry of the machine tool and thus reflects the tool path realistically.

During the simulation, various view options provide a precise and freely selectable view of details. The graphic can visualize unintended processing effects and noncompliant surface features if these result from the NC program or the machining strategies selected in the programming system

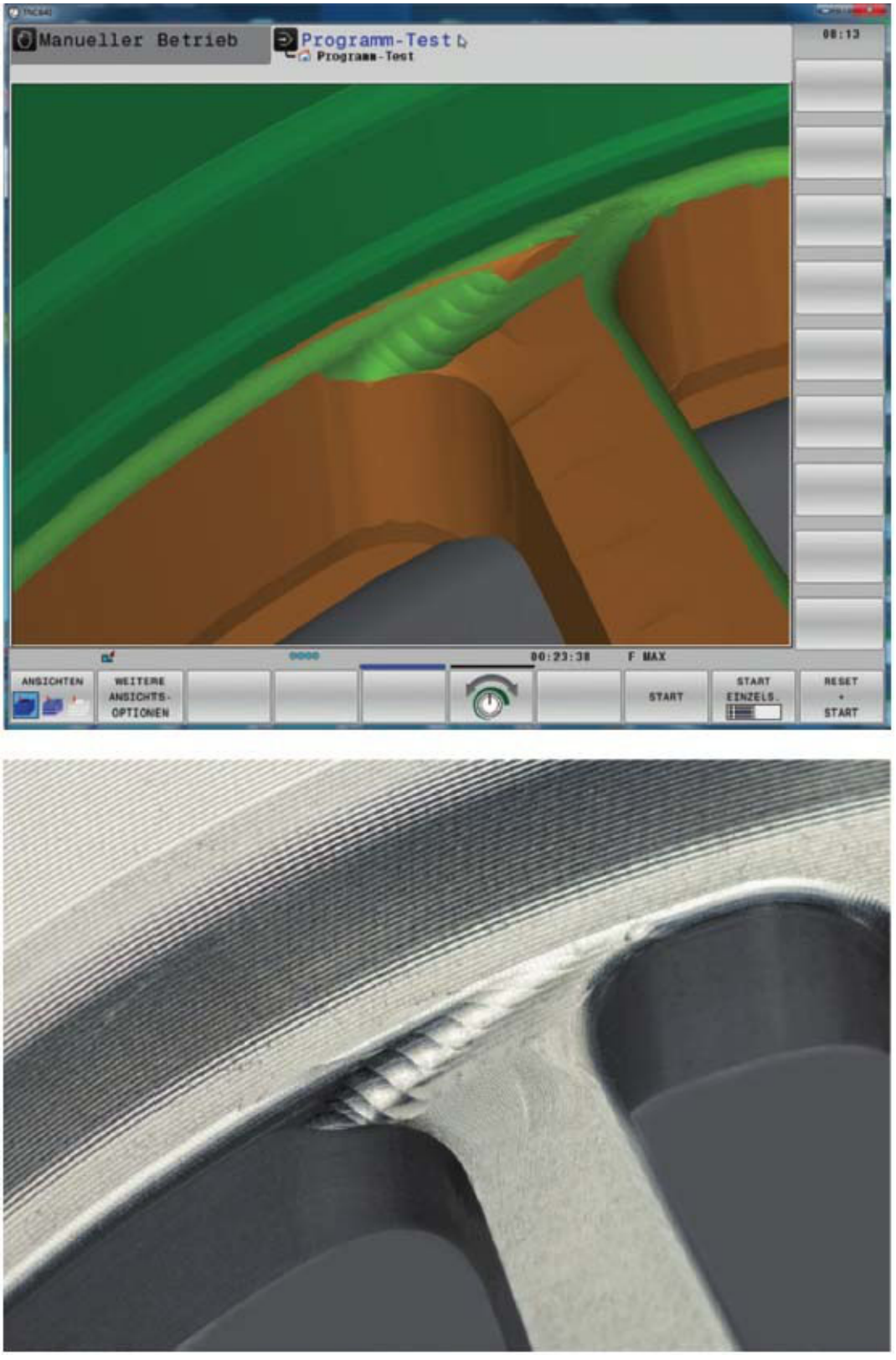


FIGURE 24.28 Preview of a workpiece surface. Details of unintended machining effects are evident in the simulation and on the machined part Heidenhain.)

The operator is in a position to view only the relevant details; for this, he or she can easily adapt the graphic by rotating, shifting, or zooming in the same way it can be done on common CAD/CAM systems. In addition, it is possible to solely view the workpiece or the tool paths or both together. There are more viewing options that can be displayed:

■ The original dimensions of the blank as a frame with the main axes therein

■ The workpiece edges as lines

■ The workpiece as transparent material to show the internal processing

■ The different processing steps displayed in different colors (This allows the operator to easily identify the tools used for each operation.)

■ The display of the tool as solid or transparent

When using maximum resolution of the 3D graphics, the CNC machine can display the ends of the blocks with the corresponding block numbers. This facilitates analysis of the point distribution, for instance, to assess the expected surface characteristics in advance.

HIGH-LEVEL LANGUAGE PROGRAMMING

The CNC programmer is increasingly confronted with special tasks that cannot be solved with classic DIN 66025/ISO 6938 or with graphic CNC programming. This calls for more flexible programming support both in work preparation and in classic NC programming on the machine.

Definition of High-Level Language

A short digression into computer technology is in order to better understand the topic of high-level language. Compared with machine-oriented assembler programming, high-level languages can be used to describe complex program sequences efficiently and transparently. This also applies in a figurative sense to CNC programming. In addition to the machine-oriented DIN 66025/ISO 6938 programming with the commands G00, G01, G02, etc., the high-level language of CNC programming supplements the flexibility of CNC programs, allowing the CNC programmer to realize demanding CNC applications. In the CNC market, the Sinumerik high-level language programming offers the basic features of higher third-generation languages such as C, C++, Visual Basic, Pascal, or Java. This significantly increases the flexibility of CNC machining programs.

Special Tasks at the CNC Programming

As an example, programming could involve parameterizing CNC programs for component families that differ only in a few geometric details. It is not uncommon that a special technology cycle has to be written, for instance, to deburr a sharp edge, because the task

at hand cannot be solved with the standard cycle. Or the generation of a simple operator message from within the current CNC program is only possible under certain conditions with the command set of DIN 66025/ISO 6938 or with graphical CNC programming. Here the use of a CNC high-level language can provide a flexible and quick answer.

Characteristics of Higher Programming Languages

The characteristics of third-generation programming languages include:

■ *Readable voice* A basic requirement for programming with high-level languages is for the programmer readable so-called mnemonic language commands such as etc.

■ *Abstract data* The programmer determines which variables are used in the program and, importantly, of which type these variables are. The variable type defines whether the variable contains an axis position, that is, a floating-point number (type REAL); a numerator, that is, an integer (type INTEGER); or the result of a comparison (type BOOLEAN).

■ *Control* Control structures are important for the illustration of program flow. Examples include conditional branching (IF ELSE) and repetitive loops (WHILE, REPEAT UNTIL).

■ In addition to basic arithmetic, high-level languages also offer higher-order mathematical functions such as sine/cosine, a log function, and Boolean algebra with functions such as AND, OR, and NOT.

Flowcharts

Each programmer of complex tasks uses flowcharts In the basic course, the program is first laid out on the drawing board in the form of a flowchart in an abstract, easy-to-comprehend way. Only in the last step does the programmer translate the flowchart into concrete voice commands. High-level languages are characterized by voice commands that allow the most efficient transmission of flowcharts.

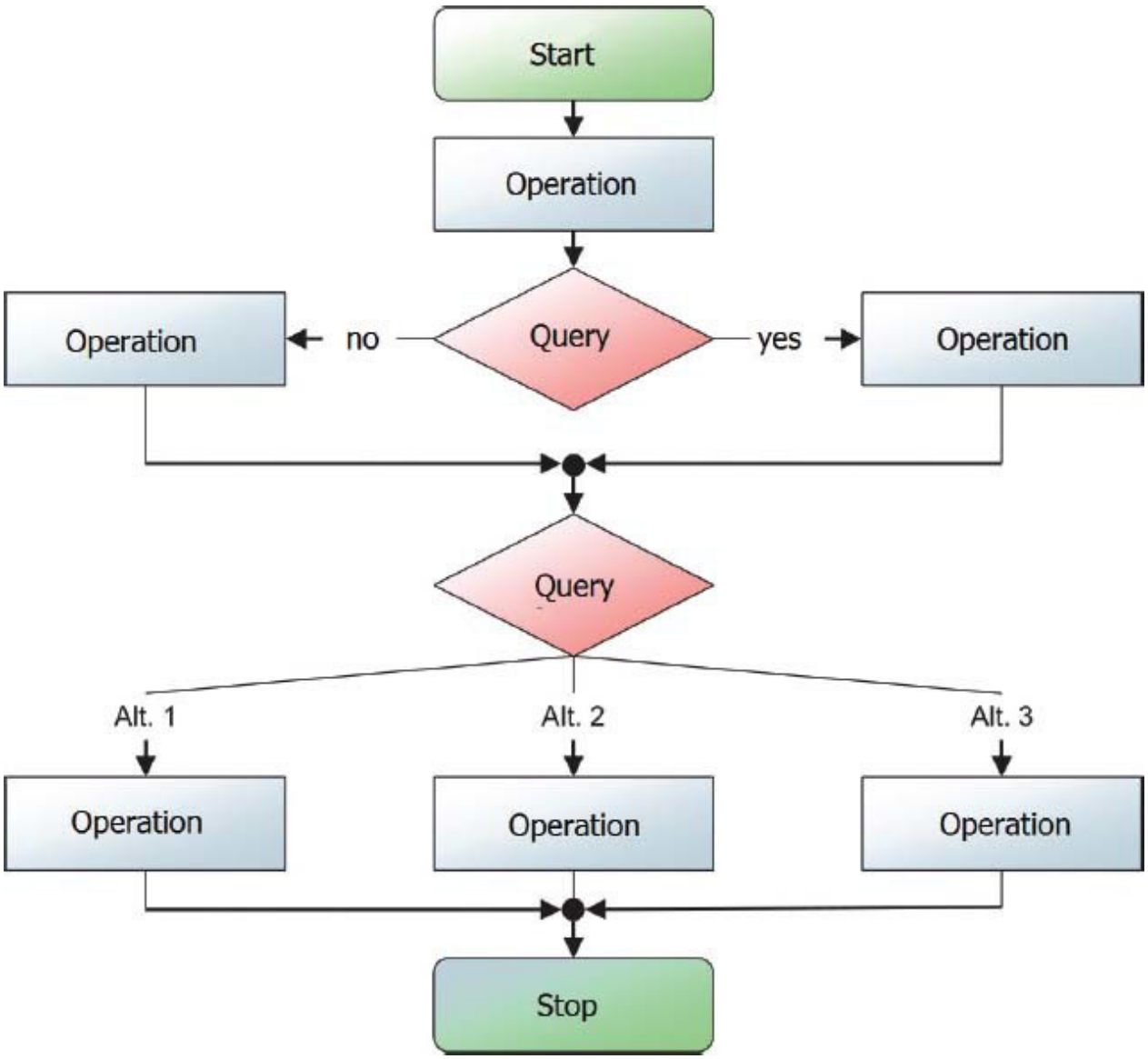


FIGURE 24.29 Example of a flowchart.

CNC High-Level Language

CNC high-level language, such as Siemens CNC Sinumerik, has basic features of third-generation programming languages See some examples below.

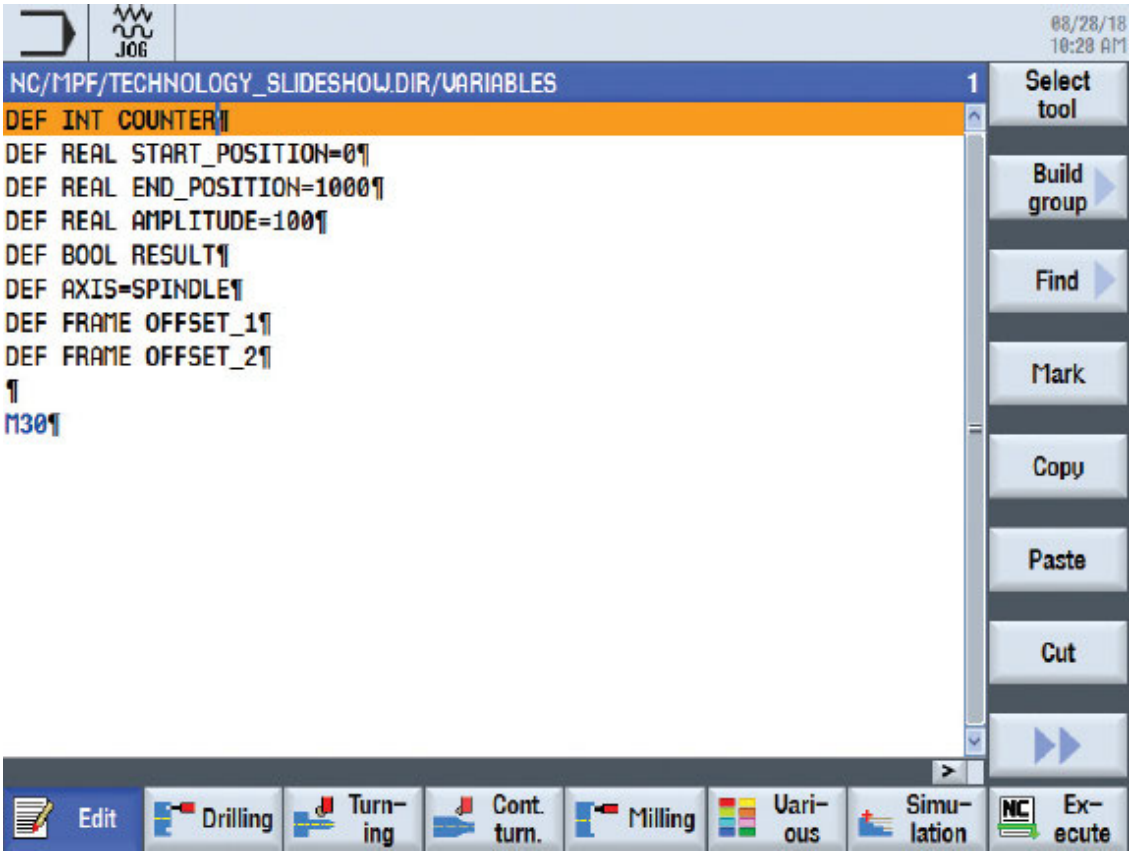


FIGURE 24.30 Abstract data types in Sinumerik CNC editor. Siemens.)

Abstract Data Types of the CNC High-Level Language

Variables of the following types can be defined in CNC programs:

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Control Structures in the CNC High-Level Language

The following control structures can be used in CNC programs

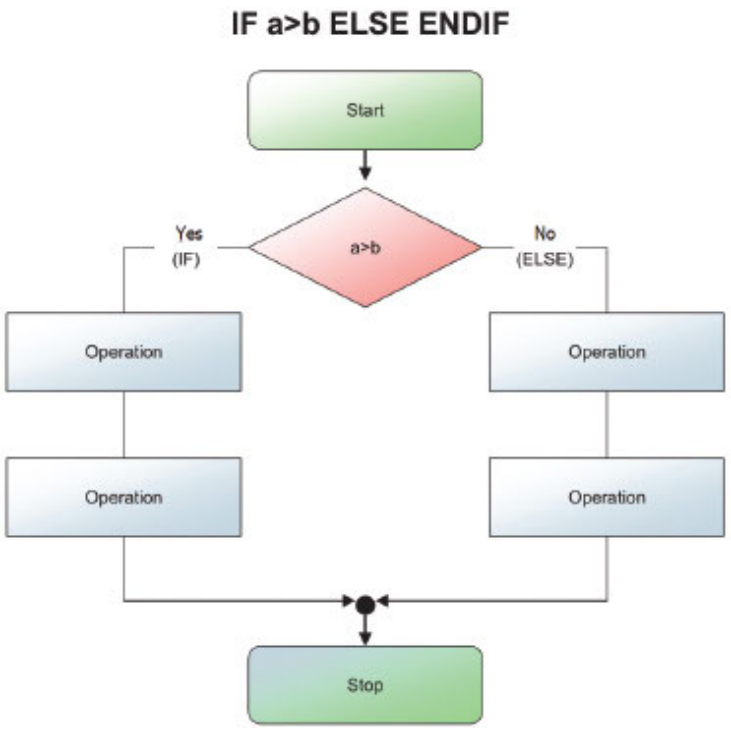

FIGURE 24.31 Conditional branching in Sinumerik CNC editor flow diagram. Siemens.)

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Operations in the CNC High-Level Language

The following operations can be used in CNC programs

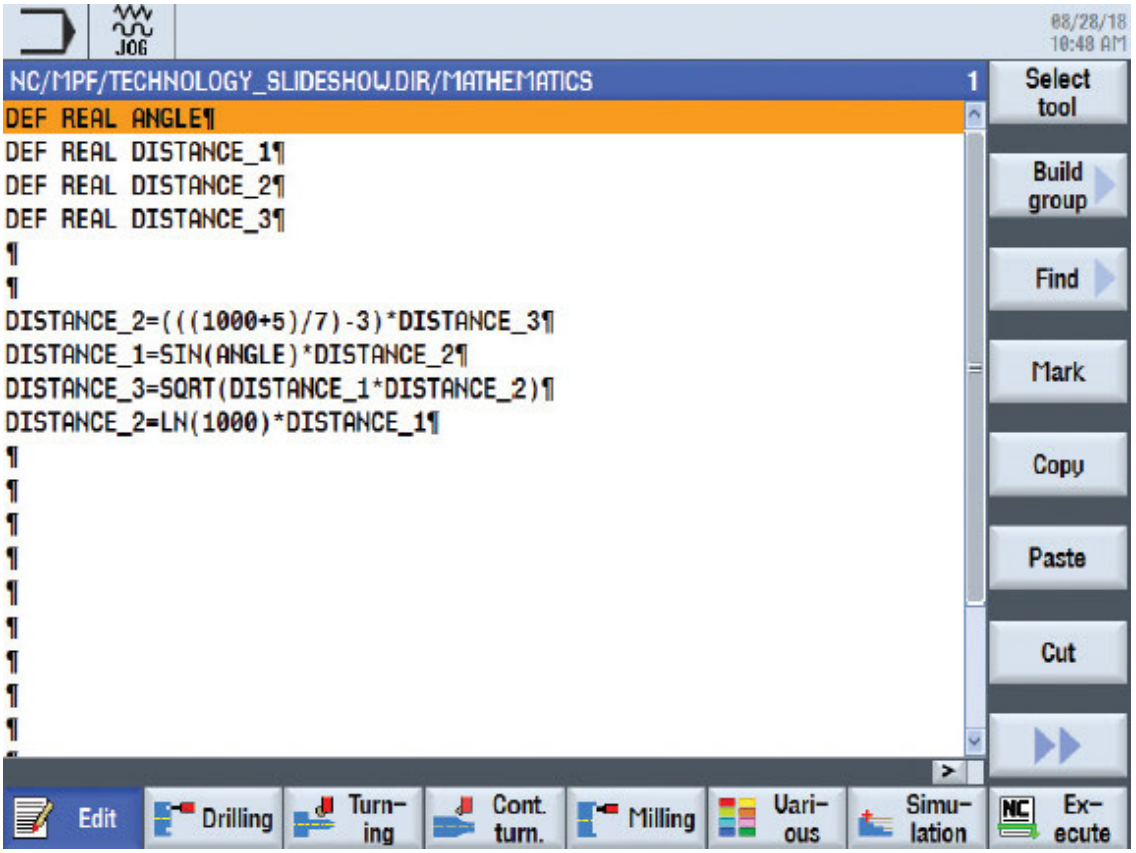

FIGURE 24.32 Math operation in Sinumerik CNC editor. Siemens.).

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Siemens.). Siemens.). Siemens.).

These examples illustrate the availability of readable voice commands in the CNC high-level language. The CNC high-level

language has the basic characteristics of a third-generation programming language and is therefore a tool to implement special tasks in CNC programming. It is an on-board tool; it thus can be used by the CNC programmer directly in the CNC editor without additional software.

SUMMARY

The NC program is a program compiled according to certain rules and special programming instructions that controls the sequence and processing steps for the production of a specific workpiece on a specific CNC machine. Such a program is generally not usable for other machines because it does not comply with their programming instructions. Nevertheless, it is essential for every machine operator and programmer to have knowledge about the general program structure in order to be able to carry out corrections and minor changes on the machine.

In practice, it is also important to pay attention to how the individual functions execute, that is, whether they take effect at the beginning or end of the block. The respective programming instructions provide information about this.

The general rules for the structure of CNC programs are specified in DIN 66025/ISO 6938, pages 1 to 3. The division of the individual commands (words) into address and numeric values makes even extensive and complicated programs clear, thus helping to make manual corrections on the shop floor.

Frequently recurring program sequences, such as drilling, turning, or milling cycles, are stored as retrievable subprograms. These must be supplemented with the respectively required parameters, such as drilling depth, retraction plane, and tool number. This reduces program length and simplifies subsequent corrections.

An essential component of all NC programs is the stored and freely retrievable correction values for tool radius, tool length, cutting-edge radius, zero offset, and other machine-specific data. Chapter 25 describes how to create CNC programs.

IMPORTANT POINTS TO REMEMBER

1. An NC program consists of a series of instructions that control the axis movements and automatic operations of a CNC machine.

2. Programming the direct position information (dimensions) and the driving conditions (G-functions) is the essential characteristic of an NC program.

3. A CNC program contains all routing and switching information as an essential feature. This information is very easy to change or exchange.

4. NC programs are stored on automatically readable electronic data media and can be transferred directly from an outside computer to the CNC machine via DNC.

5. The program structure, the address assignment, the input of the distance dimensions, the definition of the travel conditions, and the auxiliary functions are defined in DIN 66025/ISO 6938.

6. Switching commands are used for automatic switching of the machine on and off and automation functions such as speed, tool change, workpiece change, and the like.

7. Modal functions are commands that remain active until they are switched off by a corresponding counter command in the

program.

8. The dimensional data tell the axes where to go, whereas the preparatory functions (G) determine how to get there.

9. A cycle is a stored subprogram with a fixed basic sequence yet whose path dimensions are freely programmable; examples are drilling cycles, milling cycles, and turning cycles.

10. Using cycles makes NC programs shorter and safer, and manual programming becomes easier.

11. The machine zero point refers to the fixed machine-related zero point of the NC axis of the machine. It is physically determined by a reference mark of the encoder in combination with a zero-point limit switch.

12. The machine zero point, also referred to as the *home* is determined by the machine manufacturer and is precisely determined with an encoder.

13. A reference position is a fixed point on an axis with a defined relation to the machine zero point. It is used, for example, for workpiece change, tool change, or as a starting position.

14. Referencing is a control function that causes the automatic approach of the reference positions. It can be initiated by the operator at any time or when the machine is turned on.

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DEFINITION OF NC PROGRAMMING

NC programming, or part programming, is the creation of control data for the machining of a workpiece on an NC machine tool.

PROGRAMMING METHODS

Manual Programming

Here the programmer successively describes the individual movements of the tool relative to the workpiece according to DIN 66025/ISO 6938. Path and switching information and other auxiliary functions are simultaneously programmed block by block. The stored tool offsets and zero offsets are also called up. The programming takes place either in the office or directly at the CNC machine by typing in the individual characters of a program printout. This method does not support the creation of tool plans, fixture plans, and the final inspection by simulation of the result.

Manual programming with calculation of the individual movements of the CNC machine has been superseded by machine-specific or computer-aided universal programming systems. Their main characteristic is that it is no longer the individual machine movements that are programmed but the geometric data of the workpiece and the blank.

Teach-In/Playback Method

Today, a commonly used method in robot technology moves the robot arm by means of an operating device or the arm is guided manually to the desired position. Once reached, these positions are stored in the program memory of the robot CNC by the operator by pressing a key. This “teaches” the robot where to go.

In machine tools, this approach is used where an exact positioning of the tool is only possible near the workpiece; this applies to boring machines for machining bores on large workpieces. Repair shops often use so-called cycle lathes. Although these are controlled by a CNC program, they are used in semiautomatic operation. The NC program is created step by step manually by teaching the positions and with the selection of machining cycles. Here the time used for program input in relation to the processing time plays a minor role 25.1 through

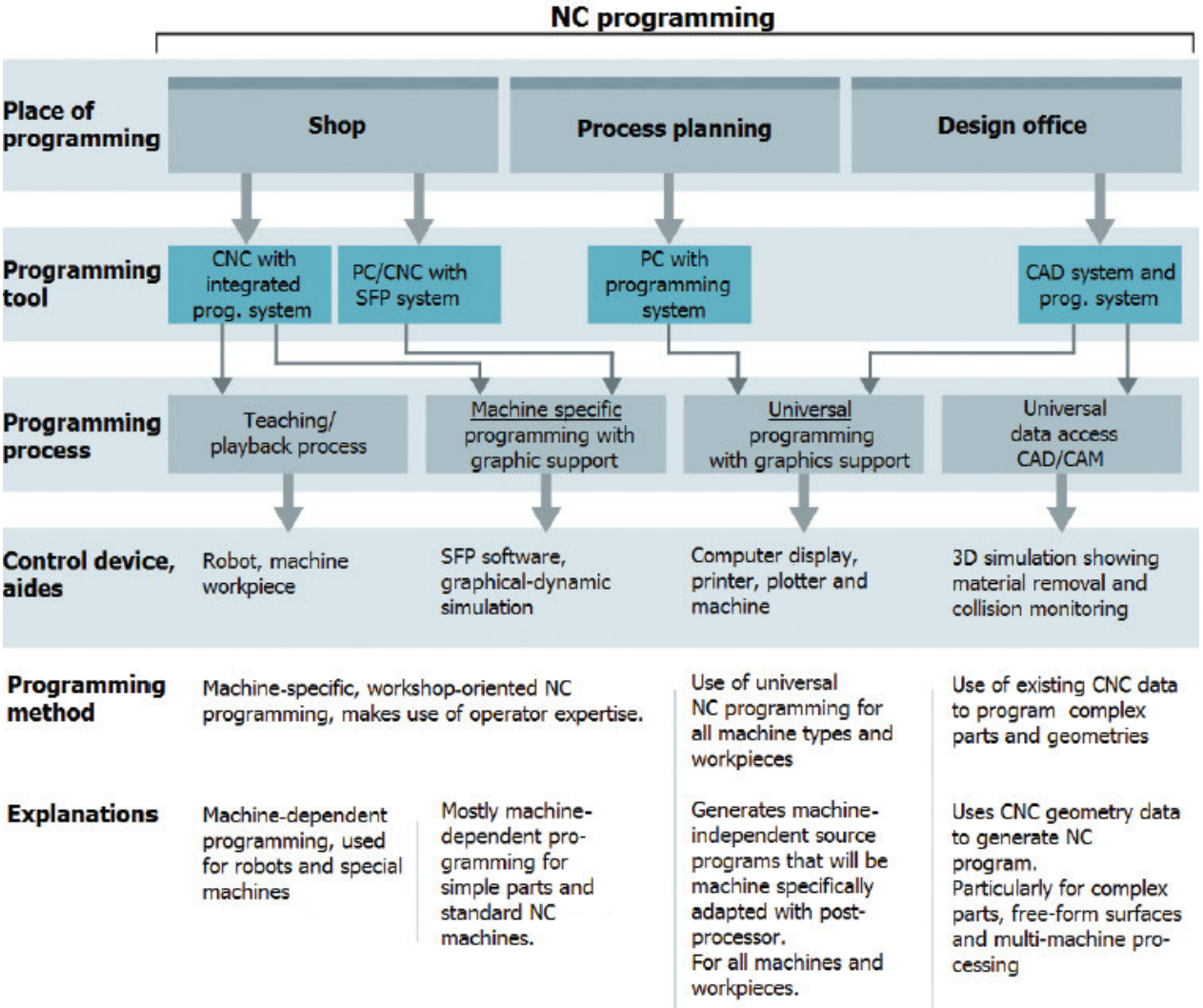

FIGURE 25.1 Interplay of programming means, process, and method in computer-aided programming.

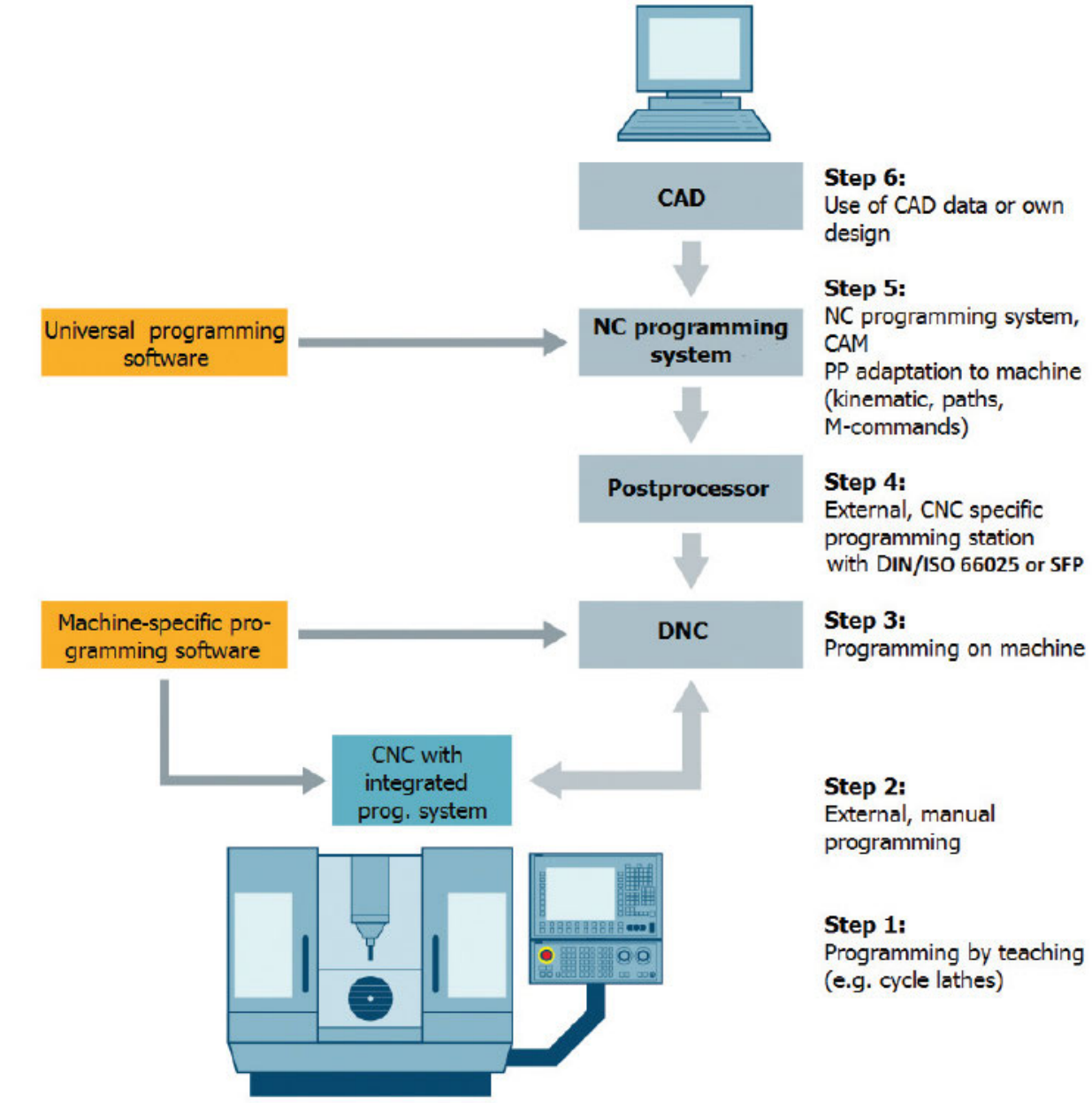

FIGURE 25.2 NC programming options, a six-step concept.

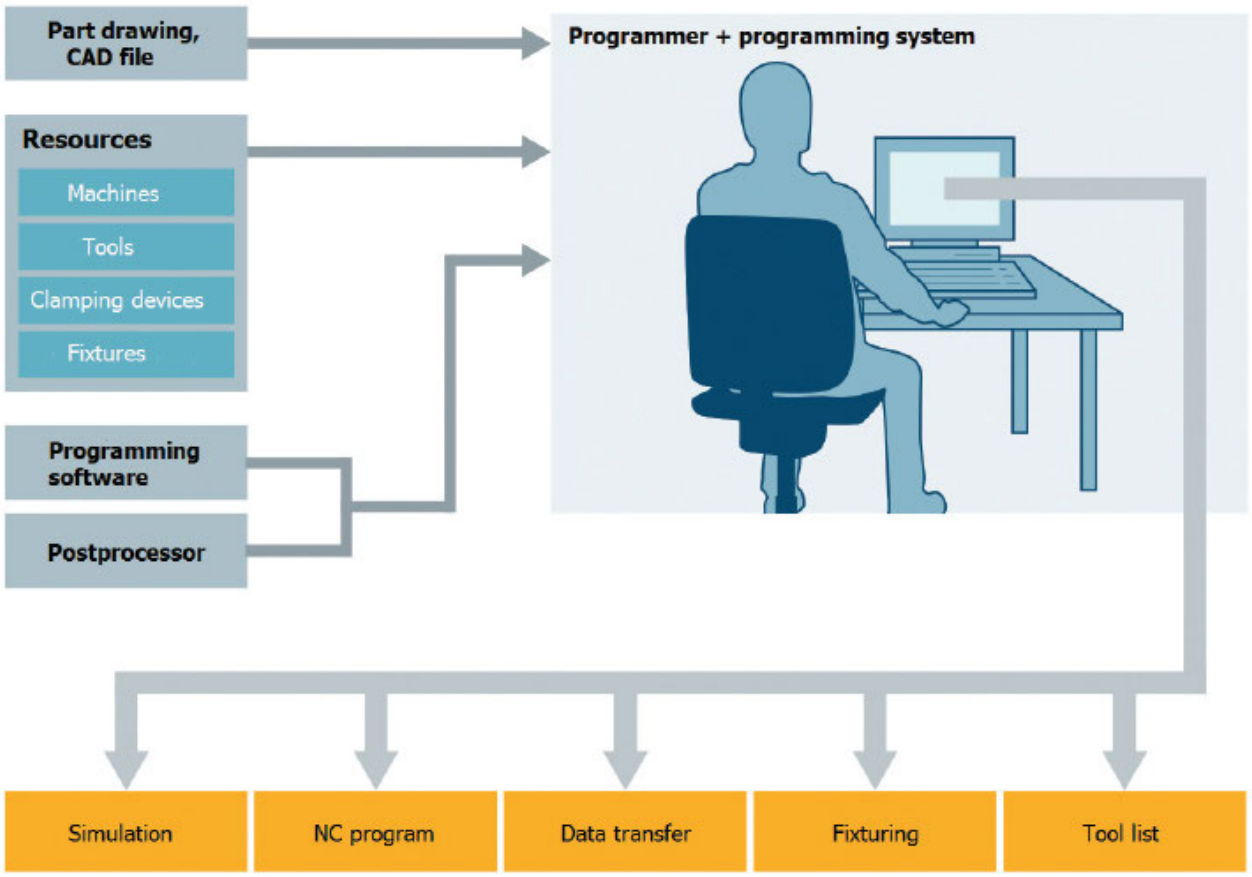

FIGURE 25.3 Principle of machine programming. The PC produces, controls, and saves all fabrication-related documents and the NC program.

CAD/CAM Programming and Production

CAD/CAM is the generic term for computer-aided design (CAD) and computer-aided manufacturing (CAM). Computer-aided NC programming (CAP) takes place in the planning office. The integration of CAD, CAP, and CAM via standardized, uniform interfaces makes it possible to access the common database from development, design, planning, and production.

If the geometric data of the workpiece that must be programmed are already available in the CAD computer, they can be transferred

directly to NC programming. This is timesaving and free from any transmission errors. The CAP system still requires geometric corrections to be made and the technological data such as spindle speed, feed rate, tool selection, correction values, and other auxiliary functions to be added. This can be done manually or fully automatically by the programming system. Finally, all production documents can be printed, such as tool lists, zero offsets, control instructions, operator assistance, and so on.

It should be noted that high-performance CAD systems are designed for much higher tasks than merely CNC programming. The use of only computer-aided parts programming cannot justify the purchase of a CAD system. In addition, the geometric data of the workpiece must be stored strictly separately from the many other data files in the CAD system.

Cutter Location Data (CLDATA)

In computer-assisted NC programming, the initial data output takes place in generalized cutter location data (CLDATA) format in accordance with the ISO 3592/443 and DIN 66215/ISO6938 standards. These data essentially contain the calculated coordinates of the tool center-point path and are used for input to the subsequent postprocessor run of the computer. These data are also referred to as a CLDATA file or source program. This must first be adapted for input into a CNC machine by means of an *adjustment* the postprocessor. Each machine/CNC combination requires a special postprocessor to be able to generate the NC part program in the appropriate format.

Postprocessors

A postprocessor is computer software that adapts the machine-independent CLDATA file to a specific CNC machine with a CNC-compatible output format. For this purpose, a separate postprocessor must be supplied for each CNC machine; it usually consists of five parts: input, control, traversing movements, switching functions, and output. Only after postprocessing in the computer does the finished NC program become available. Subsequently, further data can be printed and a graphic-dynamic simulation on the screen can be performed if the clamping device and the workpiece are also available as data files.

If the programmer has not adhered to specified limit values or has made input errors, these are now recognized and displayed with reference to the cause of the error. The postprocessor considers the size and kinematics of the machine, feed-rate limits, spindle speed, tools, outputs the correct M-commands, and maps tools, compensation values, and reference points to each other. The result is an immediately executable NC program for the specific CNC machine.

NC Programming Languages

This refers to abstract, problem-oriented, symbolic programming languages for the creation of NC programs. They are designed for use on mainframe computers and have a specific vocabulary, symbols, and semantic and syntax rules for NC programming. The universally applicable languages include, for example, APT and EXAPT. Single-purpose languages, by contrast, can only be used for a specific area of application and are tailored to specific CNC/machine combinations. This type of programming without user guidance and without graphical support is technically obsolete and no longer used today.

Shop-Floor Programming (SFP)

The computing power of modern CNCs makes it possible to integrate a machine-specific NC programming system with graphics and machining simulation. This makes the CNC machine a powerful programming system, and the operator can program directly on the machine.

SFP systems have the advantage that they are optimally adapted in terms of functionality because of their special design for a specific machine. Even lathes with two supports, and rotating tools, can be programmed in a very practical way. The complete processing, such as inside and outside, face and outside surface, as well as collision considerations, wait conditions, and the distribution of tasks to both supports, is often determined by the CNC machine much faster and more effectively than a universal NC programming system. This is why this programming has become very popular for turning, milling, and nibbling. Today, SFP is available for all CNC machine types. Additional important functions such as nesting the parts when nibbling or punching are further advantages. Postprocessors are eliminated because the programs are generated directly in the appropriate CNC syntax. However, workshop-oriented programming (WOP) systems have the disadvantage that with each new CNC make, another programming system moves into the workshop. Experienced users, however, claim that only after the introduction of SFP did the profitability of their CNC machines noticeably improve. SFP is often referred to in the literature as "stripped-down, powerful, special CAD/CAM systems." This is not correct according to the CAM definition because a shared database; a universal, reusable CLDATA file; and the printing of lists are usually not available.

CNC Programming

Programming on the CNC machine can be done during operation. However, it may turn out that the capacity utilization of the machine or short cycle times do not allow this. For this reason, several CNC manufacturers offer SFP packages for use on stand-alone PCs. This has the advantage that the handling of the software is identical on both systems, and the work can take place away from the noisy workshop environment. In addition, the machine operator can program on the programming station without additional training. The extra effort is manageable, but for each new CNC machine, the associated programs have to be newly installed or activated.

Universal NC Programming Systems

With a computer program on a PC, one can create NC programs for all CNC machines with ease. The necessary equipment expenditure for the planning office and the workshop is not great. It is helpful for machine operators and programmers to be close, particularly when a fast product change needs to be implemented or a rush order must be processed. Depending on the requirements, more or less powerful systems are available. Here buyers must do some research to find the right system for their needs.

Programming on an external programming station generally shortens machine downtimes. The programs can also be tested using a graphical simulation. Additional test runs for error detection in the CNC machine can be omitted. High-resolution graphics help to reliably identify contour violations and hidden details, even in complex 3D programs.

CAM-BASED CNC MACHINING STRATEGIES

CNC machining faces the constant challenge of continually optimizing the process and producing more parts per unit of time. Modern CNC machines are optimized in terms of their dynamics and rigidity to such an extent that it would be possible to produce a significantly higher cutting performance than is often done in practice. Tool manufacturers, by contrast, recommend cutting values that can rarely be used in practice without tool damage or excessive mechanical strain on the machines. This conflict led to CAD/CAM modules and CNC-integrated machining cycles that offer optimized machining strategies for almost all materials and cutting tools, customized for the given workpiece and machine.

Optimized CNC Milling Strategies

Conventional milling methods have limitations because of the wrap angle of the tool. When cutting in a straight line, as in creating a groove, the milling tool cuts with its complete diameter into the material; in other words, a wrap angle of 180 degrees is applied The tooth feed rate determines the constant cutting speed. The harder the material, the less deep the tool can cut, or the feed rate must be reduced to maintain the integrity of the tool. Thus the in-feed must be limited to 0.5 × tool diameter.

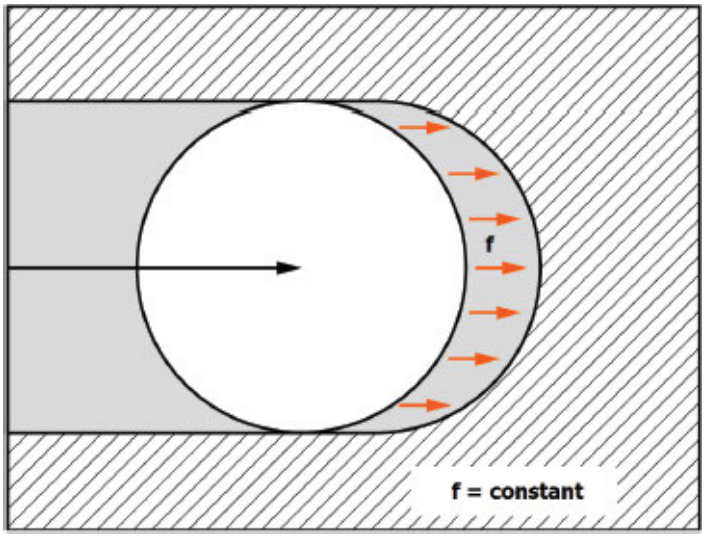

FIGURE 25.4 Example of groove milling with a wrap angle of 180 degrees. Hoffmann Group.)

The following optimized cutting strategies were developed to overcome this limitation:

- High-speed cutting (HSC)
- Plunge milling
- Whirl milling (trochoidal milling)

HSC is essentially characterized by high spindle speeds with low in-feed and large feed rates per tooth. Highly dynamic machines are required for this type of machining.

Plunge milling is used to create deep cavities in hard materials. Conventional methods of material removal with several vertical in-feeds have significant disadvantages, for instance, radial cutting forces

on the cutter and critical vibrations when using long end mills. Plunge milling creates pockets, grooves, or contours in a boring manner, and thus the roughing operation creates a maximum chip volume. Modern CNC machines usually offer comfortable machining cycles for this operation.

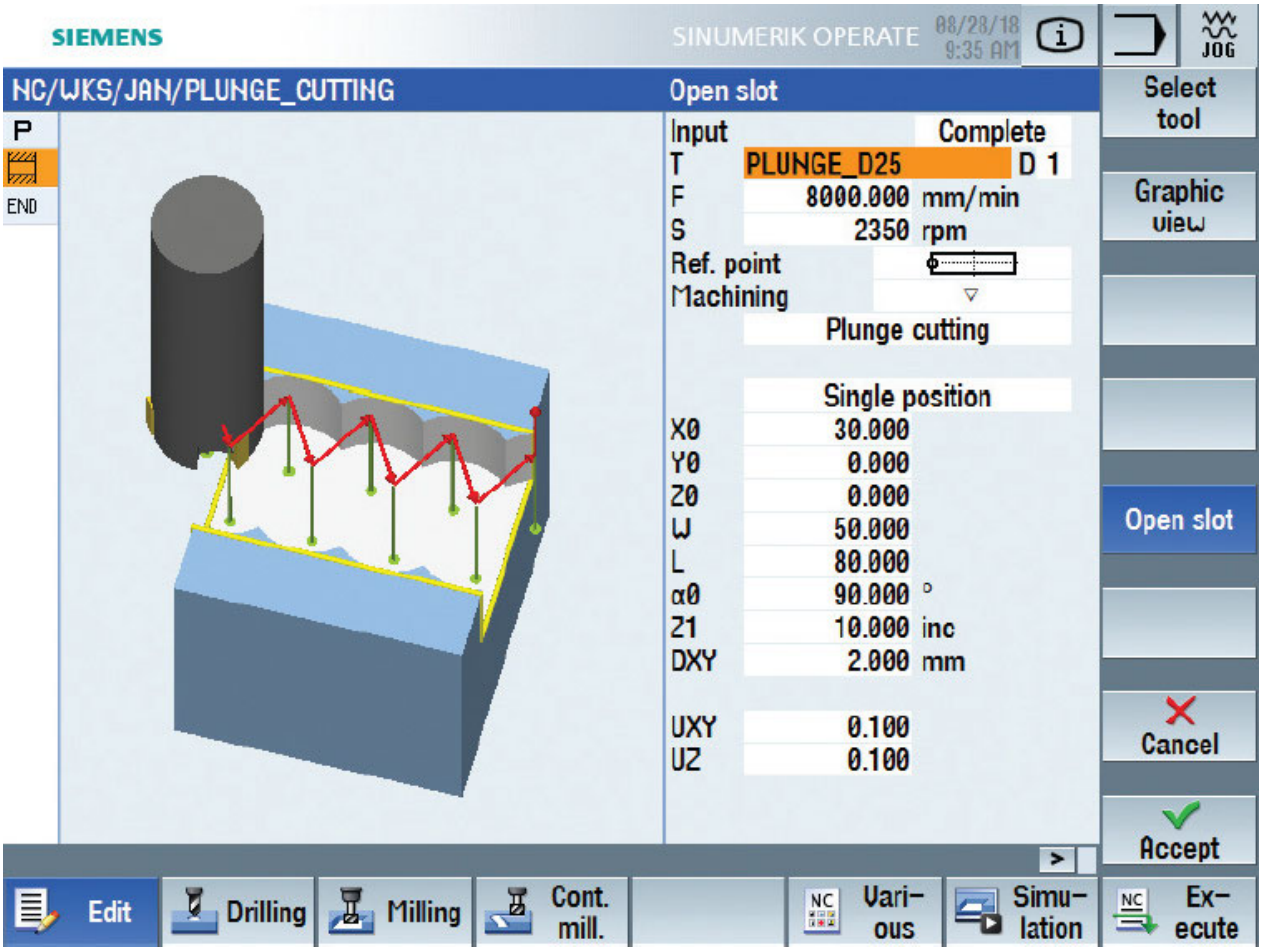

FIGURE 25.5 The principle of plunge milling on an open groove with a SINUMERIK 840D sl machine. Siemens.)

In conventional milling with a tool engagement of 180 degrees, the pressure on the cutter is extremely high. Coupled with a high feed rate, tool failure may occur, even if the entire cutting edge of the tool is not used, thus working in an uneconomical manner. This condition can be optimized with trochoidal processing Given that a

cutter is used with a smaller diameter than the groove and the tool is guided in a continuously spiraling motion through the groove, the wrap angle is only 30 to 65 degrees; the ideal angle depends on the material. The wrap angle is defined by the in-feed per circular movement and the diameter of the circular path. This leads to lower forces on the cutter and therefore allows a greater depth; the tool is used more economically. Mathematically speaking, the center of the whirling circle always advances along the direction of the groove.

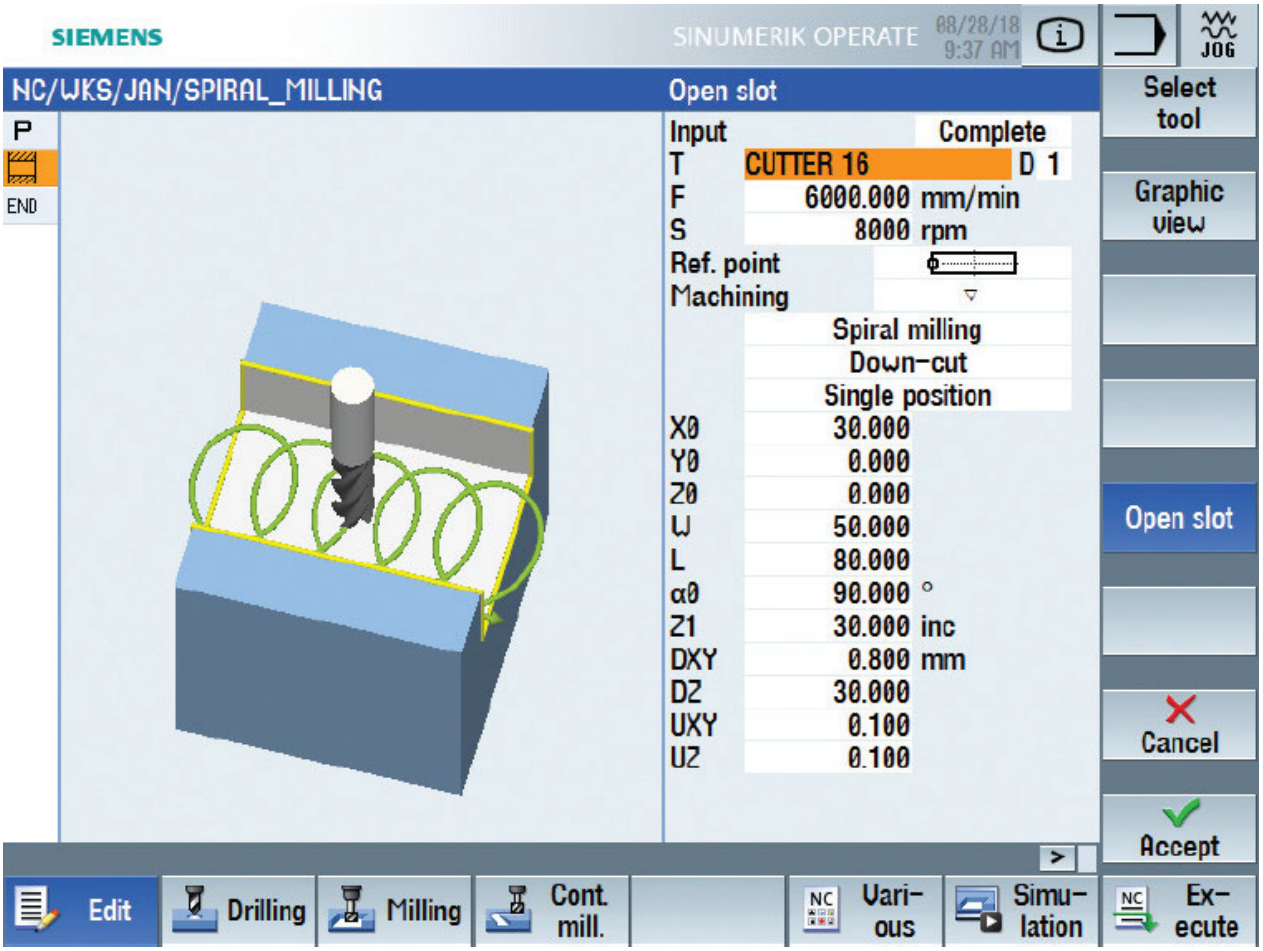

FIGURE 25.6 Principle of whirl milling (trochoidal milling) on an open groove with a SINUMERIK 840D sl machine. The milling strategy is static, meaning the principle is based on constant circular paths. Siemens.)

Because of the slow increase and decrease of the wrap angle, the cutter is not optimally used in these two cutting phases of the circular motion. The tool path is optimized using the so-called dynamic or optimized trochoidal milling method, keeping the nonoptimal phases as short as possible (see Figure This path is calculated by a complex algorithm that strives to quickly reach the largest possible wrap angle and maintain it as long as possible. As a result, the cutter experiences best possible use during the entire engagement. The process can still be optimized in the idle phase. Here the tool path can be improved by shortening the tool's circular motion and increasing the feed rate. The optimal conditions depend on the machine dynamics and differ from machine to machine. The characteristic cutter scratches on the surface can be prevented by raising the tool by 0.5 mm during rapid movement.

Many CNC manufacturers offer various cycles for their respective milling packages. The nature of these cycles, however, is always based on the described mathematics.

This milling technology can realize considerably higher cutting values. Additionally, machine, CNC system, and tool allow increasing the cutting values even further. Often, however, the optimal cutting performance fails due to incorrect programming. This gap is closed by CAD/CAM manufacturers that offer modules that in addition to geometric programming generate perfect cutting values from a database of different materials adapted to the dynamics of each machine. The milling process itself is based on the principle of trochoidal machining

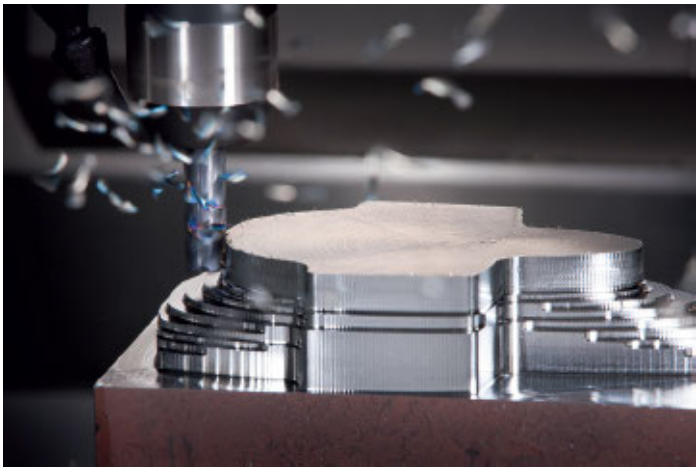

FIGURE 25.7 Highly dynamic roughing using a trochoidal tool path. iMachining, SolidCam.)

These CAD/CAM modules generate NC programs for high-speed roughing, residual material roughing, and rough finishing of free-form surfaces and prismatic parts. Unlike CNC-based cycles, CAD/CAM modules generate dynamic cycles where the milling path is dynamically generated, meaning that the spiraling path of trochoidal milling is not constant but is adapted according to the material removal rate that hast been calculated by the CAD/CAM system

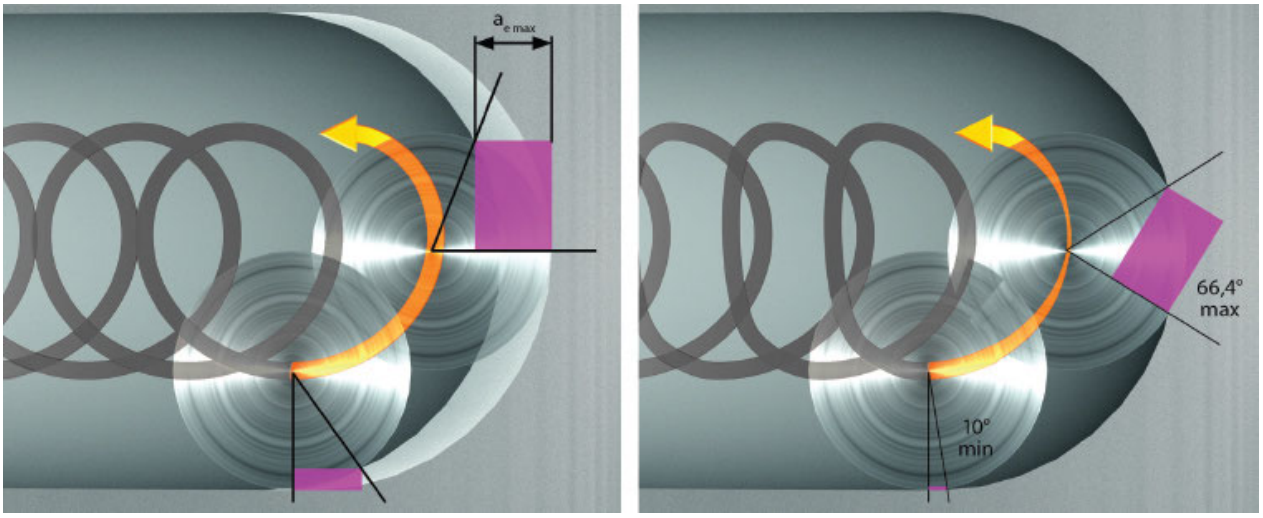

FIGURE 25.8 Difference between static and dynamic trochoidal milling operations. Hoffmann Group.)

These modules use a database that calculates the material removal values based on the following factors:

- Material of part
- Material of tool
- Spindle power of the machine
- Maximum speed of the machine
- Maximum feed rate of the machine
- Wrap angle of the tool

Based on this input, the following values and the dynamic trochoidal path are calculated for the specific workpiece:

- Highest possible spindle speed
- Highest possible axis feed rate
- Highest and lowest side feed rates of the milling tool

The tool paths are calculated optimally; that is, for a long, straight path, a small side feed with maximum possible feed rate is used; for short, straight cuts or contour elements, a high side feed with reduced feed rate is used. In the feed direction of the tool the full cutting edge length can be used. The cutting edge is thus used to the maximum, the tool life is increased, and the spindle has a smaller load than in conventional milling. Thus up to 70% of the processing time can be saved compared with conventional machining.

Optimized CNC Turning

Similar to milling, there are also strategies for turning that use a dynamic tool path with constant chip removal volume and thereby use of the entire length of the cutting edge. In conventional turning, the pressure on the cutting edge builds up abruptly when starting a cut, leading to wear or, in the worst case, breakouts of the cutting edge. A recent innovation is the tangential approach of the cutting edge to the workpiece, leading to a gradual buildup of the cutting pressure. This method reduces tool wear and is easy on the machine because it does not have to absorb the sudden buildup of forces, as the feed force increases slowly. Also, processing time will be noticeably shorter

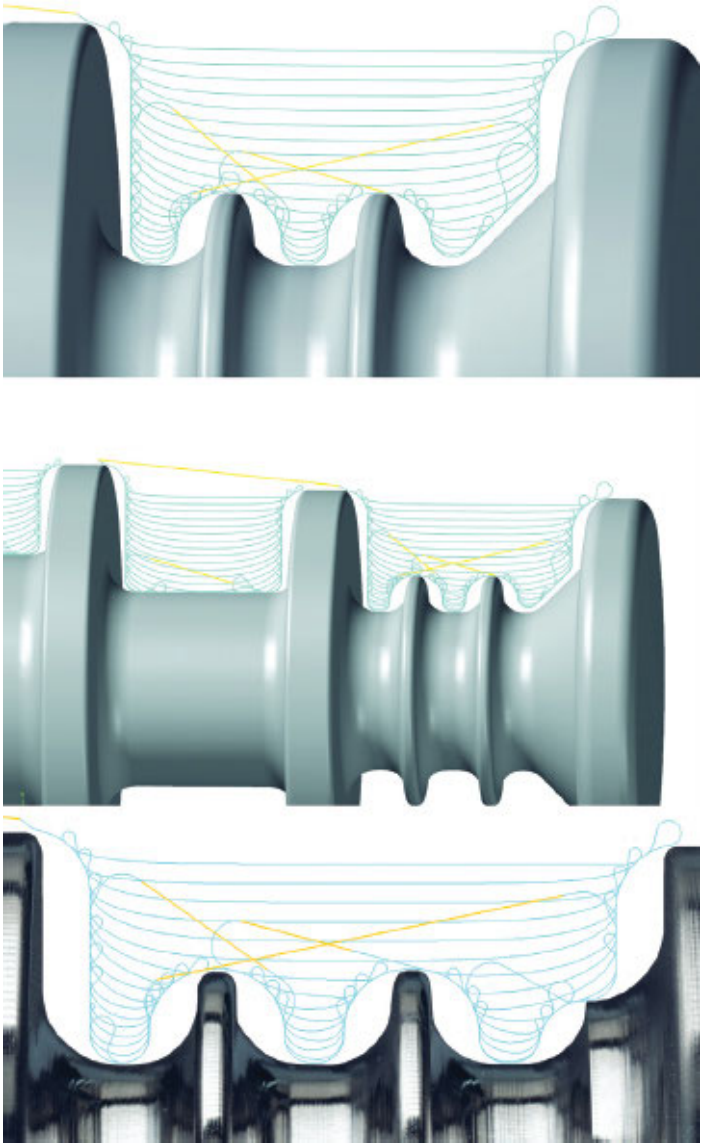

FIGURE 25.9 Dynamic engagement and disengagement of the tool increase the service life, protect the machine, and reduce processing time (programmed with MasterCAM). MasterCAM/InterCAM.)

As soon as the cutting edge is in contact with the workpiece, a dynamic point of contact between the cutting edge and the material is created. This dynamic contact point ensures uniform wear over the entire length of the cutting edge, thus avoiding a contact point as occurs in conventional cutting methods. This dynamic use of the cutting edge increases tool life greatly.

Constant cutting conditions achieve an ideal chip formation that carries away the resulting process heat from the component. Changes in direction between the cuts are made via small, programmed loops, thus avoiding empty paths, resulting in soft, dynamic changes of direction, and making ideal use of the dynamics of the machine. This *dynamic roughing* was especially developed for machining hard materials. The dynamic movement allows more effective engagement with the material and makes optimal use of the cutting edge.

USER-FRIENDLY GRAPHICS

An essential part of computer-aided programming is the graphic support. It was first integrated into the programming systems and then the CNC machines, and it proved to be a key factor in the faster acceptance and dissemination of NC technology.

The graphic aids are differentiated according to:

■ *Input graphics* for geometry and technology, revealing to the programmer blank, finished part, tools, and processing

■ *Auxiliary graphics* for displaying drilling patterns, milling and turning cycles, clamping devices, tool geometries, and other machining-specific functions

■ *Simulation graphics* that display the workflow dynamically after data entry, clearly indicating any input or process errors (The graphics must be of high quality so that the programmer does not need to rely on the machine as a means of control.)

The NC programmer prefers this type of comprehensive graphical support because it best supports workshop practices. The option of being able to follow the program structure visually step by step corresponds exactly to conventional machining, where, at any time, the actual machining can be compared with drawing requirements, albeit it is more time consuming. The graphical method “guides” the programmer in a dialog and provides a sense of security as

programming progresses, resulting in much shorter programming times for advanced tasks.

The advantage of graphics support is clearly evident in the input of complicated contours and processing after reclamping. It does not require otherwise abstract considerations about axes and motions. Auxiliary graphics will be used quite often during data input, as in the choice of tools, definition of safety zones, and for programming of drilling and milling cycles. After data input, simulation graphics enable the display of the processing, usually in several views Some systems allow the programmer to check at any time for programming errors; other systems only allow this after completing the programming. Real-time simulation allows gauging the processing time but has the disadvantage that the whole process takes too long and is therefore not always used. As an option, the processing can also be displayed in fast motion. Parallel simulation allows the machine operator to view the machining process on the CNC screen simultaneously; this can be helpful when the presence of coolant prevents a closer look at tool engagement.

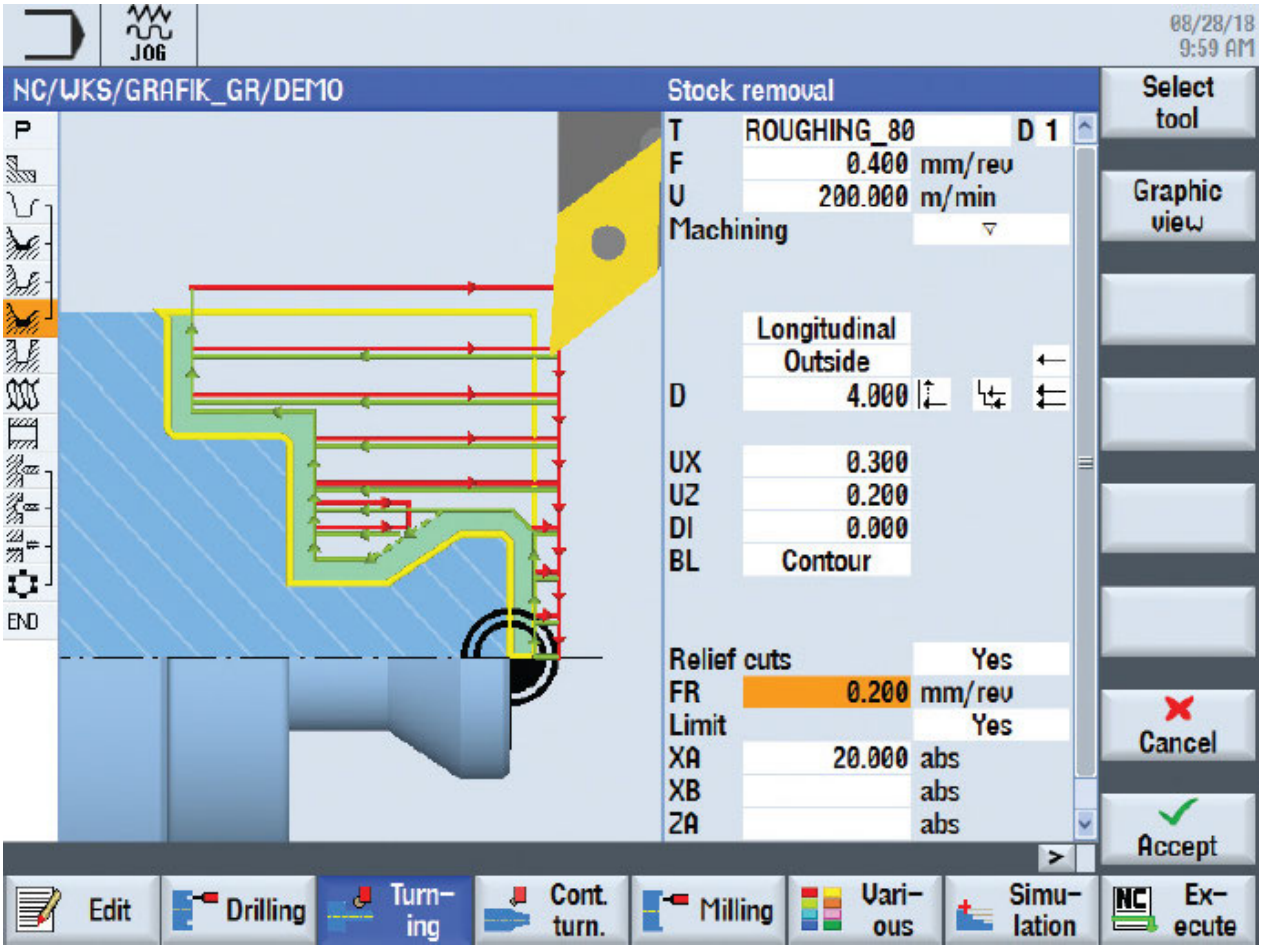

FIGURE 25.10 Sinumerik Shopturn: animated auxiliary graphics and parameter input window of the lathe cycle "roughing." Siemens.)

Most systems also display the individual tools in the correct scale to the workpiece during simulation, both for outside and inside machining. The observer can recognize how the part changes its shape, whether the tool may be on a collision course, and whether all surfaces are processed properly. This requires that the operator is in a position to enter and change tools data on the graphical user interface (GUI)

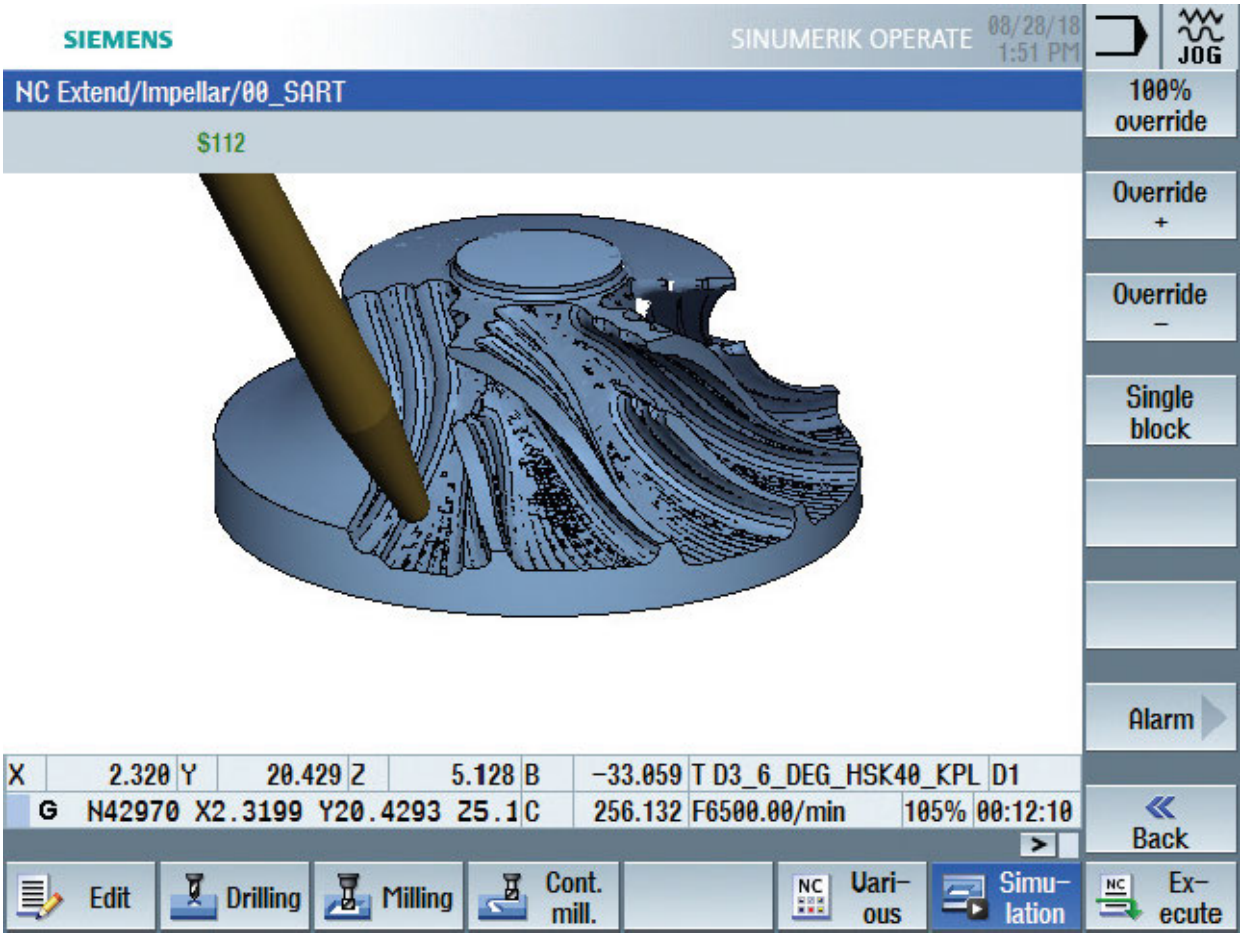

FIGURE 25.11 Sinumerik Operate: 3D simulation of a five-axis simultaneous milling process of an impeller directly on a CNC machine. Siemens.)

Simulation graphics, without a doubt, are the most important step toward higher process safety. Collisions between tool, workpiece, and fixture or geometry errors are easy to detect and can be corrected before a malfunction occurs. Thus rejects and scrap can be significantly reduced for single, large, or expensive workpieces.

CNC IDENTICAL PROGRAMMING SYSTEMS

A workpiece program can be created on the control unit on the machine, as described earlier, even while the machine is in operation. Nevertheless, it may happen that it is not possible to program on the control unit. Most CNC manufacturers, for this reason, also offer an emulation software package that allows programming on a PC. The operator/programmer can perform his or her work on a laptop with a user interface that is an exact match to that on the control unit 25.12 through This CNC programming software has many practical uses.

FIGURE 25.12 Sinutrain programming station. Programming on a programming station with the same interface as the CNC provides

ease of use. Siemens.)

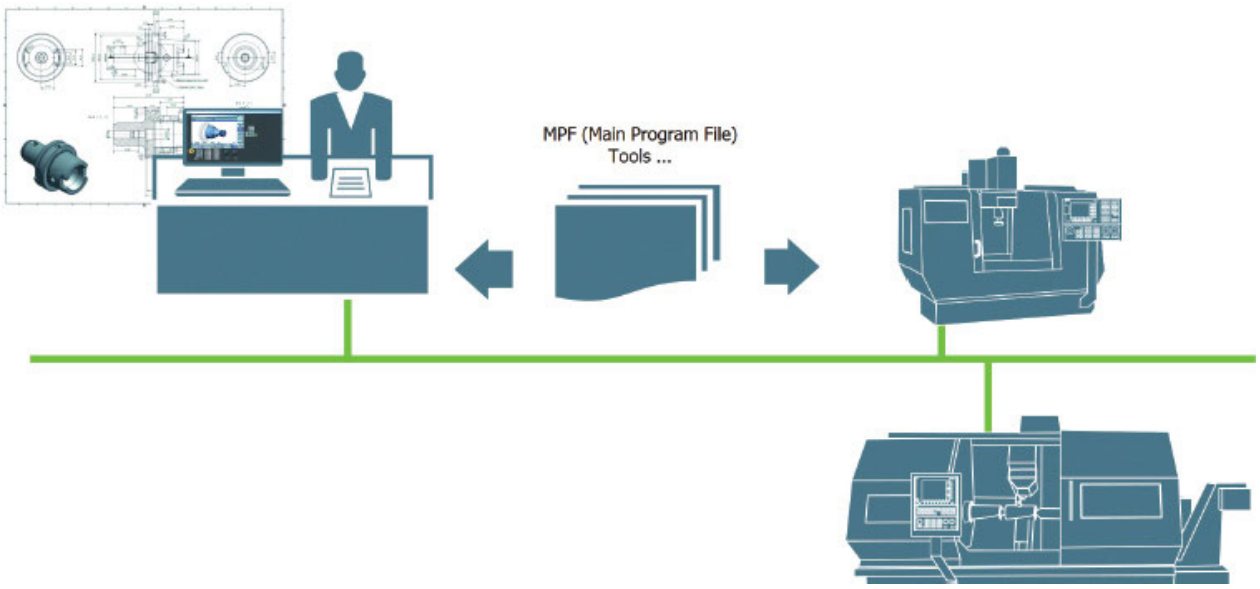

FIGURE 25.13 Sinutrain programming station. If the PC is connected to the machine tools, programs can be transferred to the CNC machine instantaneously. Siemens.)

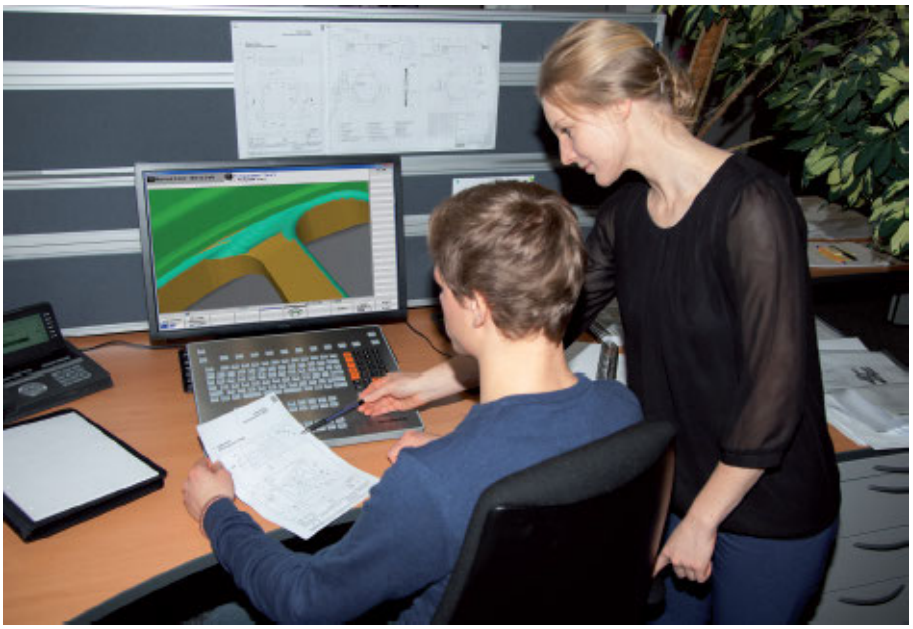

FIGURE 25.14 Externally created programs can be tested on a dedicated CNC programming station before use on a machine.

Heidenhain.)

PC Programming

Creating, testing, and optimizing an NC program on an external PC reduces downtime of the CNC machine. Because the software on the PC matches that on the CNC machine, the machine operator can program away from the machine without extra training.

Test Externally Created Programs

Programs created on a CAD/CAM system can be tested on the PC before being transferred to the CNC machine. Test runs and troubleshooting in the shop are not necessary. High-resolution graphics will help to reliably identify contour violations and hidden details, even on complex 3D programs.

Importing DXF Files

DXF files, such as a hole pattern or outer and inner contours, can be imported into the CNC machine and adapted for processing on the machine. Although most CNC models offer the direct import of DXF files, it has been shown that review of the program for gaps in the tool path due to noncontiguous lines or the deletion of unnecessary drawing features is better performed on a PC in an office than on the machine in the shop.

Adaptation to the Actual Machine

Typically, the CNC emulation software has standard settings for technologies such as turning and milling. The machine manufacturer, by contrast, adapts the CNC program on the machine so that the standard settings do not match anymore, for example, axis identifiers, kinematic configurations, custom masks, and so on. In most cases,

the CNC programming can be adapted to the actual conditions by importing the respective commissioning files from the machine. This adaptation is sometimes offered as a service of the machine manufacturer.

Training

Because a PC can have the same software as the CNC machine, a PC is ideally suited for education and training Programming and program testing are exactly the same as at the machine. This gives the trainee confidence for later working on the machine. PC programming is also well suited for programming training in schools and job training.

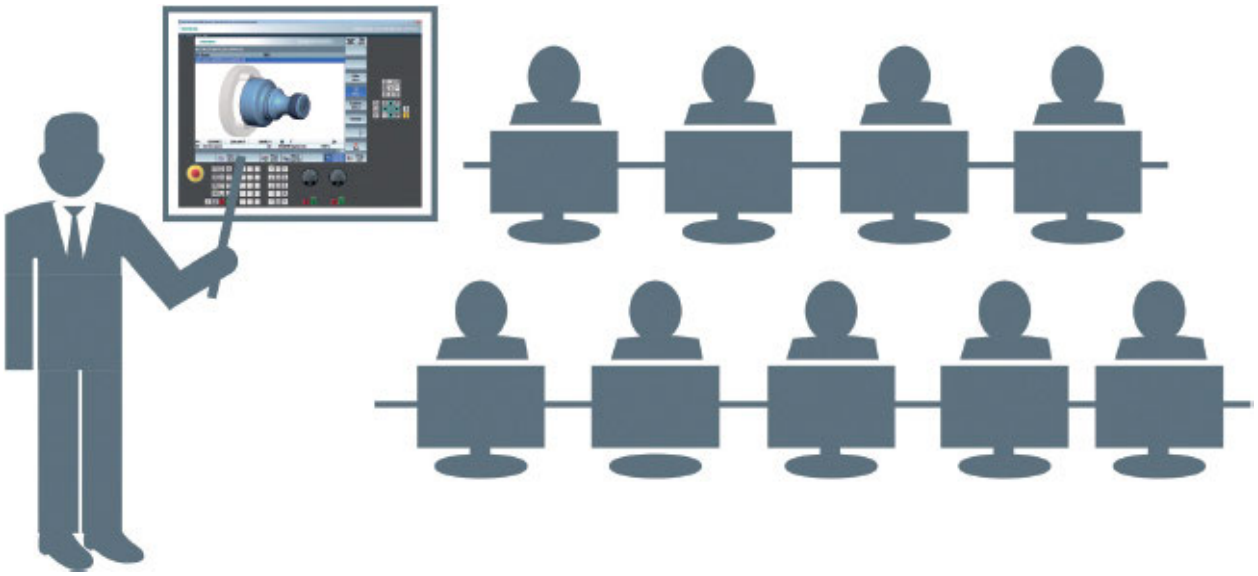

FIGURE 25.15 Programming training can be given in a classroom, just like in front of an actual machine, except that on a programming station there is no risk of a real machine collision. Siemens.)

SELECTION OF THE APPROPRIATE PROGRAMMING SYSTEM

Error-free part programs are an essential prerequisite for the profitable operation of a CNC machine. In addition, a program must be produced quickly and at low cost. The more flexible the use of a NC or CNC machine must be, the more important is powerful programming.

The decision in selecting the most suitable NC programming system on the market is difficult because each product has special benefits but requires smaller or larger tradeoffs elsewhere. The following factors can be used as a basis for decision making:

■ Workpiece:

- Part families
- Height and weight
- Degree of similarity
- Blank geometry
- Complexity of workpiece geometry
- Number of tools required

●Cost of technology research

■ Mixed NC/CNC machine park:

●Number of CNC machines

●Processing methods

●Type variety of CNC machines (machine size)

●Type variety of CNC programs

●Degree of automation

●Workpiece and tool change

■ Planning indicators:

●Number of new CNC programs per week/month/year

●Number of archived programs

●Degree of repetition

●Lot size

■ Organizational questions:

●Available computers

●New computers to be installed

●Existing or planned data network

●DNC system

●CAD/CAM coupling

●Personnel qualification

●CNC and programming experience

While the NC beginner usually has his or her own experience in the selection of a CNC machine, the choice of a programming system is more difficult and involves many unknowns. Some research will help to identify the best possible product. Powerful modern PC-based programming systems including the required postprocessors are well affordable and therefore must be included from the beginning in the planning and financing of NC manufacturing.

Influencing factors in favor of computer-assisted programming are:

■ High computing effort, even for simple workpiece geometries

- Extensive range of workpieces
- Complex workpiece geometries and surfaces
- Workshops with a large variety of machines and controls
- Machines with a high degree of automation
- Flexible manufacturing systems for large workpiece spectra
- Many new NC programs per year with low repetition rate
- Training for new NC programmers

All vendors of programming systems are convinced that their system is the best for every application. Buyers therefore must investigate on the basis of pertinent criteria which system should be preferred. A benefit analysis is in order to compare the buyer's requirements with the performance characteristics of each system, for each user has its own set of priorities. Also, a visit to one or more users of the envisioned system can be of great value to obtain the latest information in terms of handling, assessment, satisfaction, and service. These factors cannot so much be expressed in numbers but in costs.

The following features warrant a closer look:

■ Computer hardware and the operating system

■ Existing data interfaces with DNC and CAD systems

■ Geometric performance of simple and more complicated workpiece geometries, different dimensions, and so on

■ Subsequent correction options for geometry and technology

■ Technological performance in the selection of tools, cutting data, machining sequences, and cycle call-up

■ The graphic-dynamic simulation with collision monitoring between tools and machine, clamping device, and workpiece

■ The universality, meaning programming different machine types with two to five NC axes, 3D operation, lathes with live tools, and the existing postprocessors (if required)

■ Programming convenience, including user friendliness and displays

■ Included training, documentation, and start-up assistance

■ Introductory and operating expenses

- Planned future developments

- Degree of familiarity and dissemination at home and abroad

The answers to these criteria will give a good indication of whether the right system will be selected. Commitments of sales representatives for the purchase of a system should be given in writing. Most important, the programmer, that is, the person who will work on the system, should be involved in the acquisition. It is also an option to acquire different software packages for individual processes, but this comes with higher costs and additional problems.

SUMMARY

NC programming has a decisive influence on the profitability of NC production. Therefore, selection of the programming system and staff training must be done with at least the same care as machine procurement. In the later daily operation, it will quickly become evident that it is not sufficient to get a NC machine "started."

With few exceptions, such as gear-hobbing machines or tube-bending machines, which can be programmed by entering only a few values for several hours of operation, computer-aided programming systems are preferred. They save the NC programmer a lot of computational work, allow a dynamic program test on the screen, and generate an error-free NC programs in a short time. In addition, the saved source program can be transferred quickly and easily to a replacement machine in an emergency.

Efficient programming systems are essential for complicated workpiece shapes and surfaces, for large, expensive, and complex machines, and for expensive workpieces. These systems, however, do not replace the sound and thorough training of the programmer. According to the principle of distributed intelligence, programmers, programming system, and CNC machine must have sufficient power. Selection of the programming system essentially depends on the software that is suitable, available, and as universal as possible for the application. Special solutions should

be avoided because experience shows that sooner or later they lead to unsolvable problems.

The use of two or more programming systems can be called for and be economical in one case or another. This also applies to the use of manual-input CNC machines in combination with a central programming department. Both can complement each other very well in everyday life. The most important requirement is to be able to use the productivity and flexibility of the NC machines through trouble-free programming.

IMPORTANT POINTS TO REMEMBER

1. NC programming generally means the creation of control information for machining workpieces on CNC machines.

2. Manual programming means the writing and saving of a part program in block format according to DIN 66025/ISO 6938 for a specific CNC machine. Here the programmer must determine the required tool movements step by step.

3. Manual programming requires knowledge of mathematics and trigonometry and takes a lot of time for secondary calculations. Programming errors are only detected on the machine.

4. In addition to the geometric data, the programmer must also determine and enter the technological data: speeds, feed rates, depth of cuts, corrections, and so on.

5. Computer-assisted programming is the creation of an NC part program with a computer and NC programming software. The initial output is the generally valid output format, the CLDATA file. Its adaptation to a specific machine/CNC combination is carried out by the postprocessor.

6. For graphically supported programming, the workpiece to be machined and the blank are programmed. The required tool order,

the technological values, and the machine movements are determined by the computer program largely automatically.

7. Modern optimized cutting strategies are available that are easy on machine and tools and are still more economical.

8. These include trochoidal milling, plunching when milling, and dynamic retraction and extension when turning.

9. Workshop programming can be carried out on the CNC-integrated programming system or in the office on a PC.

10. The most important goal of NC programming is to create immediately executable error-free programs that produce the desired workpiece without lengthy trial runs and program corrections. Time optimization comes next in case large quantities must be produced.

11. The productivity of any NC manufacturing depends to a large extent on the quality of the programming. The more powerful the programming system, the faster error-free programs are available on the machine.

12. NC programming should not be understood as the tedious, lengthy, and error-prone solving of complicated trigonometric computing tasks but the simple systematic description of the workpiece in an interactive dialog. The generated program should be immediately controlled on the graphic display.

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INTRODUCTION

The requirements for NC programming are subject to the demanding requirements of the manufacturing industry and are therefore subject to constant change High product diversity and always decreasing product lifecycles are the new normal. It so happens that ever more complex workpieces must be manufactured with ever smaller lot sizes. For this reason, computerized numerical control (CNC) machine tools are becoming ever more powerful and multifunctional. The required flexibility is reflected in an increased installation of "almost universal" processing systems. As a result, the demand for computer-aided manufacturing (CAM) systems has risen enormously in recent years. It is becoming increasingly important that the sometimes very diverse and numerous processing methods of complete machining can be handled with the same CAM system.

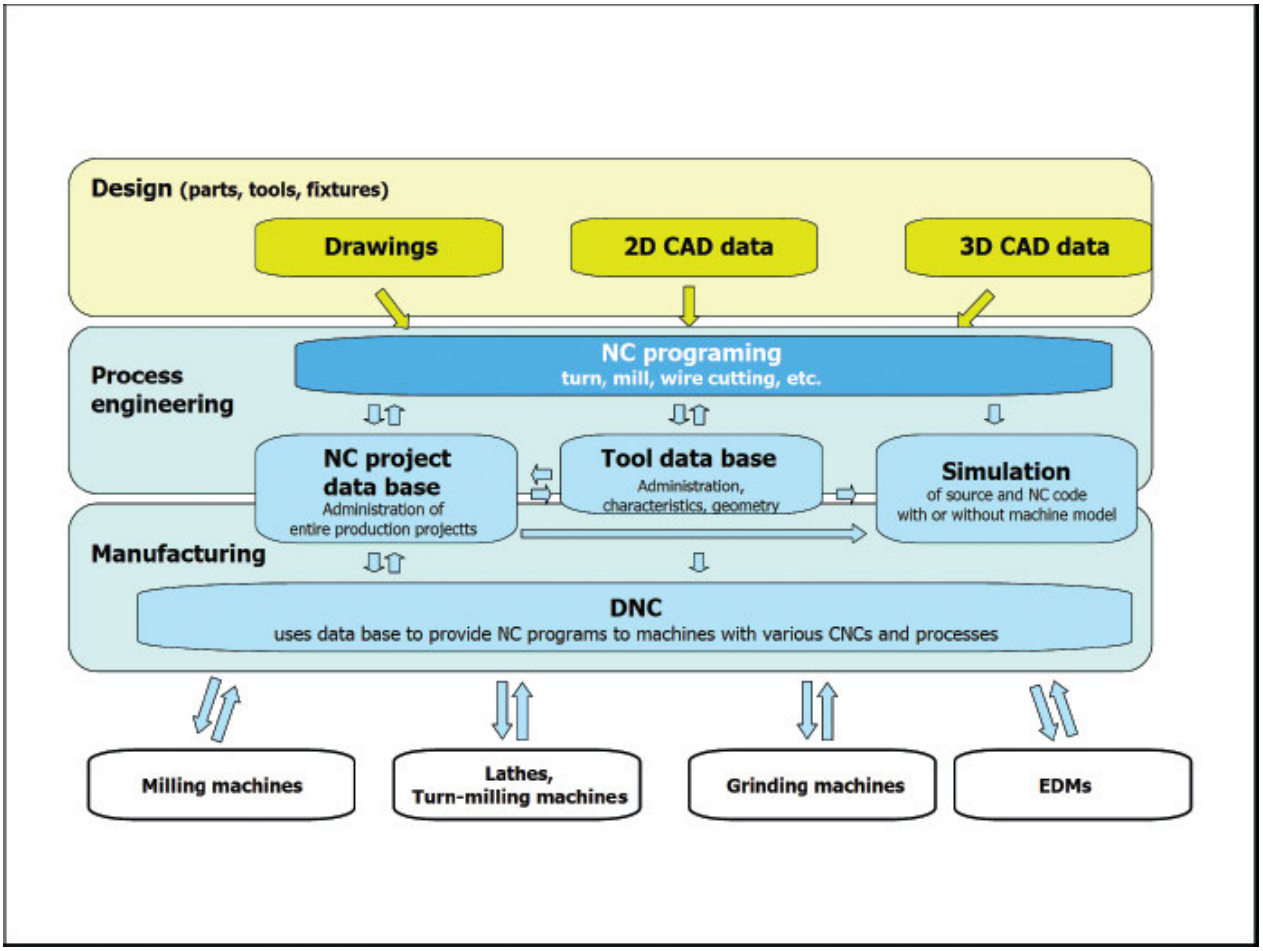

FIGURE 26.1 Overview of software modules and interfaces between design and fabrication.

CHANGING MACHINING PROCESSES

The various machining processes such as turning, milling, sawing, flame cutting, grinding, eroding, and metal stamping and the various materials such as metals, plastic, wood, glass, and stone all require specific machining strategies.

FIGURE 26.2 Computer-controlled stone saw with a saw blade diameter of 1.5 m. Robert Schlatter Company.)

Modern lathes have expanded to be universal machines and thus are also able to do drilling and milling operations. Equally, milling machines are built to perform turning jobs; these are called

multitasking Such universal CNC machines for combined machining operations are increasingly being used to achieve higher accuracies and shorter machining times. However, such machines also have higher programming requirements. Modern NC programming systems must fully master the changes between different processing methods. Users demand to program all processes in any mix of parts with the same programming system and the same user interface 26.3 and

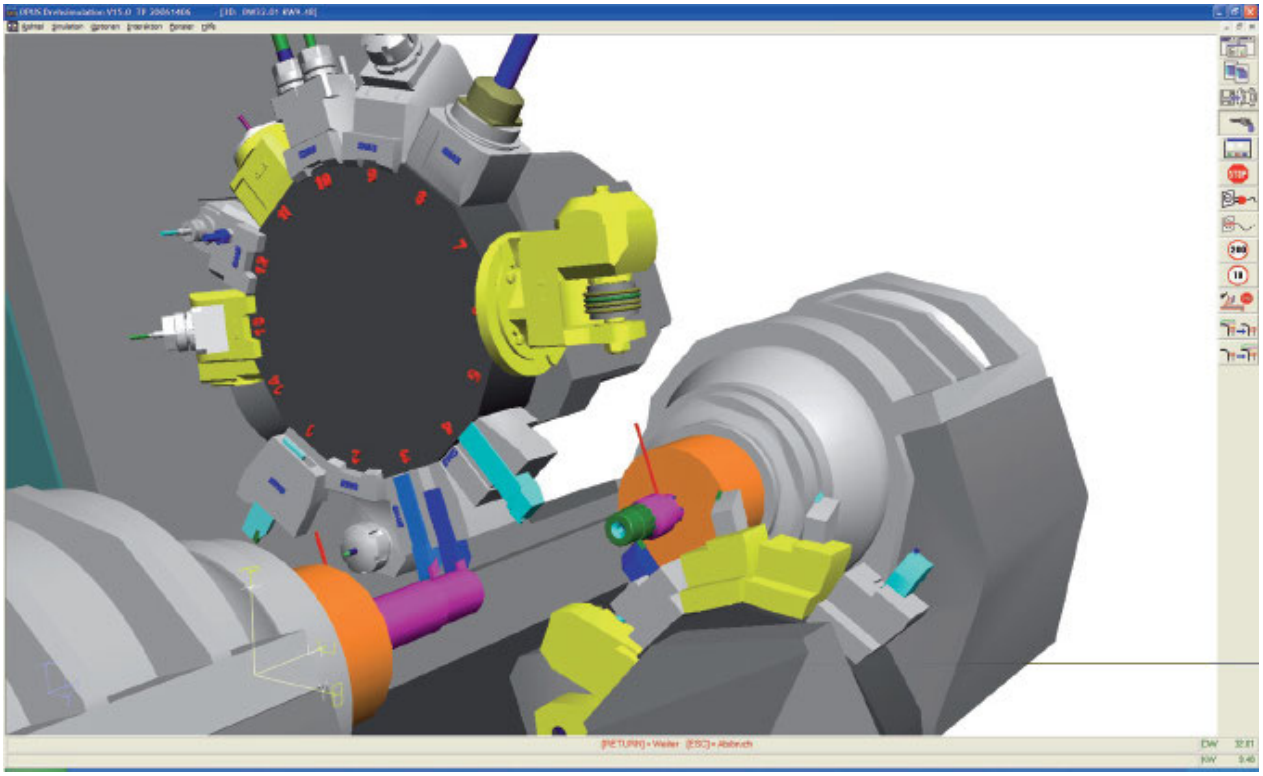

FIGURE 26.3 Simulation of an INDEX lathe-mill center.

FIGURE 26.4 Lathe-milling machine or mill-lathe. Mori Seiki.)

The trend toward process combinations continues with the addition of 3D free-form surface processing and 2½D milling/drilling operations. In the future, pure 3D processing will no longer be acceptable. There is increasing demand to perform mixed programming for both requirements on one system alone 26.5_and

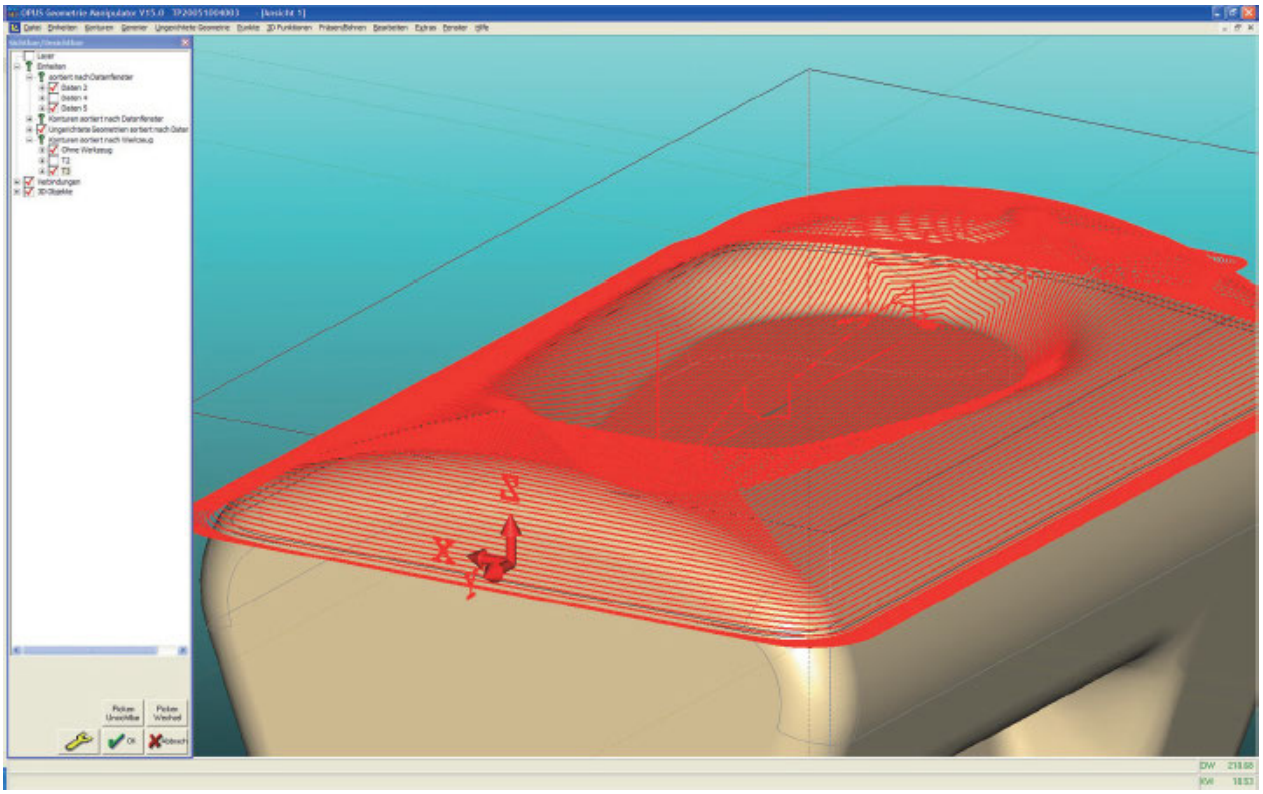

FIGURE 26.5 Picture of a free-form surface for 3D processing. The geometry is created by simultaneous movement of all axes.

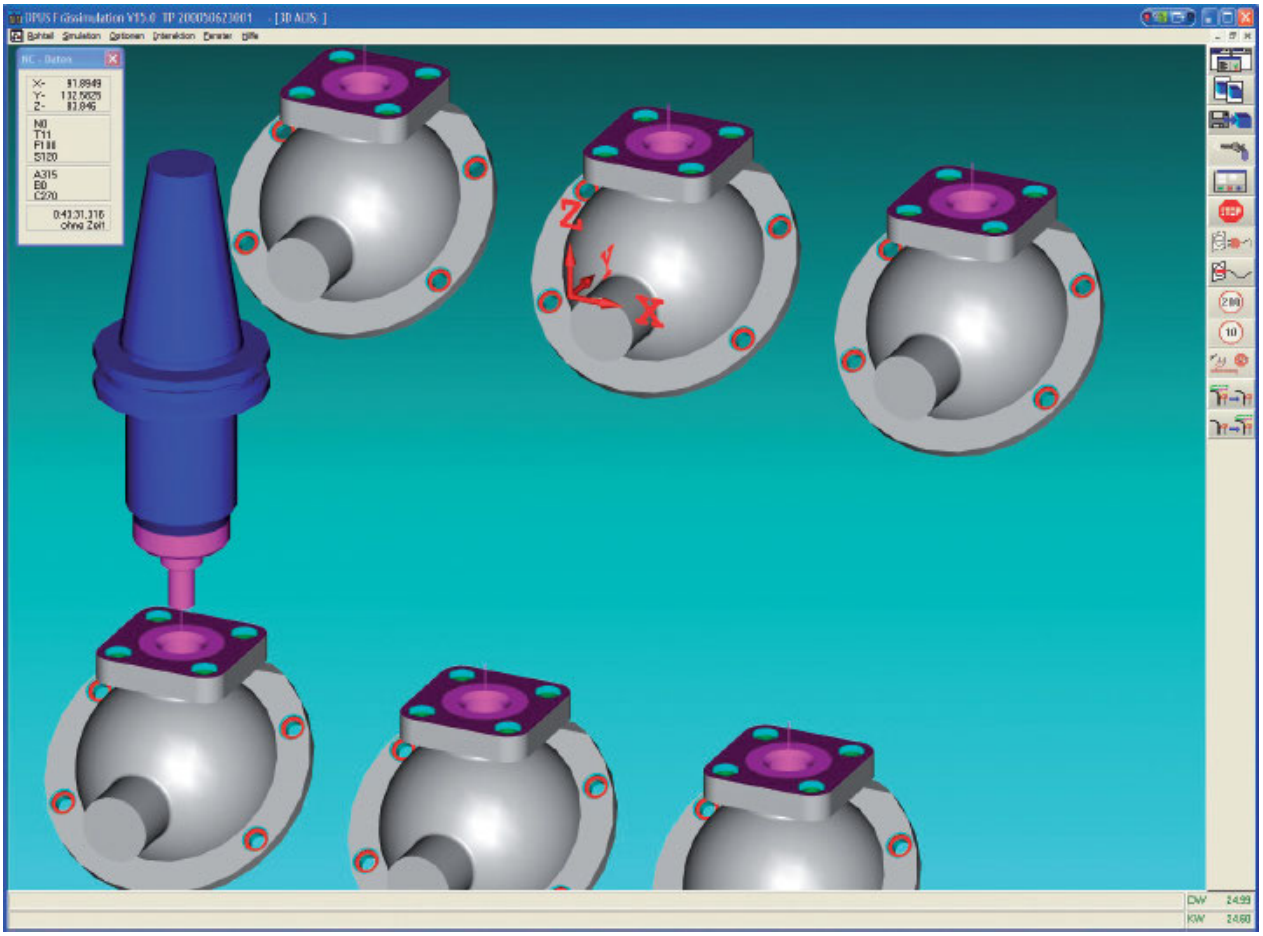

FIGURE 26.6 2½D processing. Forming tool creates the geometry by movement of the

AREA OF APPLICATION SETS THE PRIORITIES

A closer look at the areas of prototyping or single-part production, small-series production, and the actual production reveals the need for adaptability. Completely different demands are placed on both the programming system and the NC programs generated. It is characteristic of prototyping to create a reliable, collision-free program, to do so quickly, and to be able to make quick changes. The program should be implemented on the machine quickly, yet optimization of the process time is rather secondary here. Process time is not of the essence for prototypes or in small-batch production. Because several new parts/NC programs might be processed within one day, it matters more that they are created quickly and free of errors. Here the greatest savings can be realized by avoiding wait times for new programs. Part of the program should be a graphic-dynamic simulation to ensure that the program is error free and that collisions involving the machine/tool/workpiece can be excluded.

In single-part production, the blank is often very expensive, and a replacement is not an option. Therefore, *zero-error processing* is required when entering new programs

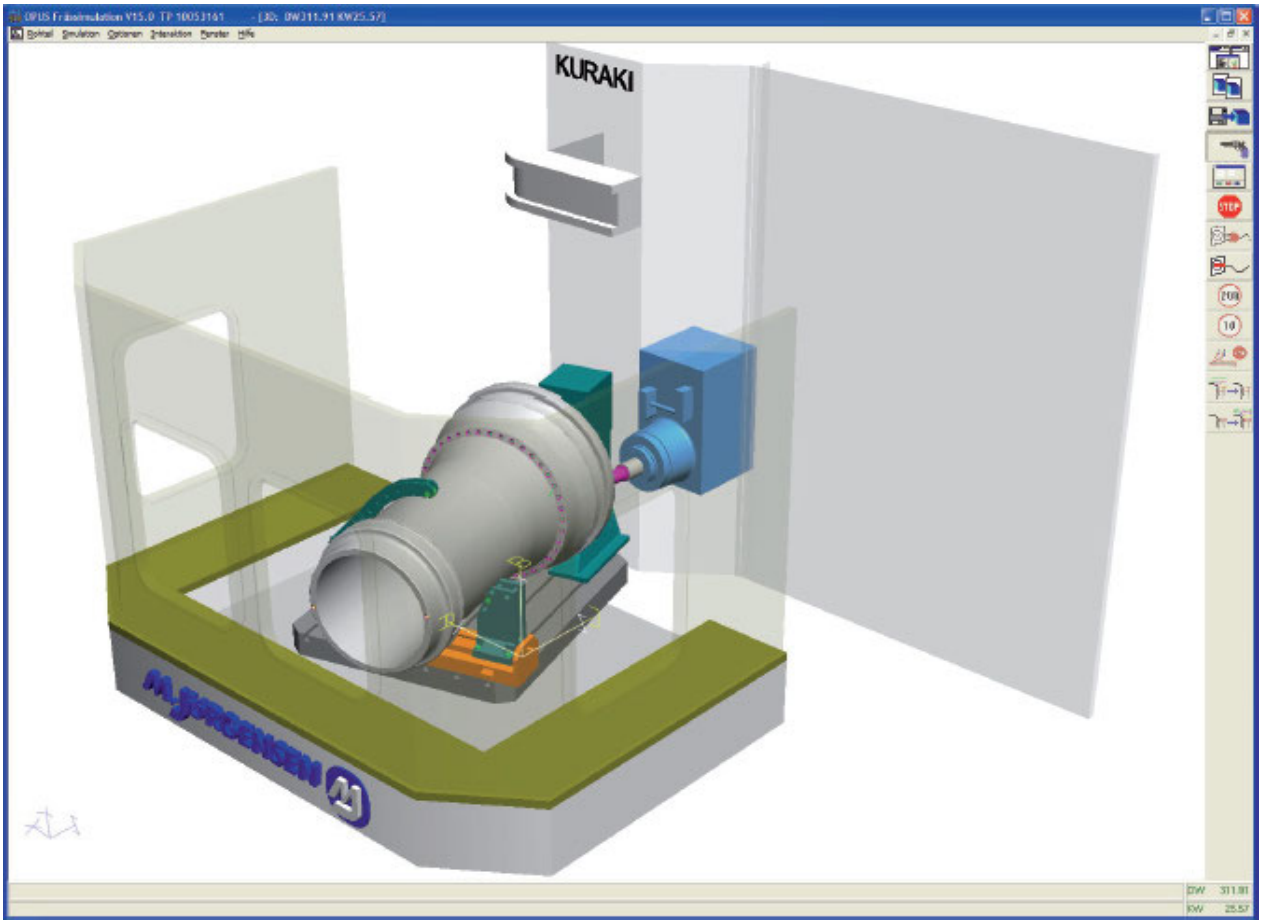

FIGURE 26.7 Cylinder liner, length about 1.5 m, an example of a very expensive blank in single-part fabrication.

The situation is completely different when it comes to series production. Here the main focus is the actual processing time. The time spent for planning and programming is distributed over many parts that are produced and is rather secondary. In series production, optimization of the process is measured in fractions of a second. Savings can be found in optimizing tools and the sequence of operations and use of multiclamping fixtures. No less important are machine-specific optimized postprocessors that use, for example, machining cycles stored in the CNC program. In addition, the risk of collision must be reliably avoided by means of qualified simulations. Otherwise, the unproductive setup times will be prolonged because of excessive precautionary measures taken by the operator.

INPUT DATA FROM DIFFERENT SOURCES

The demands on NC programming systems resulted in a range of input options becoming available. Initially, these systems consisted solely of the pure geometry data of the part that had to be manufactured. By now, 3D tool and clamping device data and technology-specific data of the individual processing methods have been added. Thus 3D models, or 2D data for lathe operations, have become standard with various interface formats, mostly DXF for 2D or .jt for 3D STEP. In addition, data are available for existing tools, machine simulations, knowledge-based technology, and more recently, feature information. Often, however, hard copies of the old-fashioned blueprint or a PDF is still the leading and binding document.

SCOPE OF A MODERN COMPUTERAIDED PROGRAMMING (CAP) SYSTEM

The tasks of an NC programming system lie in the efficient support of the programmer and exceed by far the actual creation of an NC program. They relate both to the handling of the geometry data for the part that must be manufactured, the handling of tools, and their provision in the data pool. A data model must be created with intrinsic functions that can serve as a clear basis for the automatic generation of suitable processing strategies. Part of this is provision of the associated technology data, such as the relevant tool, feed, speed, cutting speed, cutting depth, and so on. The machining strategies can be verified and optimized with the use of appropriate simulation tools.

Despite all the automatic features that provide significant time savings on routine tasks, it is also important to ensure that the system has an open structure and an editor for NC programs. This kind of system concept provides the NC programmer, the production-planning department, and others with the opportunity to customize the system and use it accordingly. This brief description of the range of functions of NC programming systems makes it evident that today's high-performance CAM systems indeed must meet very demanding requirements.

HIGH-LEVEL DATA MODELS

The programming system must check the imported geometric 2D or 3D CAD data for completeness and consistency and bring them to a uniform "level" in order to obtain a precise data model in the system. If the design drawing is available on paper, the system must have a 2D design tool so that the user can transfer the information on the drawing to an internal 2D form.

For the automatic transfer of 2D or 3D CAD data in various formats, such as STEP, .jt, Initial Graphics Exchange Specification (IGES), and some CAD-specific formats, it is important to be able to read these formats and convert them into the internal format. CAD drawings contain large amounts of data that are completely irrelevant to programming. These include, among others, hatching, drawing frames, text, dimension lines, and so on. It is beneficial to use an integrated data filter to select the right elements while the data are being acquired to avoid extra work. Once this has been done, the geometry can be processed further in a uniform manner.

CAM-ORIENTED GEOMETRY MANIPULATION

If individual lines, circles, and circle segments are completely sufficient to depict a drawing, contiguous contour segments are absolutely necessary for processing it into an NC program. Because data that have been transferred are often not of sufficient quality, the CAP system has to be able to sort the data, correct them, and place them in the correct contour associations. This may include:

- Extending or trimming contour elements
- Simplifying contours
- Splitting, connecting, and cutting
- Inserting and changing radii, chamfers, and recesses
- Shifting, rotating, stretching, copying, and mirroring
- Generating equidistant contours

It is also necessary to be able to correct elements whose tolerances are not centered, taking the connecting elements into account. In any case, it is essential to provide the system with information about the height of the body involved and the depth of any recess. If this cannot be done using the geometry data,

then it must be done later via the depth setting of the tools. This is the more cumbersome option.

The design orientation very seldom corresponds to the orientation in the NC programming or on the machine. This necessitates aligning the geometries in space in a simple manner. It must be possible to associate different sides with different zero points on the machine.

If a 3D model of a workpiece is available, a modern programming system can use it to generate a 2½D program. Based on the precise 3D data in the system, it is possible to derive 2D geometries such as planes, cylindrical surfaces, sections through volumes, and projections of surfaces as a contour with supplementary information about the position in space. If no CAD data are available, the programmer must be able to generate the entire geometry necessary to create the program using the functions available in the CAP system without any help from a CAD system.

Complex workpieces contain such a large amount of geometry data that in some cases it is hard for the programmer to maintain a clear overview. It is therefore absolutely essential to support the programmer by means of suitable tools and management functions. It is especially useful to use color, transparency, line type and size, and special edge depiction to highlight elements, contours, solids, and surfaces. It is also advisable to assign names and layers, as well as ways to conveniently show and hide relevant and irrelevant objects. One

excellent method, for example, is to automatically hide surfaces that have already been processed.

HIGH-PERFORMANCE MACHINING STRATEGIES ARE PARAMOUNT

The truly supreme aspect of a CAP system is generation of the machining strategy. This strategy consists of the geometric data of the part that must be produced, the suitable tools, associated technology data, and the individual machining steps. These typical machining operations make use of standard, canned strategies:

■ Milling:

- Cutting contours/contour areas, etc.
- Broaching of recesses with and without islands
- Thread milling
- Slot milling
- Engraving
- Drilling cycles

■ Turning:

- Rough machining
- Roughing with several passes

- Finishing

- Recessing

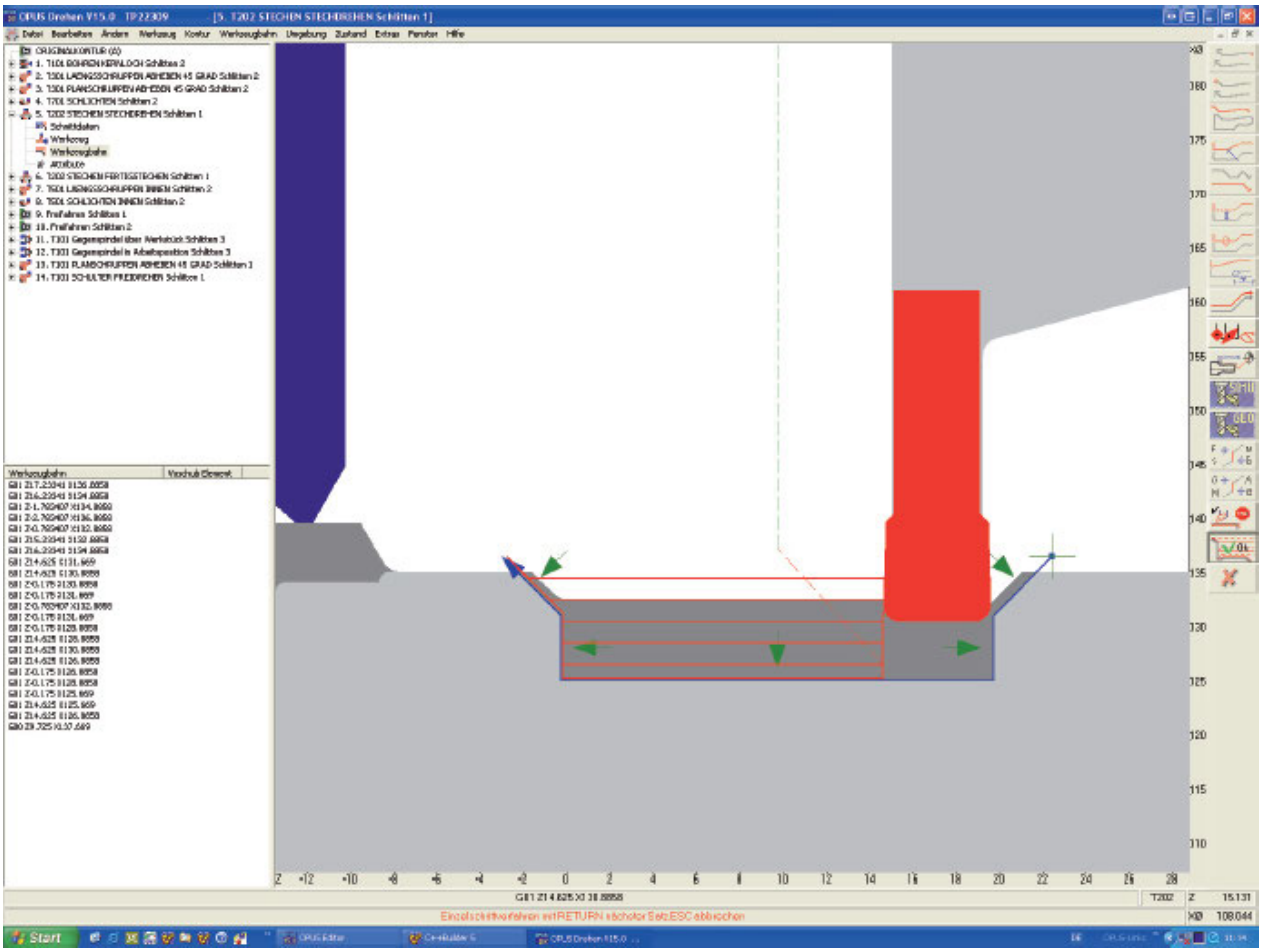

FIGURE 26.8 Path calculation for grooving operation.

These strategies can be automatically generated with a push of a button

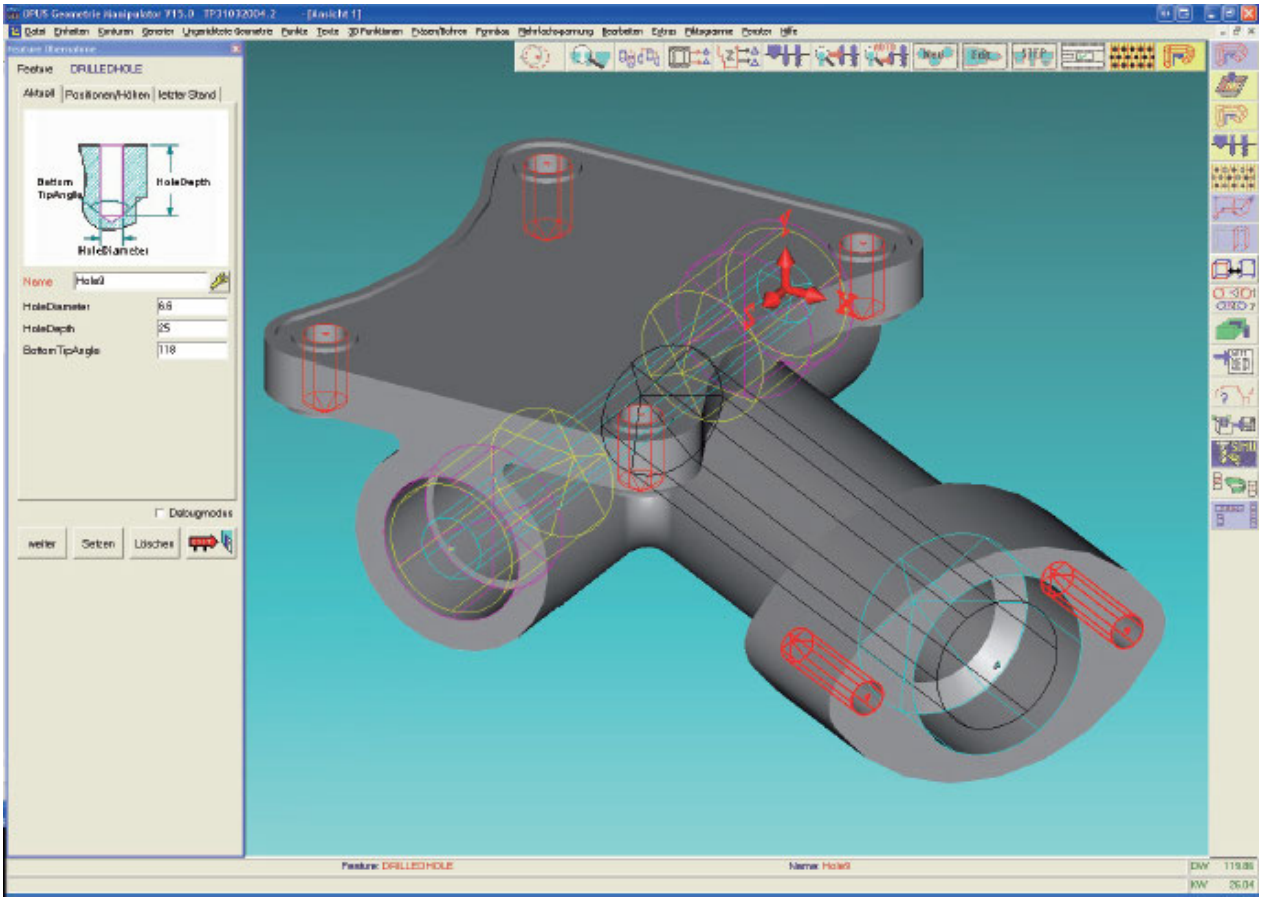

FIGURE 26.9 Model transferred from CAD to CAM; automatic generation of work processes.

Yet a CAM system must master the following challenges:

■ To provide the user with a configurable application-specific standard

■ To integrate nonstandard and new tools, technologies, and parameters

■ To incorporate user-specific requests into the system, such as tool catalogs or special knowledge-based databases

■ To transfer existing machining strategies to other geometries

■ To create a direct association between the geometry and the machining so that in the event of a geometry change, the change is made automatically in the corresponding machining operations

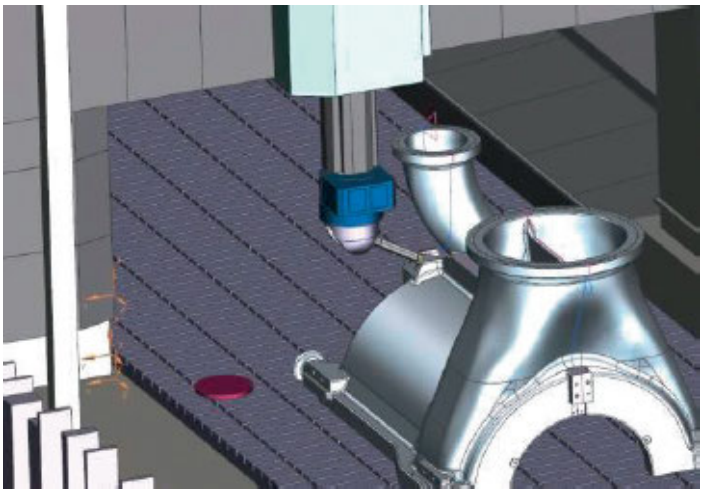

FIGURE 26.10 CMM measurements will be fed in for subsequent machining operations.

ADAPTIVE PROCESSING

For large, complex and thus expensive workpieces, such as castings, it is often useful to carry out the machining with a calculated allowance. After the initial machining, the part is measured, and the final cuts are made. This strategy can be controlled in a powerful CAM system by the postprocessor and stored in the NC program. The same applies to repair and maintenance jobs of complex parts, such as a fan blade of a turbine.

3D MODELS OFFER MORE

Modern CAD/CAM systems can use 3D model data directly to generate 2½D programs. Transferring model data from various CAD systems has become standard. Previously, the interfaces often presented a problem in terms of consistency and completeness of the data. Today, some interfaces are even capable of detecting errors in the consistency of the original model and may be able to repair them. As with drawings, good appearance does not suffice. The model has to be logically correct; for instance, there cannot be any gaps in its edges. In addition to these automatic correction steps, the user also must have an option for manual simplification of the model. In the simplest case, this can involve hiding holes, chamfers, and recesses so as to generate a suitable model of the unmachined part. It is important for the programmer to use the CAM system to make production-specific changes. Now, as it will be in the future, any direct design-related changes must only be performed by the design engineer. This position holds the power and responsibility over the product design.

Integrated CAD/CAM systems offer a great deal of time savings and higher security when it comes to changes. Design changes are recognized by NC programming, and the programmer will implement these changes in the program. Additionally, repeated data transfer (including the data check) is not necessary. The 3D basis can be used to derive the appropriate edges and surfaces for up to five motion paths thus unambiguously defining the positions and perpendiculars.

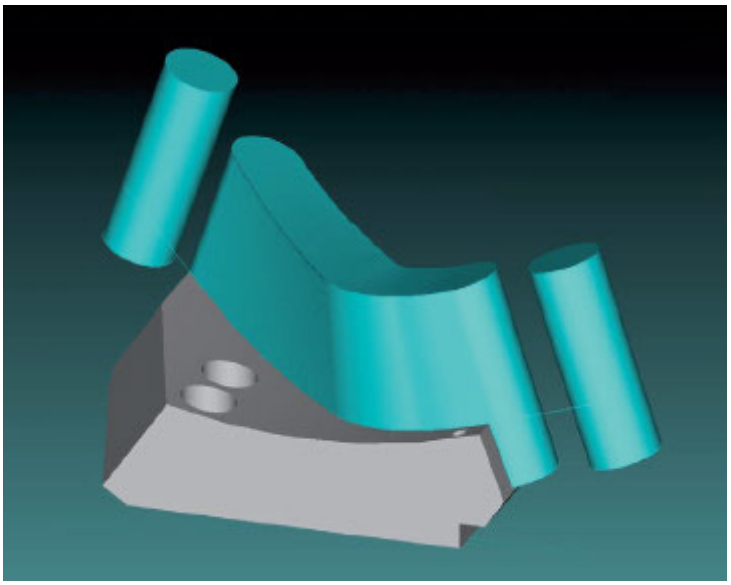

FIGURE 26.11 Five-axis path derived from surfaces and edges.

3D INTERFACES

In addition to the well-known Standard for the Exchange of Product Model Data (STEP), the JT format has emerged as a very suitable neutral 3D representation. In many industries, including in the automotive industry, it has already established itself as a quasi-standard. The JT format was originally developed for the rapid display of 3D CAD data. Today the format is used for data transmission between CAD and CAM systems because of its exact B-rep representation and the transfer of all relevant production manufacturing information such as dimensions, tolerances, surface qualities, fits, and attributes. The JT format was first officially published in December 2012 as an international industry standard (JT ISO Version 1.0, ISO 14306); it also meets the requirements for long-term archiving. More information about JT is available at:

1. ISO/DIS 14306 at www.iso.org

2. jtopen.com

3. Free JT viewer at www.jt2go.com

VDAFS and IGES are also used as 3D standards, although their use is much less common than STEP and JT.

Integrated CAD/CAM systems do not require any interfaces and therefore offer considerable time advantages and greater security, especially in the case of changes. CAD design changes are

automatically detected and marked in the NC program, allowing the programmer to focus on those changes.

INNOVATION WITH FEATURE TECHNOLOGY

Features are informational elements that represent areas of particular (technical) interest in individual or multiple products. If the 3D CAD system in use is capable of attaching expanded information to geometric elements, called product manufacturing information (PMI), the system can use this information to derive all the required tools and machining sequences. It should be noted here that only geometric and design-related information is needed in the 3D model.

Some systems try to achieve automatic program generation by attaching tool and technology information to CAD objects. Yet the developer must concentrate on his or her core competency—design engineering—and must not be distracted by production-related issues. Also, at this stage, it typically has not been determined where and with which tools the part will be manufactured. Therefore, there must be a clear separation between geometry and technology

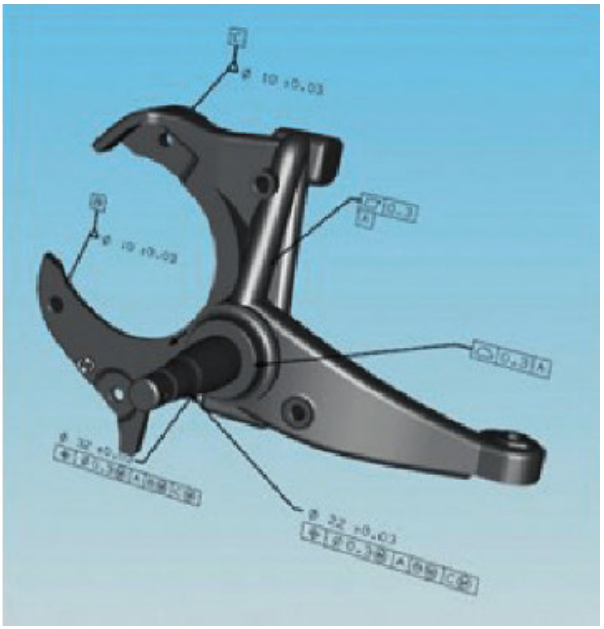

FIGURE 26.12 3D model with PMI in a CAD system (NX). Same data as a JT model, displayed in the JT2Go viewer.

It becomes obvious here that model generation has to take into account more than just appearance. Information about tolerances, threads, surface quality, and much more has to be linked to the model in a consistent, logical manner

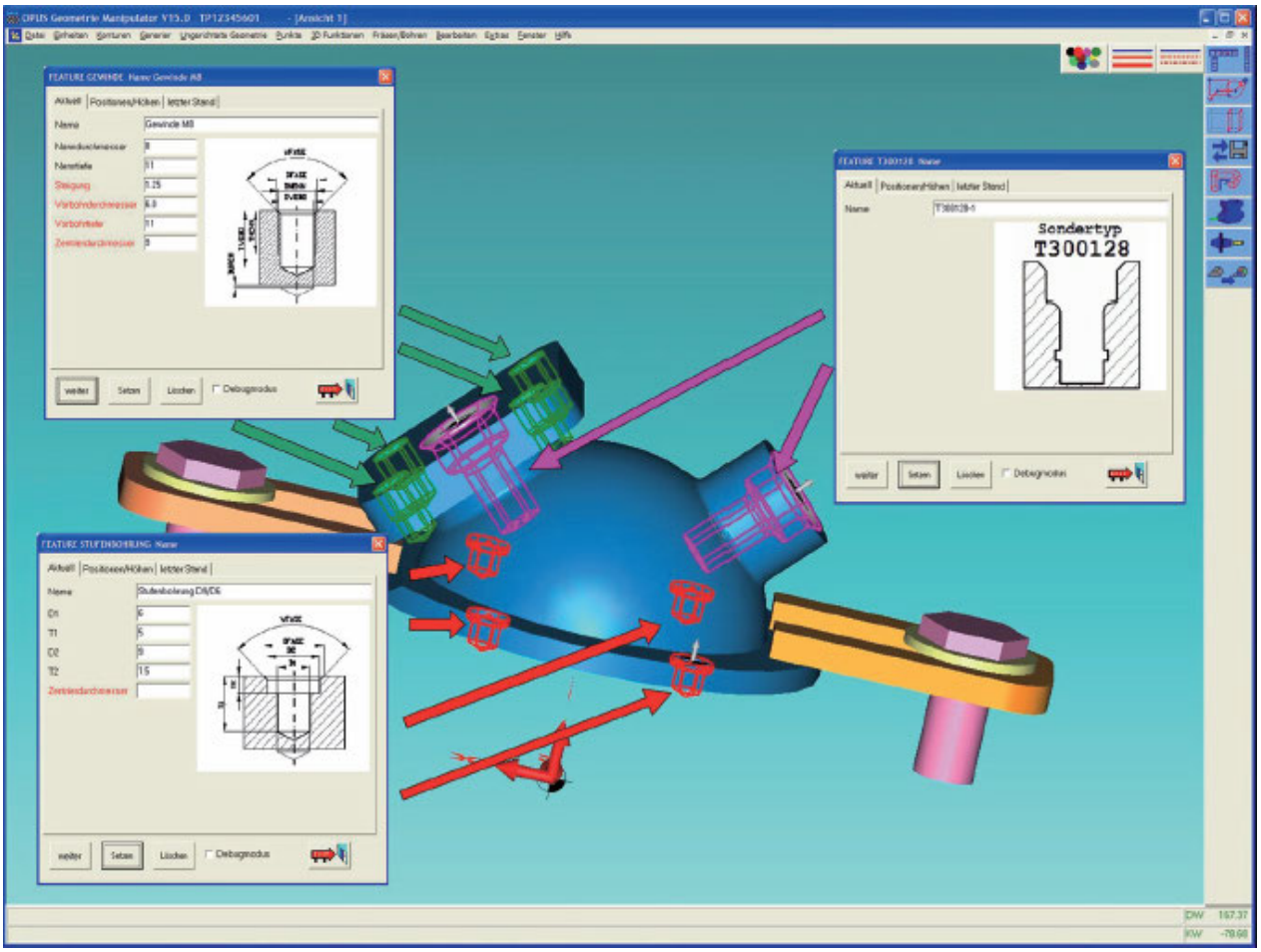

FIGURE 26.13 Part with recognized features, among others, a special hole applied with a custom tool.

AUTOMATION OF NC PROGRAMMING

It has been said that "[t]he 3D model is increasingly establishing itself as an information carrier for the entire CAD/CAM process," as quoted from "Introduction of a CAM System in the Company," VDMA. Production wants to extract as much information as possible directly from the 3D model. This includes geometric information, as mentioned earlier, dimensions, tolerances, and so on. In addition, process information is becoming increasingly important 26.14 and

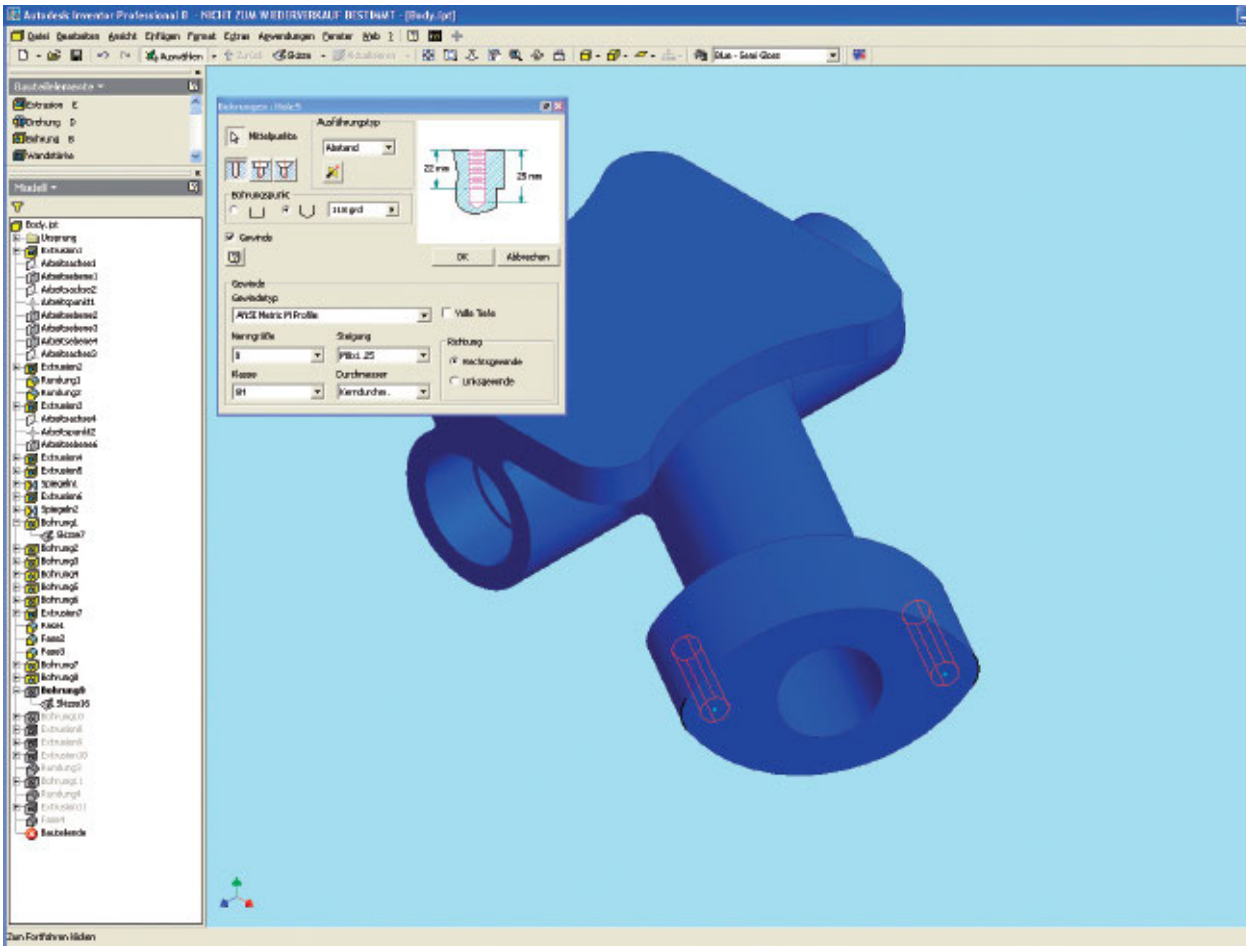

FIGURE 26.14 Features in a CAD system. Autodesk Inventor.)

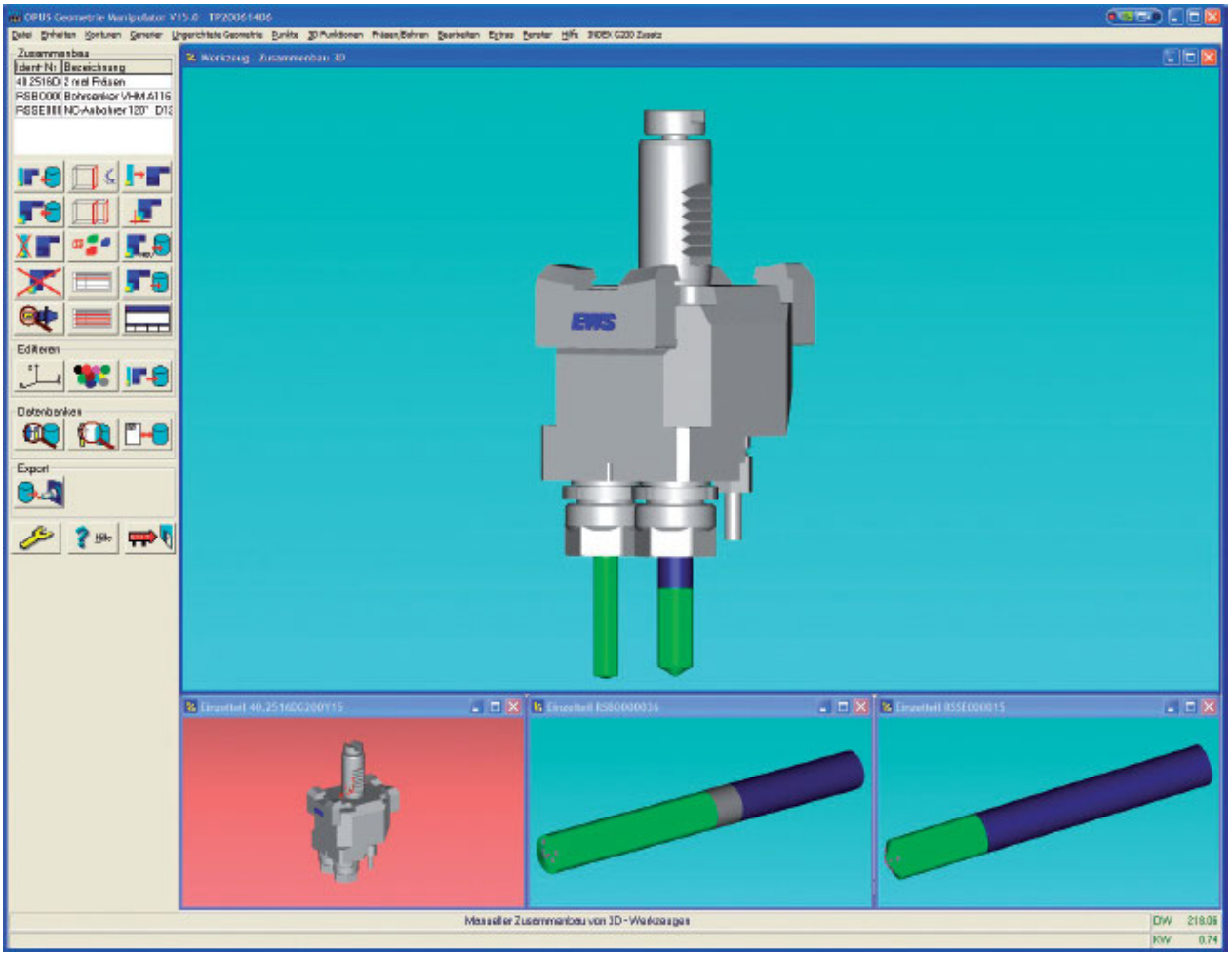

FIGURE 26.15 Custom tool for turn milling center: components and assembled tool. EMS Tool Technologies.)

In this context, production knowledge means the skill and experience of production processes that are expressed in work plans crafted with a CAM system. As the complexity of manufacturing processes increases, this knowledge can be of great value and provides a competitive advantage; it should be treated and protected accordingly.

The effective application of this knowledge can only be realized through active management, such as gathering, structuring, finding, and reusing applicable information. This can achieve the following objectives:

■ Faster creation of NC programs and all production-relevant data, such as setup sheets, etc., through automation

■ Secure programs through the use of established processes

■ Cost advantages through standardization (e.g., fewer tools are needed)

■ Optimized machine run times and longer tool life because the manufacturing know-how of the machine operator is incorporated into the rules and can be used by all others

Reuse of Knowledge

A systematic approach is essential to obtain the maximum increase in effectiveness. This generally pertains to the following:

1. Analysis of parts spectrum and NC programs

2. Analysis of production types, frequency, and required times

3. Standardization of program components for recurrent features based on expert knowledge in the company

4. Implementation of the rules of the programming system

Several possible solutions are available to implement point 4, where a higher degree of automation usually entails a higher implementation effort.

Manual Assignment of Production Sequences to the Form Elements
In this case, the programmer assigns the already defined production sequences to form elements. This requires the setup of an appropriate library in which the production sequences are given different attributes, such as material, technology, and so on, so that they can be found quickly.

Automatic Component Analysis and Rule-Based Assignment of Production Sequences

"Contrary to the manual assignment of production sequences as described in the paragraph above, the assignment of the production sequences can also be done automatically. In a first step, the component is analyzed for production-relevant form elements. Typical form elements are holes of all kinds, pockets, cut-outs, undercuts, etc. In a second step, the automatic assignment of the production sequences takes place. For this purpose, freely definable rules are typically used, which are stored in the library." Quote from VDMA, Germany: "Introduction of a Future-Proof CAM System in an Enterprise."

Finally, the NC blocks are generated and optimized with as few tool changes as possible, shortest traversing paths, and so on.

Introducing Manufacturing Information into the Design Process
This stage describes the design of a component with the use of a library of form elements consisting of geometries and associated manufacturing information. Thus production sequences are already innate in the component model, ensuring that a verified, optimized processing is used. Figure 26.16 illustrates that a geometric feature

can also contain manufacturing information. It allows generation of the intended processing steps automatically in the planning stage.

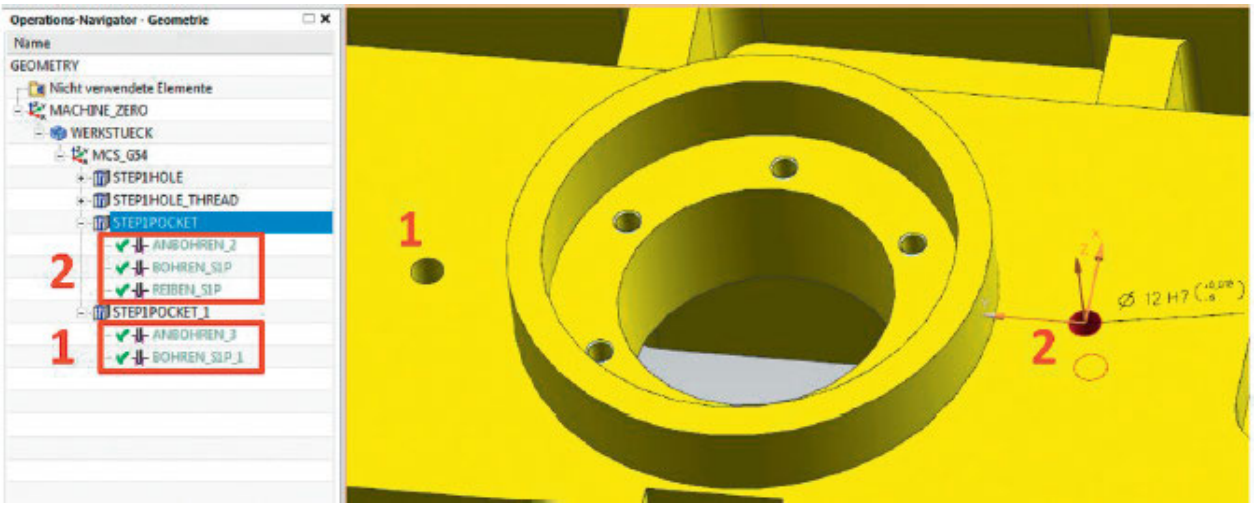

FIGURE 26.16 Automatic assignment of fabrication rules with consideration of manufacturing tolerances: (1) hole without fit specification; (2) hole with fit specification.

TOOLS

Tools are essential in this process chain. Neither automatic program generation nor quality simulations are possible without complete, consistent tool models. In manufacturing technology, tool management cannot be limited merely to the recording and saving of tool data. Both the geometric and technological characteristics have to be available in such a way that the programming system can access them automatically if needed Thus it will be possible to select the appropriate tools in conjunction with the feature information, for example, for a stepped hole. Also, fits are treated differently than regular holes (see Figure Using this method, it can be ensured that in the event of a change, say, a change from an M8 tapped hole to M10, both the machining operation and the tool selection will be reflected automatically. Entering new, technologically improved tools thus also will automatically affect future selection of the optimal tool.

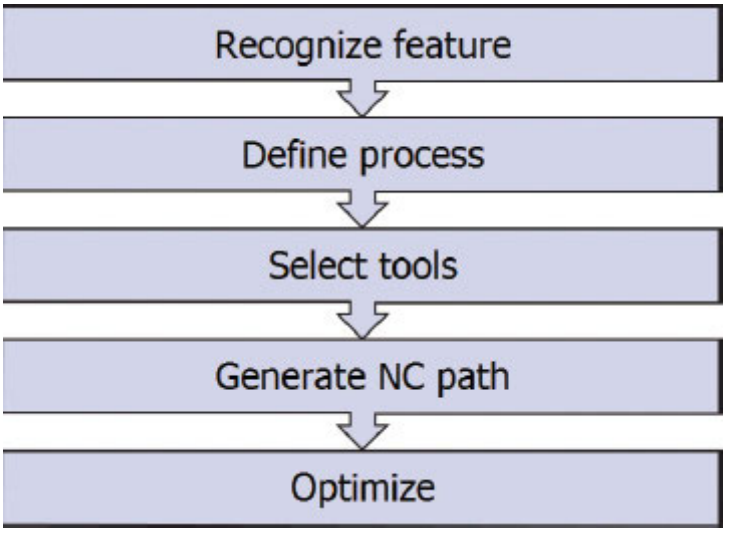

FIGURE 26.17 Internal process of a fully automated NC program generation.

CLAMPING PLANNING AND DEFINITION OF THE SEQUENCE

Once programming is complete, the programming system should be able to optimize the tool and machining sequences automatically. For example, it should compile the spot drilling operations for all the holes and optimize the newly created tool paths. This also should take into account collision geometries on the model or due to clamping operations. Evidently, the user should be able to modify the resulting sequences. All actions should be visualized immediately for maximum user friendliness 26.18 and

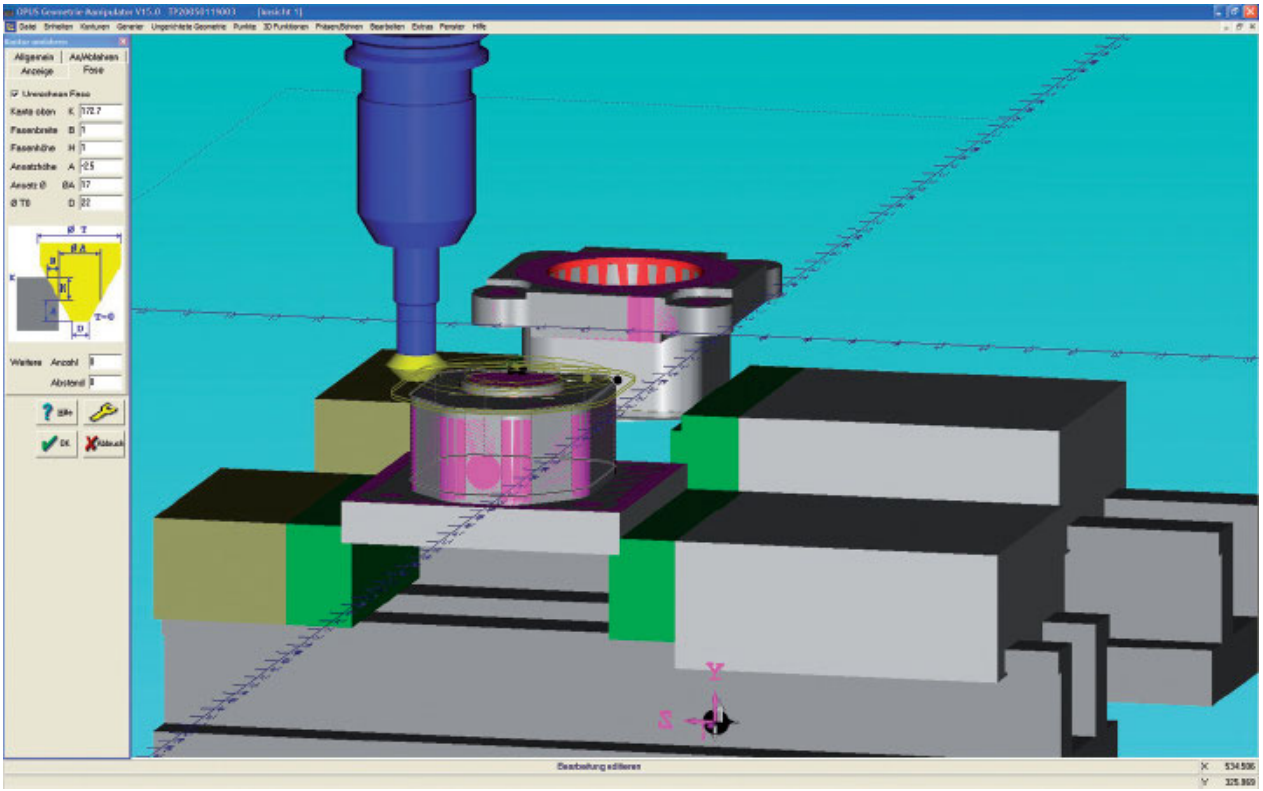

FIGURE 26.18 Setup to process the same part from two sides.

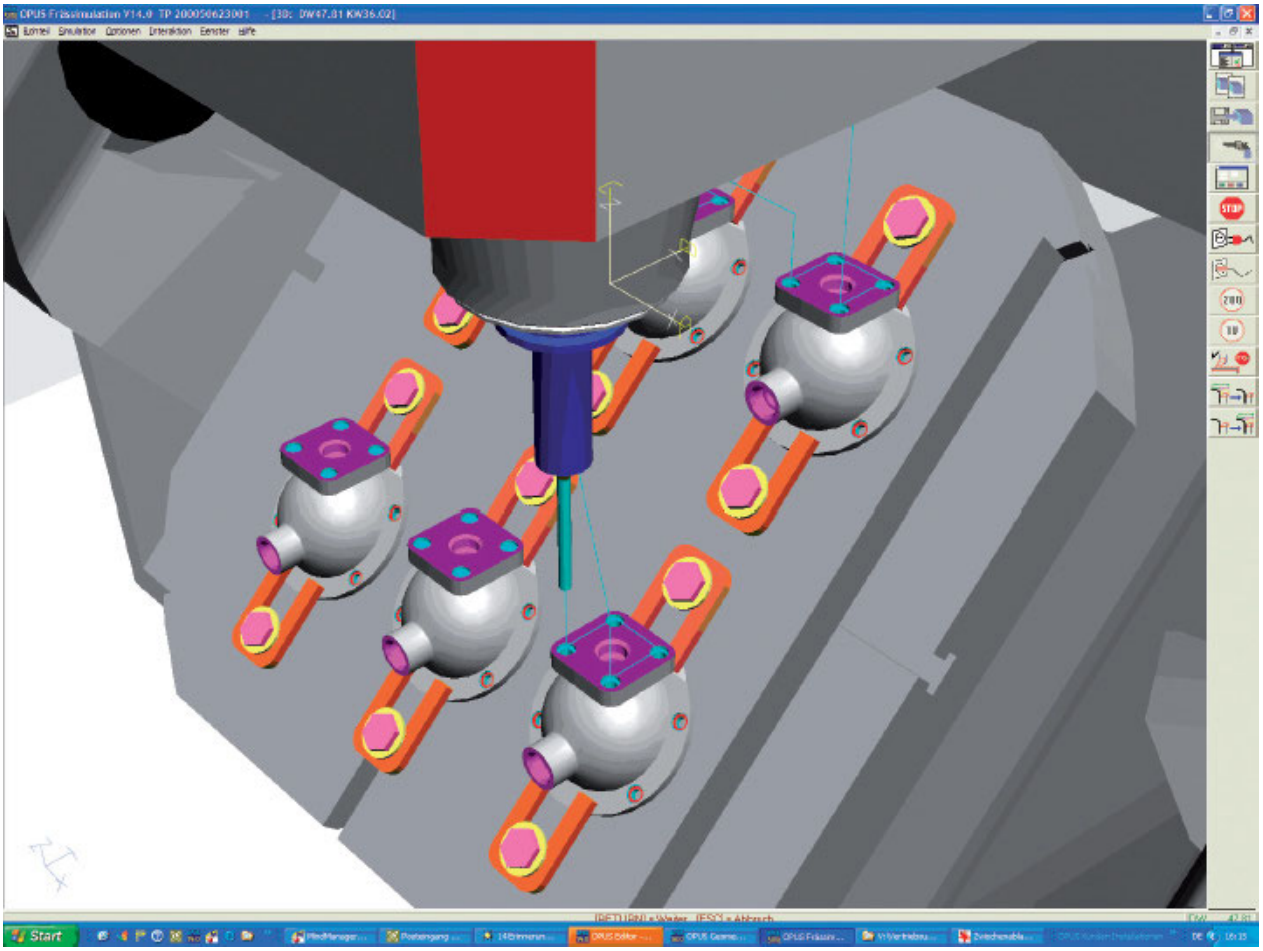

FIGURE 26.19 Simulation of a multiclamping setup.

The initial planning of the operations potentially should be independent of the machine. A part must not necessarily be manufactured in the same orientation in which it was initially programmed. Offsets and changes in position due to clamping can be taken into account automatically by the postprocessor. This means that reclamping a part in a different setup/position is very easy. In series production, multiclamping contributes to a considerable reduction of the production time per piece. The machining operations are defined for only one part and copied to the other positions that hold the same part. In this way, a number of parts are processed in various positions with the same process sequence. Here, too,

sequence optimization can play a major role and can be used to recalculate the tool sequence and processing paths in relation to the overall scenario. For traversing motions, the basic objective is to program short and quick movements. This is generally achieved by reducing the retraction distances. The principal problem here is the danger of collisions between moving machine parts and the clamped part or the clamping equipment. In series production, it is not acceptable to always pull back to a position that is safe under all conditions.

THE IMPORTANCE OF SIMULATION

Simulation in this context is becoming more and more important as an essential additional tool for NC programming. Its scope covers everything from analysis of the tool paths on the workpiece to the overall scenario on the entire machine. This should involve source code and NC code simulation, taking the specific machine model into account. One especially important aspect is the dynamic tracking of the machining progress so that the removal of material and the status of the part being machined become visible after every machining operation. This makes it possible to simulate even the most complex machining sequences after programming and to ensure that the operation will be collision free.

Therefore, before the program is transferred to the machine, a simulation of the entire process that reflects the features of the machine model as precisely as possible should be performed (see Chapter

POSTPROCESSOR

Regardless of how convenient it has been to generate the data up to this point, the CNC system must be provided with its own special NC programming code. Depending on the CNC machine type, this code deviates to a greater or lesser degree from the syntax defined by the DIN 66025/ISO 6938 standard. It is thus the task of the postprocessor, because it is part of the programming system, to convert the data that have been generated so far into the precise syntax of the specific CNC-machine combination. Well-designed systems have a modular structure, which means that the postprocessor is not buried in the general system code. Nevertheless, the system supplier also should take care of this last step because the postprocessor has a decisive influence on the overall results of programming work. At this point, it is determined whether control cycles and subprograms can be used and likewise whether full use can be made of the cutter radius and/or tool-tip compensation. Last but not least, the postprocessor is also responsible for the generation of additional data such as tool lists, clamping plans, and auxiliary programs, for example, for the tool-presetting device. It also performs preassignment of milling operations on a lathe and distribution of the overall machining tasks among a number of individual machines.

GENERATED DATA AND INTERFACES WITH THE MACHINE TOOLS

When integrating the NC programming system into the existing machinery, the user's expectations should be taken into account if at all possible. This can include a number of additional production-specific requirements:

- Assignment of NC programs to specific machines/groups
- Enabling/disabling of individual NC programs (including groups thereof)
- Returning optimized programs
- Comparing the original program with the returned one
- Recording data transmission, service interventions, and so on

To implement the range of these requirements, it is necessary to have an NC program management system that is connected via direct numerical control (DNC; see Chapter

SUMMARY

The profitability of a CNC manufacturing operation depends heavily on the performance of the NC programming system. Programming comprises not just the inputting of the workpiece dimensions but also provision of the appropriate specifications for the entire manufacturing process for each machine. All essential factors have to be taken into account. Therefore, before committing to a particular manufacturer, it is essential for the purchaser to obtain extensive information and to compare the various systems.

It necessary to take not only the various machining processes and CNC machines that have to be programmed into account but also the:

- Variety of parts with 2½D and 3D machining operations
- Qualified simulation of the finished NC program
- Options for data transfer from the CAD system
- Feature programming to make work easier
- Ways and means for recording and calling up tool data and/or entire tool catalogs in a simple manner

■ Automatic provision of the associated technology data such as feed rates, speeds, cutting depths, and so on for each of the materials being machined

■ Ability to make changes or modifications quickly to finished programs without having to start again from the beginning

■ Generation of an error-free machining strategy

IMPORTANT POINTS TO REMEMBER

1. CAM is the abbreviation for *computer-aided manufacturing* and is a generic term grouping together all technical and managerial shop floor activities. CAP stands for *computer-aided* which could be part of CAM. All modern CAP systems provide graphics support and simulation.

2. The difference between 2½D and 3D programming does not refer to the nature of the graphics support. 2½D programs are also generated on a 3D model using high-performance systems.

3. In the case of 3D programs, the tool is moved along the workpiece during the machining process with simultaneous participation of at least three axes of the CNC machine tool. The shape of the workpiece thus is created directly by the tool path (typical for mold construction).

4. 2½D programs are needed for all processes in which a maximum of two axes are interpolated simultaneously during machining. This type of machining is typical for drilling operations and milling jobs such as surface, contour, and pocket milling.

5. A modern programming system should manage a mix of different machining processes, for example, turning and drilling/milling, without a change of the programming software module.

6. With modern interfaces, it is possible to transfer models from various CAD systems to external CAP systems without a data loss.

7. The tool database is of central importance in the CAD/CAP/CAM process chain. Both in program generation and in simulation, it must be possible to access not only the numerical data but also realistic model data at run time.

8. Today, simulation is an indispensible aid in NC programming. This is essential to prevent collisions. The better the model data, the more meaningful is the simulation outcome.

9. The postprocessor generates the actual NC program for the specific CNC-machine combination. It also can supply additional data such as tool lists, clamping plans, and programs for the tool presetting device. A CAP system can be used only if the postprocessor is delivering the proper output.

10. It is advantageous if CAP systems have feature functions that can execute programmed machining operations directly in the event that small geometric corrections must be made.

11. During the design phase, it has generally not yet been determined which CNC machine will be used. Therefore, the CAP system should provide for a strict separation between geometry and technology data.

data. data.

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INTRODUCTION

In recent years, the simulation of computerized numerical control (CNC) machines has become established as the standard method for the verification of complex machining processes. In modern numerical control (NC) simulation systems, a real manufacturing system is reproduced true to life in a 3D graphical environment. Machining processes can be viewed and followed from any angle 27.1 and

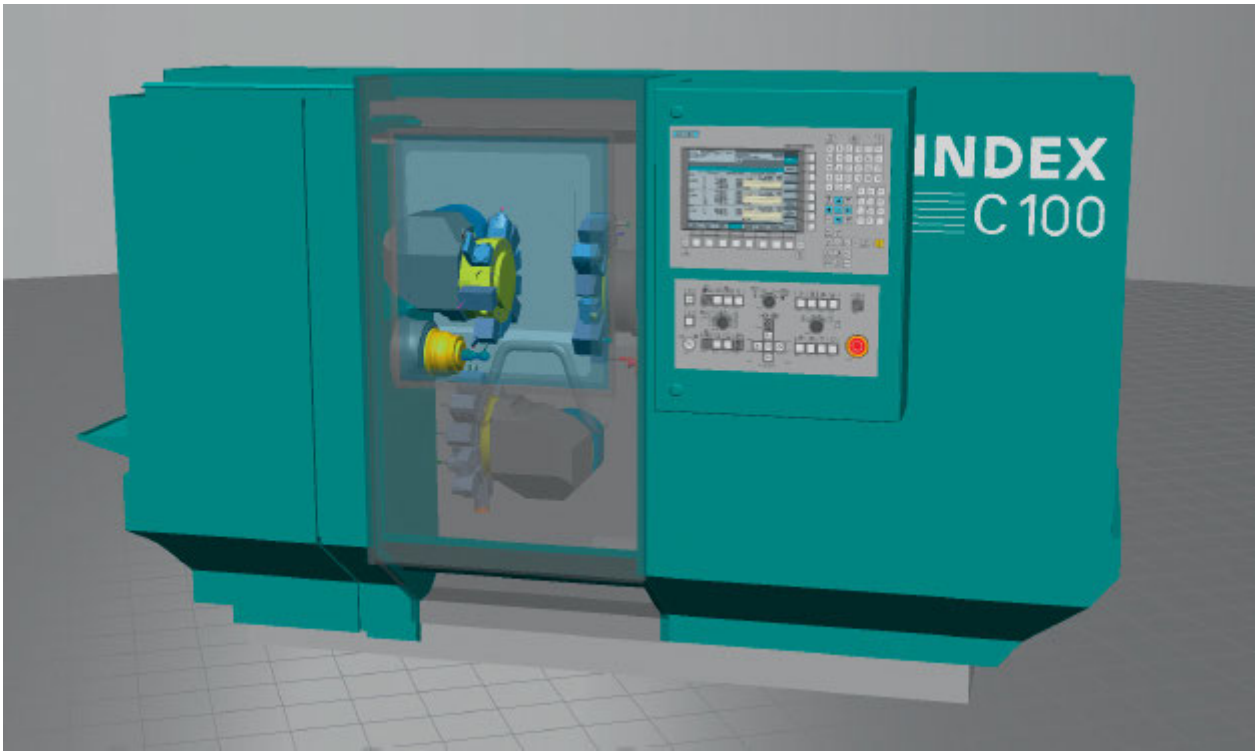


FIGURE 27.1 Machine model of an INDEX C100. Simulation on the computer display.

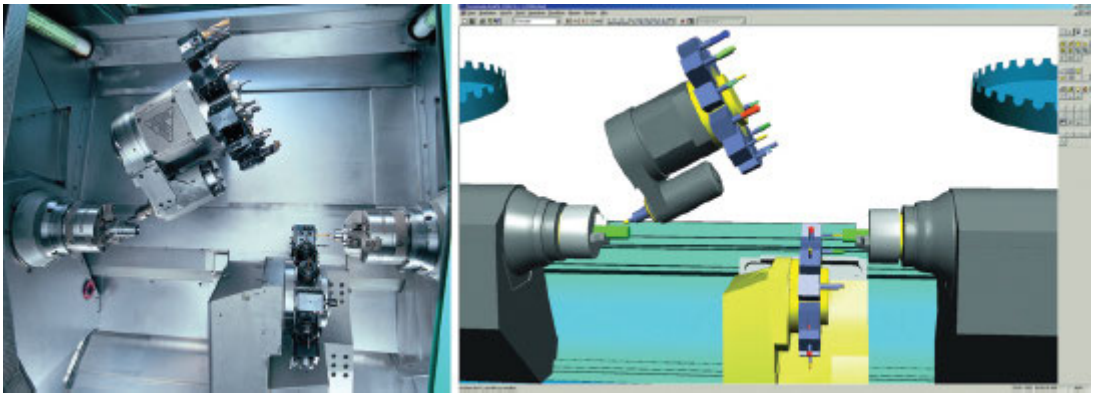


FIGURE 27.2 Comparison of work area of a lathe in reality and in simulation.

In contrast to this, a CNC machine allows a close observation of the machining action only to a very limited extent. If the enclosure of the machine allows any observation at all, it is generally from a very disadvantageous angle. The clamping of the part and the presence of coolant also obstruct the monitoring of a modified or new program.

QUALITATIVE CLASSIFICATION OF SYSTEMS

NC programming systems often include simulation components that show the motions that take place between the tool and the workpiece on the basis of the NC source code and before transmission to the postprocessor. This method is well suited for performing an initial check of the results of programming. For exact geometric investigations and analyses of the run time, systems that are based on the final NC codes should be preferred for the following reasons:

■ Errors in the postprocessor are not detected by the simulation system but only come to light during the initial run on the machine.

■ Only postprocessing will determine the machine on which a program will be processed; this also defines the workspace and machine parameters.

For programs that are created manually on the machine with the editor, that is, without the NC programming system, the "pre-postprocessor" simulation is eliminated from the beginning. In this case, it is particularly important to verify the programming result because this programming method is very error prone.

Truly definitive simulation results are only possible on the basis of the actual NC program; that is, the simulation uses exactly the same program code that is processed on the actual machine. This includes, aside from the program itself, all subprograms, cycles, and parameter tables called up by the program, such as zero-point offsets, tool-compensation values, and so on.

The text that follows focuses on the state of the art of modern NC simulation systems. The functions and applications described correspond to the capabilities of the most powerful systems available. Not all suppliers offer the same level of performance, however.

Simulation with CNC Emulation

For many years, the required computing power was a limiting factor for 3D depictions, collision checks, and machining simulations. Today, though, high-performance systems can run on standard computers

TABLE 27.1 Comparison of Different Simulation Approaches

Approaches Approaches Approaches Approaches
Approaches Approaches

Modern systems represent all motions in a 3D machine model. Interfering elements in the workspace can be either depicted transparently or hidden. They are nevertheless taken into account in the collision-detection process that is running in the background, thus ensuring that possible collisions are not ignored. The point of view in the simulation system allows very detailed examination of all

machining situations. The purely 2D representation of the workspace components in line graphics of only a few years ago is hardly used anymore.

In addition to visual output, high-performance NC simulation systems provide such functions as:

- Practically complete depiction of a wide variety of CNCs
- Depiction of the material removal
- Automatic collision detection
- Syntax verification of the NC program
- Precise time analyses
- Depiction of system variables, axis values, and other process parameters
- Documentation of actual errors and collisions

In order to differentiate among the systems available on the market, it is necessary to analyze the machining process being simulated. As a general rule, a distinction can be made between manufacturing processes with 3D machining and those with 2½D machining.

In a 3D machining process, the feed motion of the tool takes place in at least three axes simultaneously. The shape of the workpiece is created directly by the tool path, for example, five-axis

milling. In 2½D programs, two axes are moved with interpolation. These machining operations are typically drilling and turning operations.

In modern turning/milling centers, it is even possible to execute both 2½D and 3D machining operations in parallel. Through the integration of various technologies in one machine tool, it is no longer possible to make a strict distinction between lathes and milling machines. A modern simulation system therefore must not only support all kinds of machining operations but also has to be able to perform various machining operations successively on one or several parts if it has been so programmed.

Virtual Machine

Because the scope of functions and complexity of CNC machines have increased greatly in recent years, it has become much more difficult to adequately depict all functions in the emulation software. In the case of complex, multichannel machines, the effort required for programming a CNC emulation has risen to such a degree that it is no longer possible to emulate the machine completely.

The remedy for this situation was found in the form of virtual CNC systems (see Table Unlike a simulation with CNC emulation, the behavior of the CNC machine is no longer emulated. Instead, the CNC manufacturer provides a software component that contains the complete behavior of the CNC machine. This development was helped by the fact that the functions of a modern NC system are no longer realized in the hardware but rather in the software.

This has made it possible for CNC manufacturers to provide a virtual CNC machine for simulation whose functions are identical with that of the actual CNC machine. A virtual CNC is generally the software of an actual CNC machine that has been encapsulated in such a way that it can run on a standard commercial PC and can communicate with simulation systems. This virtual CNC machine is operated with the data of an actual machine. It represents an exact copy of the CNC machine and could be called a *digital*

Use of the virtual CNC machine makes it possible to add to the simulation the user interface of the actual machine. Because the user interface is also software, it can be operated with the help of the virtual CNC machine in the same way as the actual machine The term *virtual machine* has been established in this context in the industry.

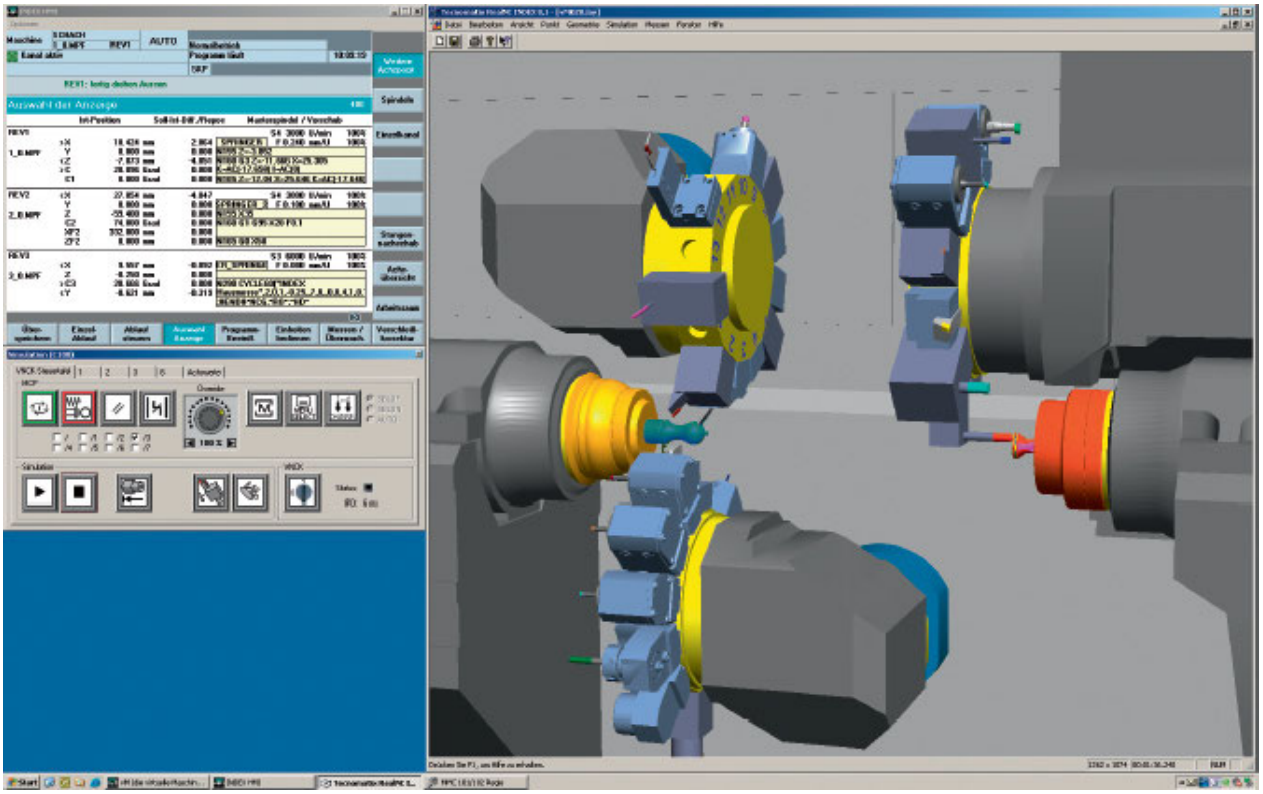


FIGURE 27.3 Virtual machine with control panel and 3D machine with tools.

The virtual machine has the following characteristics:

■ Material removal, 3D depiction, and collision calculation according to the CNC simulation with CNC emulation

■ Complete range of functions, such as syntax checking, runtime analysis, and settings and parameters as on the actual machine

■ Use of the machine operating panel in the virtual environment

■ Simulation that behaves like the actual machine in as many areas as possible

COMPONENTS OF A SIMULATION SCENARIO

Machine Model

A *machine model* refers to the true-to-original emulation of the physical machine on a computer. At the least, a machine model contains the following components:

- Geometric models of machine elements such as the frame, guides, and cover plates
- Kinematic structure
- CNC model or virtual CNC

At a minimum, the geometric elements of the machine model must describe the workspace precisely. Additional elements, such as parts of the enclosures, may be relevant in terms of collisions but also have recognition value. For the purposes of simulation, they can be made transparent or hidden entirely

The kinematic structure contains the actual machine axes as virtual axes. The sequence of the axes and axis distances corresponds to the actual conditions. Not only NC axes are defined as such, but PLC-controlled axes, turret axes, and hydraulically actuated clamping elements can be a part of the kinematic structure.

The CNC model reflects the most important characteristics of the actual CNC machine. This means that high-performance CNC models can execute almost the entire range of commands of the original CNC machine. This is essential for functions such as motion planning, interpolation, cutter radius compensation, and so on. It also should be possible to support high-level language elements such as jump commands, conditional jumps, loops, and the programming of variables and parameters.

In a virtual machine, a virtual CNC system is used instead of a CNC model. The virtual CNC system uses the data of the actual machine and thus is functionally identical to the actual machine. In this way, it is ensured that all CNC functions are exactly the same in both the virtual machine and the actual machine.

Virtual machines also make use of the machine user input panel. The user of the virtual machine has identical access to all the inputs and displays that are present on the actual machine. It is thus possible to use the virtual machine not only at the shop-floor level but also in a production-planning environment.

Workpiece Geometry and Clamping Devices

Today, workpieces generally are designed on 3D CAD systems as unfinished and finished parts. The unfinished parts' geometry required for simulation is transferred via the CAD interfaces. The same applies to the clamping fixtures. If no CAD data are available, some simulation systems provide easy-to-use CAD functions that can create complex clamping kinematics from standard geometric figures such as cuboids and cylinders High-performance systems support typical series production methods such as multiple-clamping setups in machining centers and multiple-spindle fabrication on milling machines and lathes.

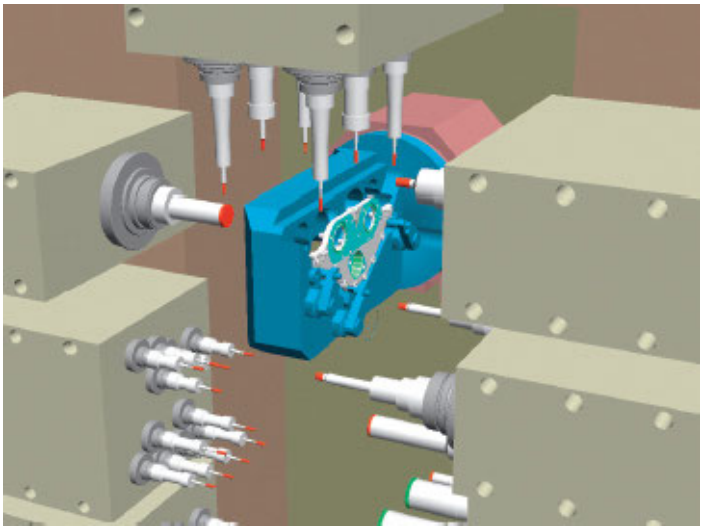


FIGURE 27.4 Work area of a processing center with clamping device and workpiece.

Tools

Tools are divided into the following categories:

- Rotationally symmetric tools, such as drills and milling tools
- Nonrotationally symmetric tools, such as lathe tools and single-blade tools
- Complex tools, such as angle drilling heads and drilling heads with more than one tool

Rotationally symmetric tools generally are easy to draw because they can be created via rotation from a simple 2D contour.
Nonrotationally symmetric tools are more difficult to model.

There are two different approaches for generating tools for NC simulations. Tools can be either generated or assembled from multiple components. With generated tools, the user defines the geometric characteristics of the tool using a number of defined parameters. Next, the system generates a complete 3D model consisting of the tool holder and a cutting edge

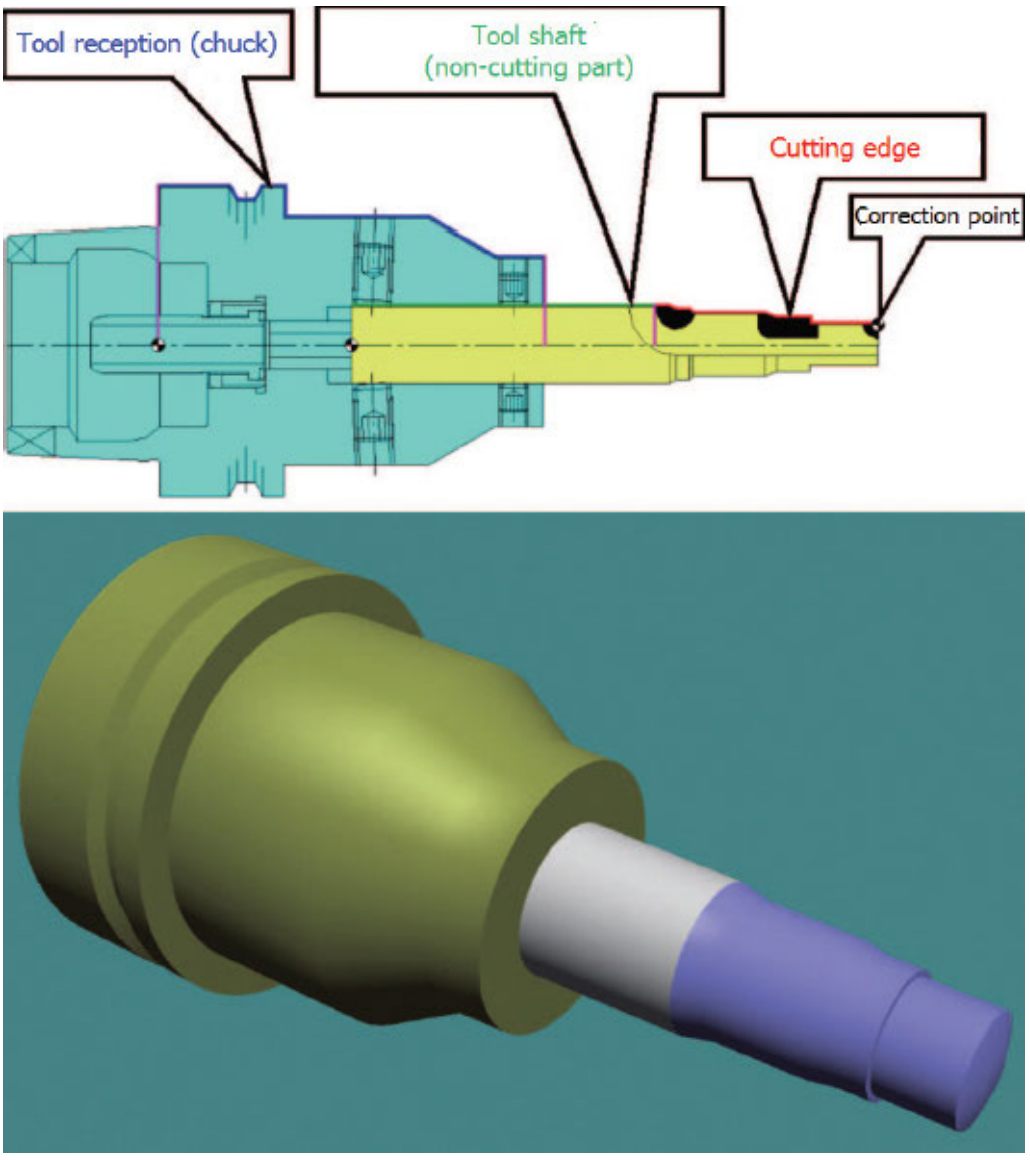


FIGURE 27.5 Generated tool: 2D representation and 3D tool in simulation

Tool systems that generate tools have the following advantages and disadvantages:

- Very simple operation
- No knowledge of CAD required
- Sufficient for many simulation applications
- Only predefined tools possible

In the case of assembled tools, 3D geometries of individual tool components are stored in a database. The geometries are provided by the tool manufacturer. The user then selects and assembles the appropriate stock components to create complete tools 27.6 through

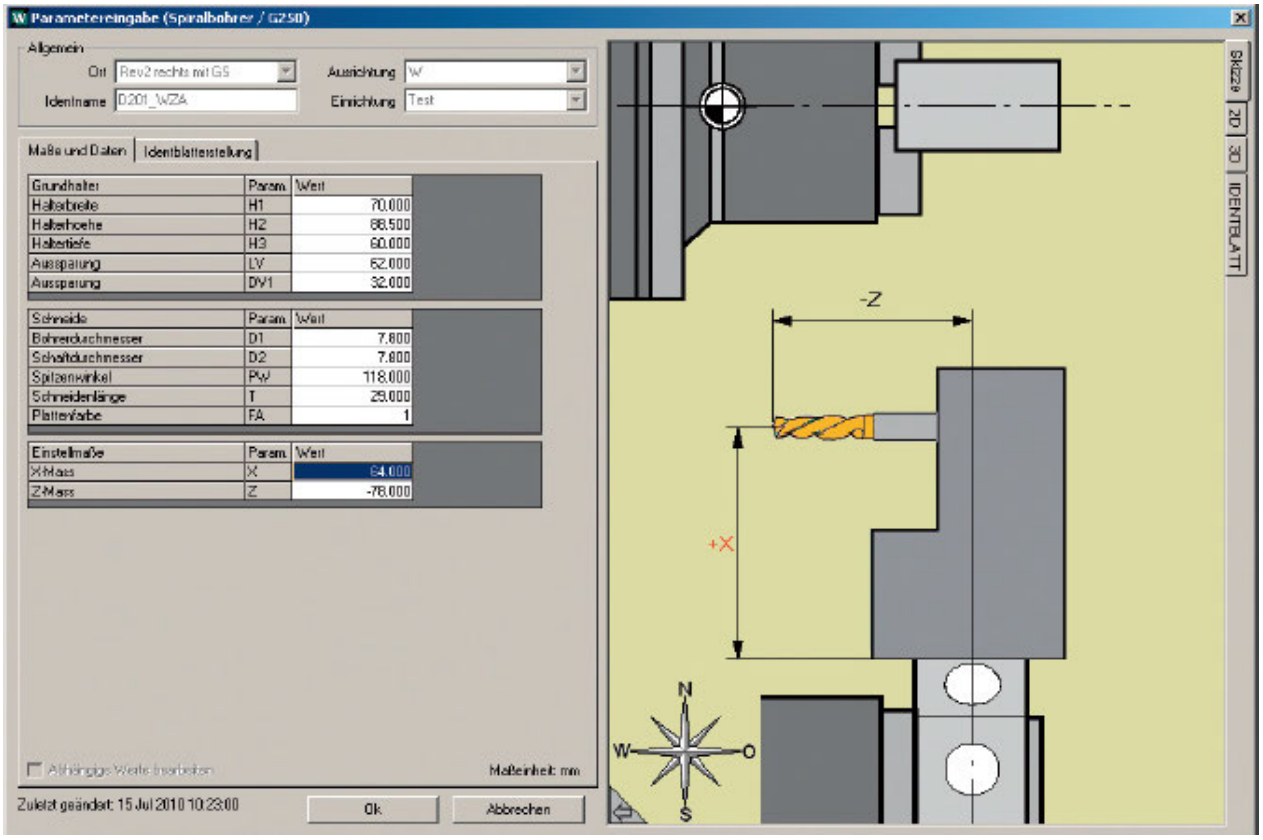


FIGURE 27.6 Tool assistant to generate 3D tools.

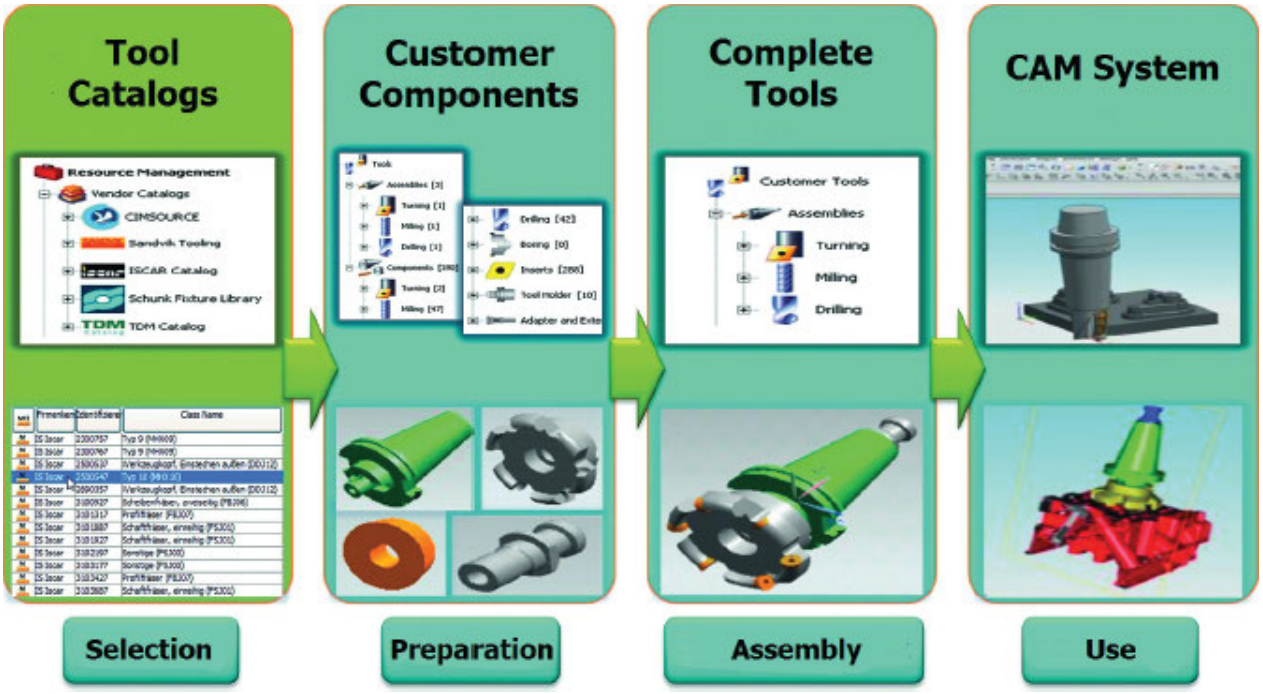


FIGURE 27.7 Procedure to create assembled 3D tools.

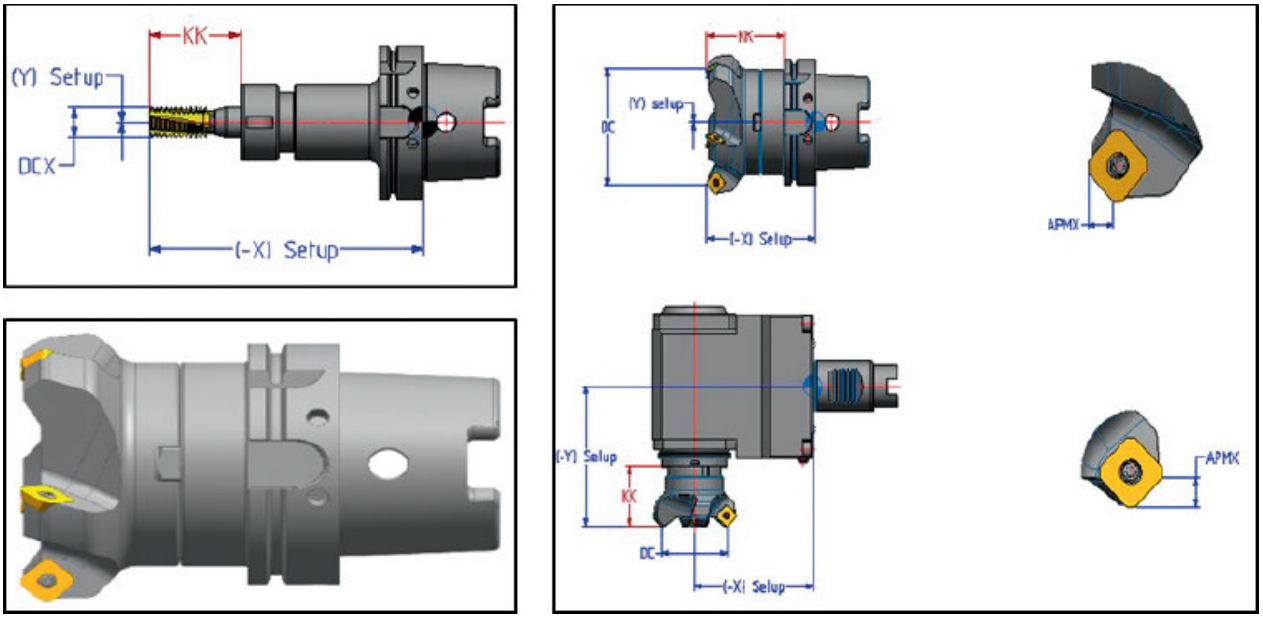


FIGURE 27.8 Examples of assembled simulation tools.

Tool systems with assembled tools have the following advantages and disadvantages:

- Any 3D geometry
- Precise representation of the tool geometry
- Some effort required to maintain database and create new tools

In some simulation systems, both types of tool creation are used, and the user can decide from case to case which approach is correct for the specific application.

Periphery of the Machine

Peripheral components such as pallet-changing devices, handling units, and magazines can be depicted and included in the simulation using the methods just described.

PROCEDURE FOR NC SIMULATIONS

Graphical Depiction

In simulation, the lowest level of detail depicts workpiece and tool. The next level adds clamping fixtures and the components that carry the tool, such as angle head, turret, and tool spindle. The complete graphical depiction covers the entire machine with all way covers, tool-changing devices, measuring devices, and so on that limit the workspace

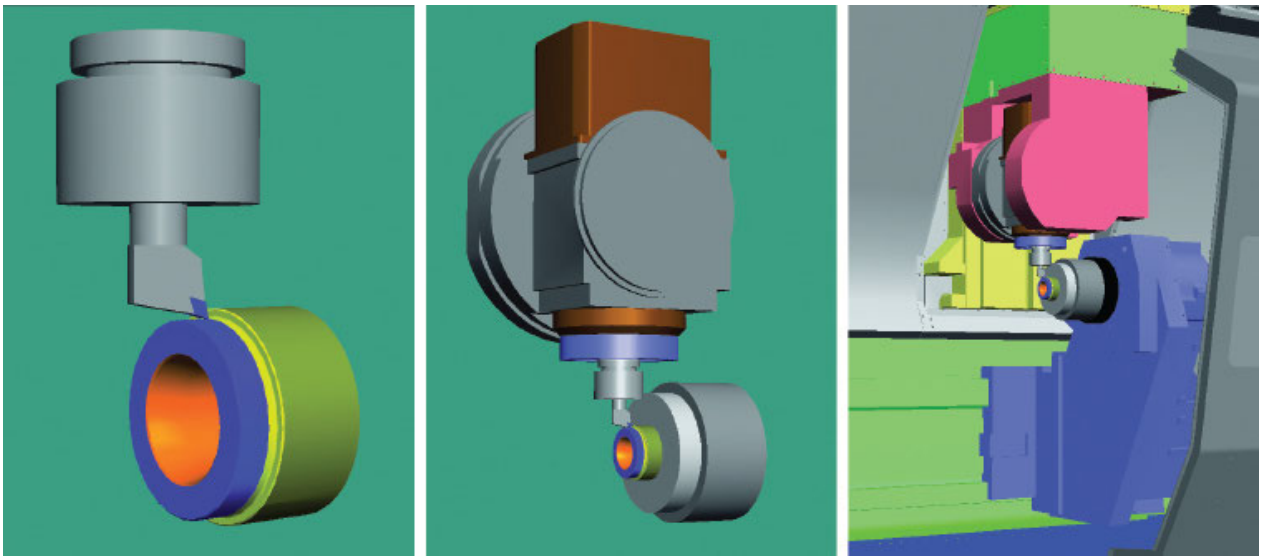


FIGURE 27.9 Levels of details in simulation views.

After the simulation is started, the NC program is executed like in an actual machine. The NC blocks are prepared and converted into motions of the virtual machine axes. A video-like presentation details the material removal on the workpiece. The new surfaces created on the part are given the color of the cutting tool being used.

As an option, the tool path is displayed during the machining process. In this manner, it is easy to retrace the machining sequence, for example, a drilling pattern

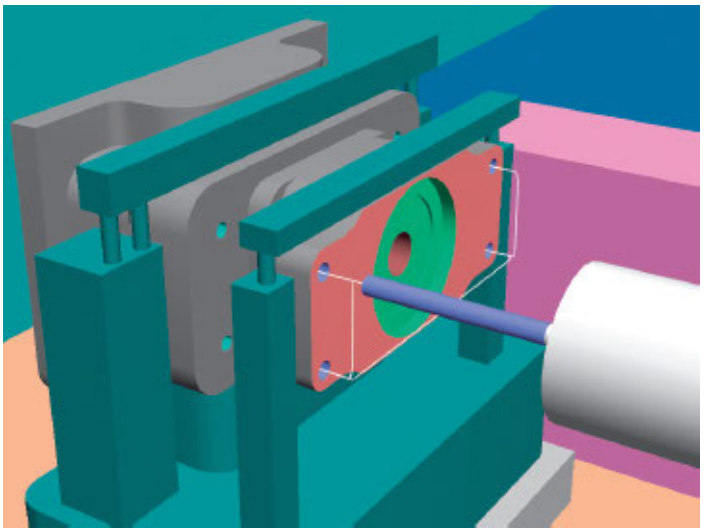


FIGURE 27.10 Material removal; machined surface takes color and path of tool.

Automatic Collision Detection

During the simulation, the components of the workspace are checked for collisions and/or inadmissible contact. If these occur, then the simulation sequence is halted, and an appropriate message is generated. In addition, the colliding components are highlighted Some simulation systems also detect errors of a technological nature. If machining is started without coolant or if the maximum permissible spindle speed and feed rate are exceeded, a warning message will be displayed.

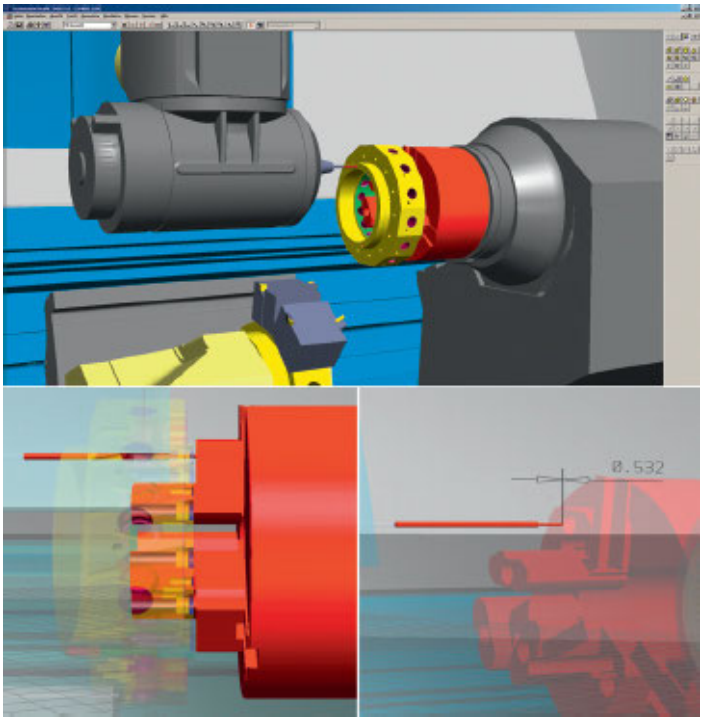


FIGURE 27.11 Illustration of a collision. The tool cuts through the workpiece and drills into the chuck.

Editing Options and Analysis Methods

While a simulation is executing, the pertinent line of the NC program or subprogram will be displayed. Some simulation systems allow making changes "on the fly" and test the changes immediately. In NC simulations with CNC emulation, it is possible to execute the program in single-block or automatic mode, just like during an actual CNC operation. Furthermore, it should be possible to simulate the sequences individually in each interpolation cycle. It is thus possible for the user to track, analyze, and optimize the motion sequences with an accuracy of milliseconds.

INTEGRATED SIMULATION SYSTEMS

Some CAM systems have a simulation module with the same capabilities as specialized simulation programs. The advantages of integrated solutions include:

- Quicker learning through uniform handling
- Uniform system environment (Tools, fixtures, etc. must be created one time only.)
- Problems recognized in simulation can be repaired quickly and in the same system
- Simulation aids programming for optimization
- Tool data are entered only once
- Easy updates

FIELDS OF APPLICATION

Testing New Programs

The use of NC simulation before testing a new program on the machine has the following primary objectives:

■ A test run can be performed on a computer in the office instead of on an expensive machine.

■ Machine production is not interrupted while the new part is being tested virtually.

■ Testing time on the actual machine can be reduced by up to 80%.

■ A dramatic reduction of collision risk occurs.

■ Reduced risk of fabricating rejects due to errors when processing expensive blanks (especially in single-piece and small-series production).

■ Reduction of down times and costs for repairs.

■ Better compliance with tight schedules thanks to shorter test times.

Through the use of simulation, it is possible to detect and correct a wide variety of errors at an early stage. This includes both syntax errors and faulty coordinates, incorrect tool correction switches, and even incorrect or missing zero-point offsets. In addition to errors in the NC program, it is also possible to analyze the interaction between clamping fixtures and tools. If an axis limit is exceeded by variation in the clamping position, then this fact is detected automatically. The errors thus described are corrected before the NC program is loaded into the machine. This significantly reduces the time for testing because troubleshooting on the machine is a very time-consuming process

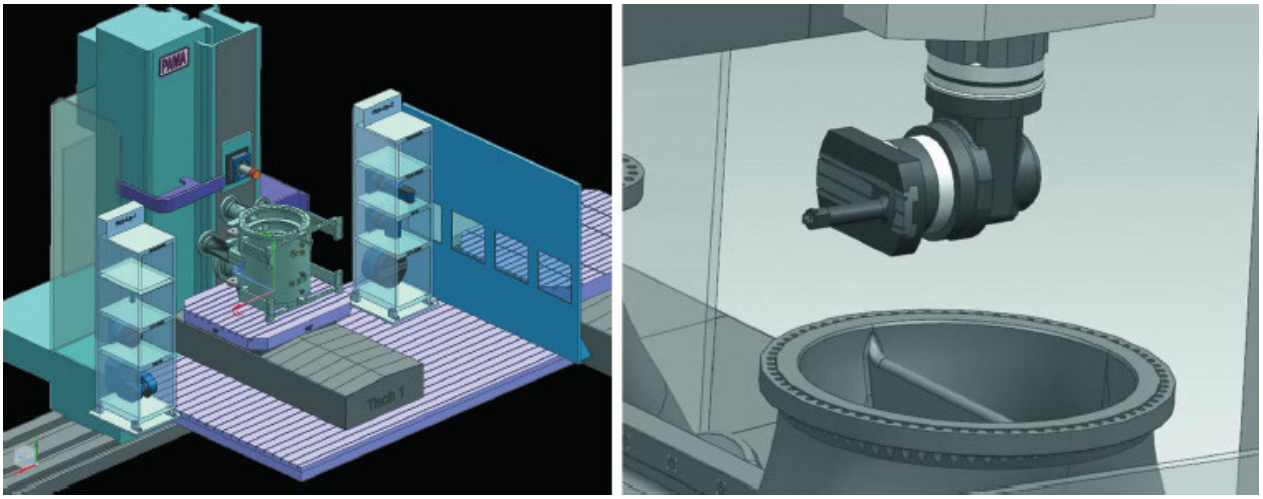


FIGURE 27.12 Optimization of tool lengths through integrated simulation; thus higher cutting speeds are possible with the same quality. Siemens, Business Unit Compression.)

The potential savings depend on the specific conditions. Before making a decision with regard to the use of an NC simulation, the user should ask the following questions:

■ To what extent is it possible to reduce the programming time of new NC programs through the use of NC simulation? This question is especially relevant when no NC programming system is used.

■ What additional value can be generated from the newly gained machine capacity?

Program Changes during Operation

Changes must often be made to the NC program, especially in the series-production phase of a manufacturing system. This can be for the following reasons:

■ Changes in the geometry and tolerances of the workpiece

■ Expanded range of parts (new variants)

■ Use of different tools, such as combination tools

Such changes affect first of all the NC program and the tools; it might also be necessary to make changes in the clamping hardware. Changes and/or expansions in the NC program are performed either during production planning or directly on the machine via an editor on the control panel. CNC simulation in these scenarios is capable of accepting necessary changes on the PC while the machine is still in production mode. The modified CNC program is transferred to the CNC machine only after the changes have been verified and accepted by means of simulation. This minimizes machine downtime.

Optimization of the Production Process

In series production, CNC simulation is used not only for the verification of NC programs but also for cycle-time optimization. The exact geometric and temporal reproduction of the machining process in the simulation system makes it possible for the user to optimize motion sequences on the machine or workstation using methods that would be too risky or too complicated if CNC simulation were not used. When projecting cycle-time savings over the lifetime of a production process that may be several years, even a single-digit percentage reduction in the cycle time may result in potential savings that far exceed the expense of achieving such optimizations.

The following methods may be used for optimization:

■ Minimization of safety clearances

■ Parallel motions, for example, workpiece positioning and table rotation

■ Fewer tool changes through modification of the operation sequence

■ Optimization of use of linked systems

Planning Phase in Series Production

In series production, the system manufacturer is required to provide not just the physical components of the production system such as CNC machines and interlinking and transport media but also implementation of the entire production process with all CNC programs. It is the system manufacturer's task, among other things, to commission the system successfully and to fulfill predefined

acceptance criteria such as units produced per given time and maintaining product quality.

Today, many system manufacturers already use NC simulation in the development and planning phase. The main emphasis here is twofold: the development and verification of machine concepts and the validation and optimization of the production processes before the machine is commissioned.

Training

The current and future relevance of CNC machines for our industry is generally underestimated. Therefore, students and trainees should be introduced very early to CNC technology. Training departments generally do not have the resources to provide modern CNC machines for training purposes. If such hardware is available, operator errors often lead to extended downtimes and high repair costs

With a CNC simulation system, it is possible for trainees to learn how to work with a CNC machine in an ideal way. No damage will be done when programming errors and collisions happen in a simulation. Thus both trainers and trainees no longer have to worry about avoiding expensive mistakes and can concentrate on learning the craft.

What is more, it is possible for each trainee to work on his or her “own” machine. Training becomes more diverse and realistic because it is possible to simulate machines and CNC systems that are generally not available in real life for student training.

When one considers that many job training shops rather not use CNC machines for training for fear of damage, learning in a simulation environment is the better and more economical alternative —the more so because simulation systems are available for most CNC machine brands, and most manufacturers can provide PC-based training systems at acceptable prices, including the introduction for teachers. CNC simulation is also used in production as a means for user training. Especially when it comes to complex manufacturing systems and transfer lines, system operators can be instructed by way of simulation about the working of the system.

Virtual machines provide even greater potential. If the virtual machine has the original operating input panel of the actual machine, it is possible to teach not just NC programming but also operation of the machine. This means that programmers and operators can train and gain experience with the new machine before it is actually delivered. It is then possible to put the machine into operation more quickly because the operators already have learned how to work with it and have already programmed the first workpieces.

Graphic-dynamic simulation on the computer display is therefore very well suited for various reasons to provide students from a variety of schools and skilled workers with a reasonable introduction to CNC technology. The fundamental difference from training on an actual machine is that no machines, tools, clamping devices, workpieces, and technological knowledge are necessary. Instead, graphic-dynamic 3D simulation systems are used because they are already widely disseminated in industry today. This software allows a very realistic representation of the machine, mostly with a top view of the machine and workpiece from all sides. Thus the programmed processing sequence can be observed in much greater detail than on

a real machine because here close observation is obstructed by hardware elements and the presence of coolant. Collisions between tool, workpiece, clamping device, and machine are displayed graphically without causing any damage.

Under these conditions, a good teacher will be well able to explain the use and potential of CNC technology understandably and comprehensively, often better than with use of a real machine. In addition, different machine types can be represented, such as mills and lathes and multisurface processing of complex geometries.

The advantages of simulation compared with the use of CNC machines in training include the following:

- No hardware and machine infrastructure is needed.
- No cleaning and maintenance costs arise.
- Significantly lower investment expenditures is the rule.
- No need for parts, tools, clamping devices, etc.
- No dangerous situations due to incorrect operation or collisions.
- No downtime resulting from required maintenance and repair of the CNC machine.
- Much better representation of the machine operation and the consequences of programming errors.

■ Immediate implementation of corrections in the NC program.

■ "X-ray vision" of the operation allows a look "into" the workpiece. In the instance of drilling, the trainee can use 360-degree vision to determine whether the operation executes as planned.

■ Unprocessed surfaces and residual material are displayed.

■ Processing sequence can be displayed in time-lapse or slow-motion speed.

■ Simultaneous multiuser use (on several PCs) is possible.

■ Software updates are possible at low cost.

■ Expansion to other machine types, for example, turning, milling, and laser machining, is possible, if required.

Student experiences with modern simulation systems can be very impressive. The importance of simulation in industry and trade is undisputed and increases steadily. Buyers today require the machine supplier to first provide the simulation software in order to shorten the commissioning time and to examine the CNC programs in advance for errors or possible improvements.

The trainee should experience and, at the same time, understand the advantages of simulation. In addition, it eases the initial fear of an elaborate, complicated, and complex programming system. Exposure to CNC programming would overwhelm the novice because

it requires knowledge of machines, materials, tools, cutting values, clamping devices, and machining and should be left to seasoned workers.

SUMMARY

Components of a Simulation Scenario

A simulation scenario represents the entire production facility, such as:

- Machine model with all geometric elements and axes
- CNC emulation or virtual CNC with machine operating panel
- Workpieces and associated clamping fixtures
- Tools, drill heads, adaptor heads

Procedure for NC Simulations

- All machine motions are represented in three dimensions with maximum realism.
- Material-removal simulation reveals how the workpiece changes during the machining process.
- Automatic collision detection reports on all impermissible contacts between the hardware components within the workspace.

■ The simulated NC program is executed in single-block or automatic mode and can be edited easily at any time.

Further options include:

■ Depiction of the tool path

■ Detection of technological errors

■ Simulation in the interpolation cycle

Fields of Application and Potential Use of Simulation

Most work when testing a new program should take place on a PC. This saves as much as 80% of the testing time and increases machine availability accordingly. Repair costs and downtimes due to collisions during the virtual operation are completely eliminated.

Program changes can be made and tested during ongoing operation. Transferring the changes to the actual production equipment requires only short downtimes on the machines. In series production, CNC simulation is used for cycle-time optimization, among other things. In the simulation scenario, safety clearances can be minimized, feed motions are parallelized, and the machining sequence of the tools is exchanged. The prerequisite for this is the exact depiction of the action control response with regard to motions and temporal response.

The main focus in the planning phase is first, the development and verification of machine concepts and second, the validation and optimization of production processes before the machine is commissioned. During vocational training, the ways of working with NC machines are imparted in a simple manner by means of NC simulation systems. Programming errors and collisions are of no consequence and serve as a teaching moment. Both trainer and trainee can work without pressure and can concentrate on the actual contents of the instruction.

IMPORTANT POINTS TO REMEMBER

1. *Simulation* refers to the reproduction of a system with its dynamic processes in a model capable of experimentation in order to gain knowledge that can be transferred to reality (VDI Standard 3633).

simulation (1) refers to the graphic dynamic representation of an actual system using a model, for example, for:

a. Design of components and their assembly

b. Work scheduling, handling, clamping, and production of workpieces

c. Structural analysis and response of components

d. Investigation of the kinematic and dynamic behavior of bodies (FEM)

e. Optimal design of flexible manufacturing systems, such as material flow and machine layout

simulation (2) pertaining to a manufacturing technician involves:

a. The graphical-dynamic simulation of an NC program on a specific machine

b. Representation of machine, workpieces, and tools in the correct relative size for analysis of the motion behavior during machining

c. Depiction in real time, time lapse, or slow motion with optional stops for detection and investigation of problems

d. Tool and workpiece changing

e. Detecting and eliminating empty travel, safety margins, collisions, programming errors, etc.

4. Simulation of NC programs has the following objectives:

a. Help in the time optimization of NC programs

b. Detection/avoidance of collisions

c. Reduction of the test phase for new programs

d. Increased machine service lives

e. Cycle-time optimization of a flexible manufacturing system (FMS) through coordination of machining times with multimachine processing

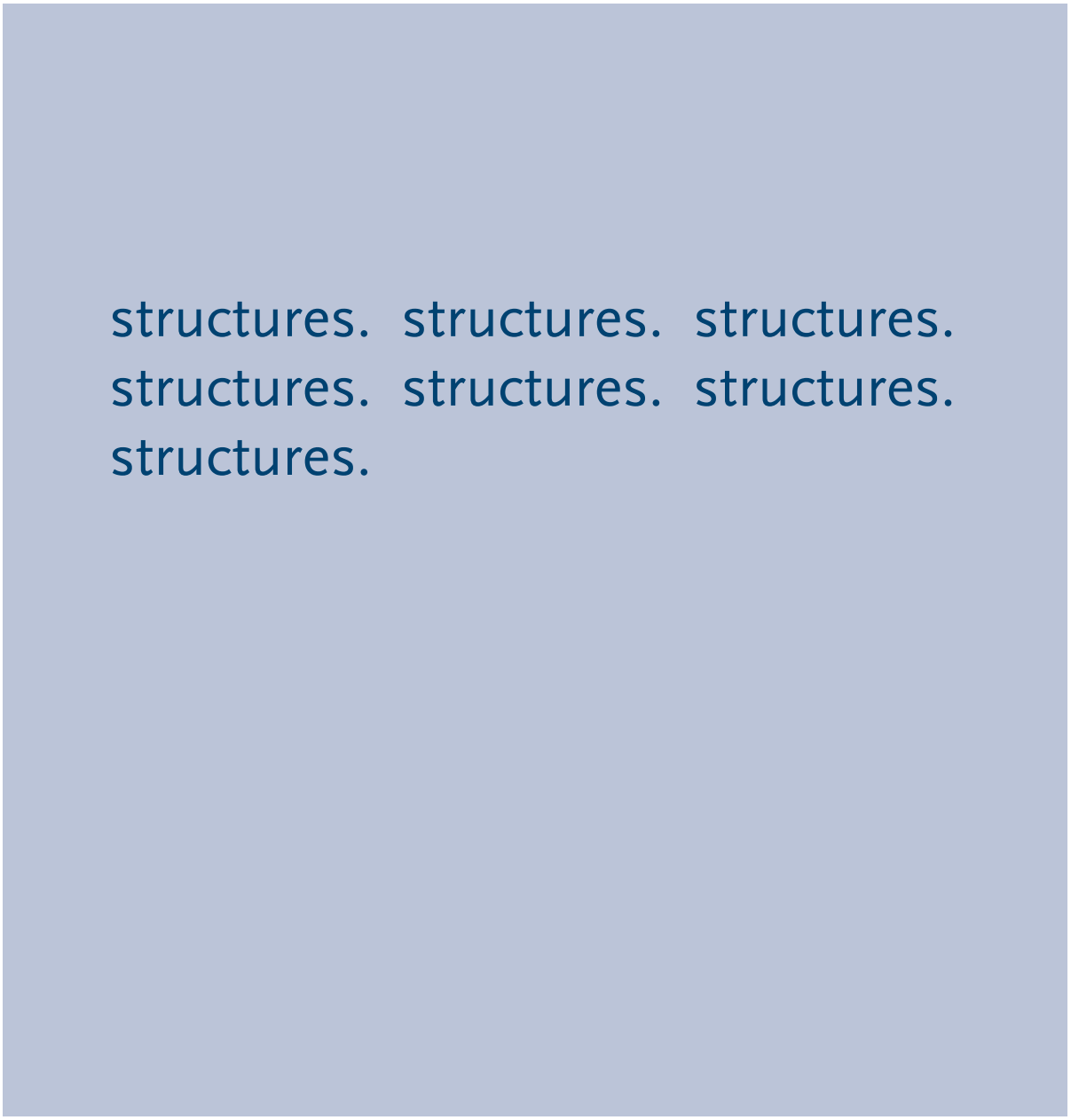
f. Generally preventative damage control and a productivity increase

5. A distinction is made between the following:

a. Process simulation emulates complex production systems in such a way that it is possible to perform optimization with regard to the arrangement of the machines and design of the overall system and sequences.

b. Graphic 3D kinematic simulation is possible for investigating the kinematic behavior of systems, such as robots, machines, or even humans.

c. FEM simulation is possible for modeling and analysis of the physical response of materials and complex structures.



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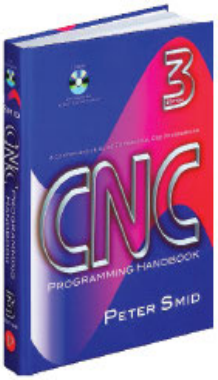
TAP INTO PETER SMID'S DECADES OF CNC EXPERTISE



CNC PROGRAMMING HANDBOOK, THIRD EDITION

640 pages, ISBN 978-0-8311-3347-4, $89.95

This is the book that literally defines CNC programming. Noteworthy for the author's careful, uncompromising attention to detail, the 3rd Edition incorporates comments and suggestions from hundreds of professionals in the field. The comprehensive result is an extraordinary volume. The 3rd Edition is packed with over one thousand illustrations, tables, formulas, tips, shorcuts and pragmatic examples.

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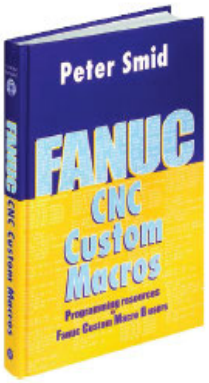
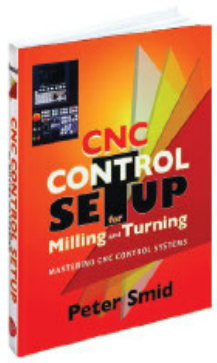


This book is an invaluable companion to the author's best selling *CNC Programming Handbook*. These programming resources provide a general introduction to the subject of macros (known as Custom Macros or User Macros). Users learn what macros are, how to develop them, and how to use them effectively. Fanuc CNC Custom Macros also explores important related subjects and identifies several other helpful topics in this increasingly important and exciting field of CNC programming.



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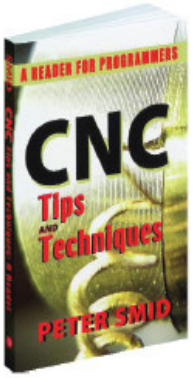

This compilation of more than 60 focused articles the author wrote for *Shop Talk* magazine is organized by topic and covers all aspects of CNC, such as hardware, software, programming, codes, and macros. These articles will appeal to both veterans and newcomers with tips and techniques that can be applied at work and speed up the learning curve.

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DEFINITION

The abbreviation *DNC* originally stood for "direct numerical control." Recently, terms such as *distributed numerical control* and *distributive numerical control* also have been used. The term refers to a mode of operation in which multiple CNC machines and other production equipment, such as tool-presetting devices, measuring machines, and robots, are connected to a computer by cables. The direct transmission of data has eliminated the data-storage media that were previously used, for example, punched tape, magnetic tape, and diskettes, as well as the devices required for reading and writing to these media. This yielded several technical and economic benefits.

According to the VDI 3424 Standard, the essential feature of DNC is the "management and timely distribution of control information to multiple CNC machines, in which the computer can assume responsibility for the numerical control functions." The last phrase no longer applies to modern DNC systems, however. Machine control functions now remain within the purview of the CNC system. Data networks and powerful DNC software allow all systems connected to the *local area network* (LAN) to communicate with one another.

FUNCTIONS OF DNC

Although the specific technologies have changed greatly in recent years, the basic functions of DNC systems have remained the same even today. A DNC system has to fulfill two basic tasks:

- Guaranteeing secure, timely data transfer from and to the CNC machines

- Managing many NC programs

The first task, guaranteeing secure data transfer, protects the company against the possibility of expensive damage to the machine and parts. NC program management, by contrast, ensures the proper organization and storage of what are generally large amounts of data that represent a significant monetary investment. Both these tasks can be solved by means of a modern system, thus contributing significantly to increased production and quality assurance in the manufacturing process.

The German Association of Electrical and Information Technology (VDE) guideline that appeared in 1972 made a distinction between basic functions and expanded functions of DNC systems, such as tool management and workpiece management in highly automated manufacturing systems. This will be discussed in greater detail later.

APPLICATION CRITERIA FOR DNC SYSTEMS

A company's requirement for introducing a DNC system can be based on a number of criteria, including the following.

Frequent Program Changes

The smaller the lot size, the greater is the problem of always having the correct NC program available at the right machine at the right time. In DNC operation, the NC program is available in the machine immediately after calling it up. In expanded systems, all the additional data, compensation values, and operator information are also available.

Number of NC and CNC Machines

Profitable DNC operation can begin just with two to three CNC machines, provided that a number of program changes are necessary every day. The case in favor of DNC increases with each additional machine. In fact, some manufacturing processes assume that data will be provided via a DNC system.

Number of NC Programs

The problems of administrating several thousand NC programs with the associated modifications, updates, and changes can hardly be managed without the use of computers. A DNC system can make this work easier and minimize the risk of human error.

Program Length

If programs are so large that a number of portable data-storage media would be required, there is a risk of confusing them with potentially costly consequences. If the programs are larger than the memory capacity of the CNC machine, a DNC system may be essential even for a single machine in order to be able to operate without interruption for several hours.

Many New Programs

If a company depends on many new programs or frequent program modifications, the direct transfer of programs from the CAD/CAM system to the CNC system is essential. Especially with shop-floor programming, that is, when the machine operator creates a program directly at the machine, is it very important to be able to save the programs that are generated.

High Transmission Rates

High-speed cutting (HSC) machines and laser technologies require an extremely high data throughput. It is therefore necessary to transfer the NC program data to the CNC system very quickly so that the machining process does not stop due to a lack of data. This requirement can only be satisfied with a DNC system.

Computer-Aided Tool Management

Integrated management of tools and tool data can provide enormous cost savings. Better use can be made of tool lives, and unnecessary disassembly and reassembly of tools can be avoided. The summarized transfer to the CNC systems of tool numbers with all the tool data reduces time requirements and increases safety.

Flexible Manufacturing Systems

Flexible manufacturing systems (FMSs) represent a special group that is categorized by the fact that basic DNC functions and the recording, storage, and management of pallets, compensation values, measurements, and so on are performed by a dedicated host computer. This computer is generally provided by the supplier of the overall system and is equipped with customer-specific software.

The DNC computer provides not just NC programs, subprograms, and cycles but also current tool data, zero-point offsets, and correction values. In the case of FMSs with complementary machining operations, it is necessary to provide each machine with a number of appropriate program sections for each workpiece.

With appropriate software expansions, it is possible for the FMS/DNC computer to make backups of the status data for each machine, such as the placement of the tools in the magazine, the interruption point for the machining operation, the compensation values, and other data. This provides substantial time savings in the event of data loss in the CNC memory if the machines have to be restarted.

Conclusion

As a general rule, DNC is a fundamental component of *computer-integrated manufacturing* (CIM) and should be included in the overall concept from the very start. DNC systems must be viewed as essential when one considers that the increased use of CAD/CAM systems, tool-management systems, and presetting

devices means that increasingly large amounts of data have to be processed and made available in less and less time.

DATA COMMUNICATION WITH CNC SYSTEMS

Initial efforts attempted to make NC path controls less expensive through the use of central computers and to provide the remaining residual NCs with precalculated data. Residual NCs were no longer able to function autonomously, however, which led to major problems during commissioning at the machine manufacturer's plant and in the event of computer failure. It also became evident that unexpected bottlenecks were already occurring in the provision of data to a few CNC machines. The rapid drop in price for CNC systems marked the end of the DNC principle using residual CNCs.

Before standardized serial interfaces became available, NC programs were loaded by means of punched tape that was read into machines by tape readers. Later, the RS232 (v.24) serial interface became standard and widely used because it was designed to work bidirectionally; it could be used either for saving a program or transmitting one to a machine. Early DNC systems based on the minicomputers that were available at that time—which were very expensive compared with today's PCs—were already capable of multitasking and equipped with multiple serial interfaces. They were thus capable of handling several data transfers simultaneously operated from a single terminal. These minicomputers also were used to store NC programs. All these systems operated with transfer technology; that is, the CNC machine was set to the operating mode "Read-in," after which it was possible to initiate data transfer to the machine from the terminal.

Because serial data transfer is very much subject to interference —the RS232 guarantees reliable data transfer only over 15 m and has only rudimentary data validation—manufacturers of the so-called mold-making CNCs (e.g. Bosch, Heidenhain, Fidia, etc.) quickly realized that the data transfer had to be secured by means of a protocol. Therefore, the older control units of these manufacturers transmit in a block fashion; that is, each data block is provided with a checksum that is recalculated by the CNC machine, and the correct result is acknowledged back to the computer. If a deviation is detected, the CNC machine automatically demands that the packet be sent again. These protocols, FE1, FE2, LSV-2, etc., do in fact result in lower transmission speeds but also ensure error-free transmission. Additionally, they allow the reading in of excessively long programs that are larger than the memory capacity of the CNC machine.

Thanks to the long service lives of NC machine tools, today's shops use almost all transfer modes that were current when the machines were first used, such as:

- BTR (behind tape reader) interface, parallel interface for punched-tape reader and puncher

- RS232 (v.24), serial interface for data input and output

- Ethernet interface, if the CNC is PC based

For CNC machines that are integrated into a network, that is, when the CNC has an Ethernet connection, the entire spectrum of operating systems and transfer protocols can be encountered, such as CNC machines based on Unix, Linux, DOS, and Windows. While the majority of Japanese CNC manufacturers favor FTP as the transfer protocol, European manufacturers use all the other protocols, such as Netbios, Netbeui, and NFS. This diversity should be taken into account when selecting a suitable DNC system.

METHODS FOR REQUESTING PROGRAMS

While in the past punched tapes, cassettes, or floppy disks were used, today it is possible to read programs into the CNC machine directly without having to deal with data-storage media as long as the CNC machine is set to the operating mode "Read in." Two different methods are used today to load programs into the program memory of machines with a serial interface.

The Transfer Method

The programs are sent by the computer or by the terminal that is assigned to the machine. That is, the CNC machine first has to be set to "Read in," after which the program is sent to the machine from the external DNC computer.

The Call-Up Method

This method is used in systems without terminals. Here a calling program, also known as a *dummy program* or *runner* requests the program that must be loaded. The DNC computer makes the program available, specified in a comment in the request program, and then waits for the operator, who still has to set the CNC machine to "Read in." This method has now become established as the standard and is used widely.

Network machines with PC-based CNC systems can access the server directly via the network. In this way, it is possible to load and save programs directly from the CNC machine with a few softkeys.

DNC SYSTEMS CURRENTLY AVAILABLE

All current DNC systems connect the CNC machines to the computers via either standard network cables or serial cables. There are three different concepts, which are described next.

DNC Systems with Serial Cabling

These systems are encountered primarily in small installations with only a few machines Generally, a single central PC is used for saving programs and as a communication device. This computer often is equipped with a multiple serial interface card and connects to the CNC machines via RS232. If copper cables are used, the transfer rate is usually restricted in order to increase transfer reliability, thus increasing the downtime of the machines. Therefore, fiber-optic cables are used instead to eliminate interference. Fixed cabling is a disadvantage when the DNC computer has to be moved to a different location.

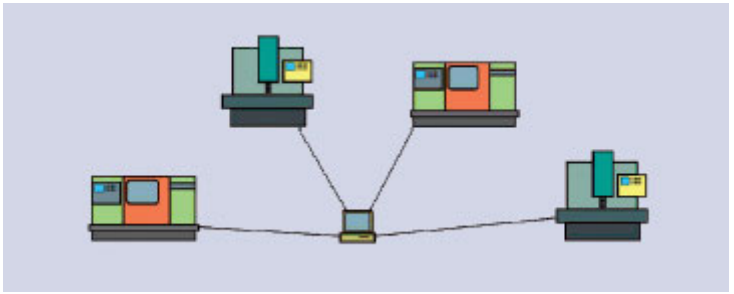

Figure 28.1 DNC system with serial cables.

This type of DNC system is suitable for small companies with only a few machines, where the computer is located close to the machines, ideally less than 15 m away. Both the transfer method and the call-up method can be found in such systems.

DNC Systems with Terminals

These DNC systems, which were quite common during the 1990s, use a terminal for data communication between the server and the machines Used for what is called *paperless* they bring all the manufacturing information to the machine. The operator can view all the manufacturing-related data and documents and can use the terminal to load the NC program. Often these systems are also supplemented with manufacturing data acquisition (MDA)/production data acquisition (PDA), have access to relevant signals from the programmable-logic controller (PLC), and, in the case of a malfunction such as a machine stoppage, are able to report back to the central computer.

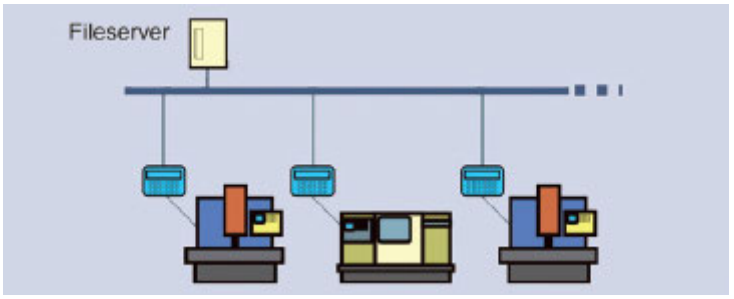

FIGURE 28.2 Terminal DNC system.

For a long time, these types of DNC systems were the only ones that avoided the disadvantages of long serial cables because they were based on network technology from the very beginning.

These terminal DNC systems provide maximum convenience but require thorough training of the personnel and are, accordingly, expensive when first acquired.

Network DNC Systems

These systems use network adapters for data transfer; that is, the CNC is integrated into the shop's internal Ethernet with the serial interface by means of a network adapter, also called a *device server, com* or *terminal server* This makes it possible to request the NC programs directly from the CNC machine with no intermediary terminals. These systems overcome the typical problem of transmitting data over long distances because correct data transmission is ensured via network technology. Because they are relatively inexpensive, these systems are equally suitable for both small and large companies. Wireless LAN (WLAN) is also often used today instead of conventional Ethernet cabling. Modern PC operating systems, mostly Windows, rarely Linux or Unix, allow transfer to or from multiple machines simultaneously.

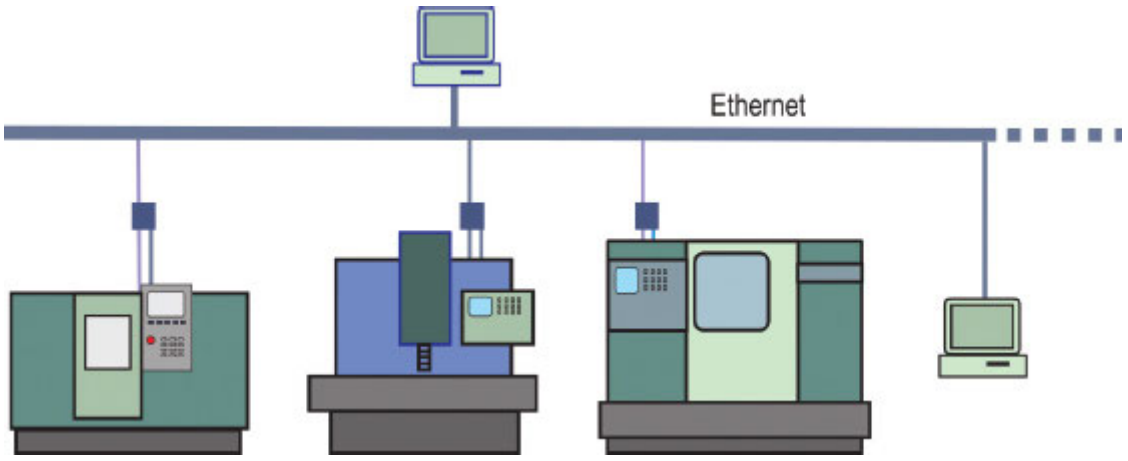

FIGURE 28.3 Terminal DNC system.

NETWORK TECHNOLOGY FOR DNC SYSTEMS

Protocols in standard networks, which today are almost exclusively Ethernet, ensure the error-free transmission of large quantities of data over long distances The Transmission Control Protocol/Internet Protocol (TCP/IP), on which networks are based today, ensures transmission even in industrial environments where there is all kinds of interference, guaranteeing absolutely error-free communication.

FIGURE 28.4 Modern devices to set up a DNC system: device server with WLAN interface (Lantronix brand); intelligent network adapter with DNC functions (Quinx brand); WLAN card with digital interfaces for PDA/MDA.

Today's DNC systems use Windows-based computers and standard networks (LANs) almost exclusively. In order to connect CNC

machines that have only a serial communication interface, network adapters, that is, com servers and device servers, are used as media converters. These transform the data from serial to Ethernet and vice versa. Highly customized network adapters contain the actual DNC functions and operate like separate computers with their own data-transfer program and implemented filter functions.

WLAN: Wireless Local-Area Network

Another network standard is WLAN. Wireless networks are Ethernet networks that check the data traffic using TCP/IP They operate in the gigahertz range and transfer data without any direct cable connection. This is done via an access point that forms the bridge between the cable network and the wireless network. The access point has transmitter and receiver functions and can also be used to connect two cable networks. On the receiver end, at the CNC machine, either a network adapter with a built-in antenna or a conventional Ethernet adapter is used, as described earlier. This is in addition to the WLAN-Ethernet bridges that convert from WLAN to cable-based Ethernet.

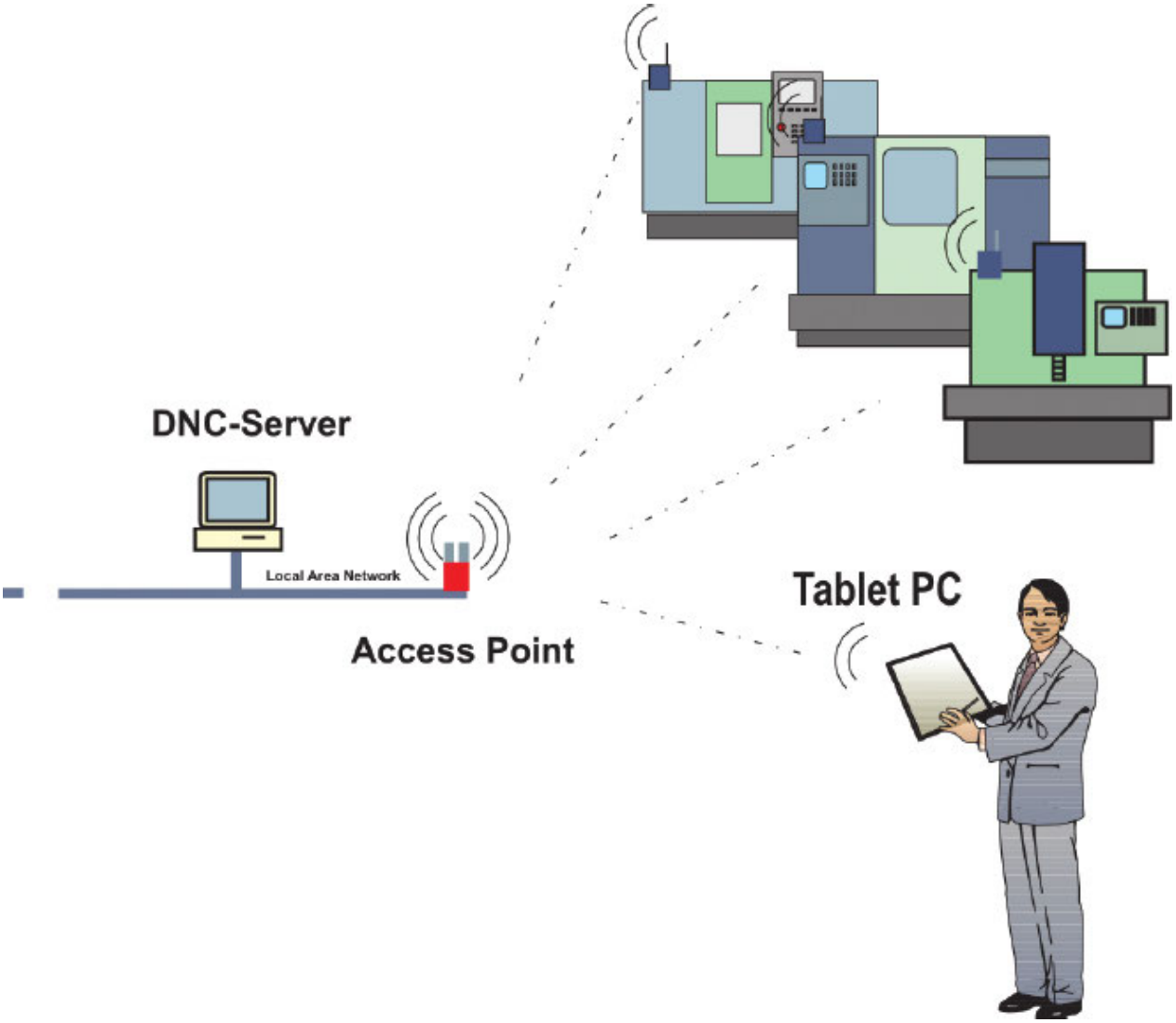

FIGURE 28.5 WLAN wireless data transfer to machines.

Benefits and Risks of WLANs

The use of a wireless network is especially advantageous under cost considerations. Instead of creating a wired infrastructure in the manufacturing area with the use of cables and switches, in many cases all that is needed is an access point. Installed at some distance above the floor, receivers can operate at ranges of up to 100 m. Conventional Ethernet cabling carries an average cost of about $300 to $600 per connection. In comparison, the cost of a WLAN is only half as much.

The risks should not be underestimated, however. Computer magazines continuously report on the latest “cracking methods” for various types of data encryption, and one must assume that no encryption will remain secure in the long run. This leaves the door wide open for industrial espionage and sabotage. Moreover, in high-traffic areas, various WLANs may overlap and interfere with each other. This can lead to lost production if no emergency strategy is implemented.

DNC for CNC Machines with an Ethernet Connection

For machines with an Ethernet interface, the question is often asked whether DNC is even necessary because access to the computer for loading and saving programs is easy to implement. To be sure, quick and error-free data transfer is no longer a problem with this type of machine, but in practice, the following problems are frequently encountered:

■ Because the data memory is very large, no regular data backups are made. A defective hard disk can result in an expensive loss of programs.

■ The machine operator is granted full access to the directories and thus can delete or overwrite programs on the central computer or move them to locations where they are impossible to find. This can represent a security risk.

■ All PCs in any company are vulnerable to computer viruses.

■ Without a DNC system, transfers can no longer be traced. No logbook is kept.

While the first three problems can lead to expensive losses, the last point is relevant in terms of compliance with ISO 9001. Therefore, there are many companies that manage all their machine programs via a DNC system. Other companies avoid the risk of viruses by requiring that all connections be made via a serial interface.

ADVANTAGES OF USING NETWORKS

The use of standard networks (Ethernet) offers many advantages:

■ Absolutely error-free data transfer thanks to automatic error detection and correction

■ Centralized management of all NC programs and production data

■ Connection of an unlimited number of devices

■ Networking of machines and devices even over long distances

■ Use of the maximum transfer rate of the CNC's serial interface

■ Trouble-free expansion of the system to suit company needs

■ Direct communication between multiple computers, such as CAD/CAM systems, NC programming computers, production-planning system (PPS) computers, shop computers, DNC computers, and CNC systems

■ Simplified centralized management of all data and network devices in the company (computers, machines, etc.)

NC PROGRAM MANAGEMENT

Often too little attention is paid to data management of programs. Because older controls only accepted four-digit NC program numbers, data management was adapted to the limited capabilities of the numeric controls, which meant that significant organizational work was required during production planning. Four-digit numbers generally do not allow the use of article numbers or part numbers, which generally have many more characters. This resulted in the use of comparison lists or complicated management systems that had to be developed in order to assign the appropriate part program to the article. These old habits continue to exist in many places.

Modern DNC management systems overcome the limitation of four-digit NC program numbers and use a comment line within the program for unambiguous identification of the NC program independent of the NC program number. This makes it possible to use the information contained in every production order to request the required NC program number for the part being manufactured without the operator having to know the NC program number.

Modern network-based DNC systems manage NC programs almost completely automatically. New programs that are sent from the machines or transferred from the CAM system are automatically placed in the database and are immediately ready for loading into the machine. Modified programs are automatically compared with the original and stored separately. A click of the mouse will show all the changes so that the person responsible for the NC programs can enable the one that is desired. As long as a duplicate exists, the

original program should remain disabled. Programs with a missing or invalid identifier should be automatically detected and sorted out by the DNC system.

Modern efficiently designed DNC systems reduce the amount of handling required for NC programs by more than 90% compared with conventional work methods, according to research by the Quinx AG. This means that these systems pay for themselves extremely quickly.

A detailed logbook listing all transactions is essential, especially when traceability is required, as in ISO 9001 and in medical technology governed by DIN EN ISO 13485:2003. In this manner, it is always possible to determine what part was produced on what machine using which program version.

Requirements and Functions

A modern NC data-management system:

- Manages NC programs organized by machines or groups

- Manages manufacturing information, that is, documents of all kinds, pertaining to the NC program

- Manages NC programs according to a logical identifier in accordance with the conventions of the production-planning system (PPS)/enterprise resource planning (ERP) system

- Indicates ongoing transfers

■ Automatically disables and enables programs that are in use, that is, that are being transferred or are open in the editor

■ Is designed for multiuser operation

■ Allows integration of external editors, for example, the CAM system

■ Shows with a mouse click all the changes in a modified program, that is, performs program comparison

■ Provides import and export functions for programs and documents

■ Provides automated data import from CAM systems, tool-management systems, and presetting devices from a wide range of manufacturers

■ Keeps a logbook listing all transfers, such as actions of the PC users, loading and saving of programs from the machines, and so on

■ Automatically archives obsolete program versions

■ Maintains statistics of file transfers

Examples are presented in Figures 28.6 through

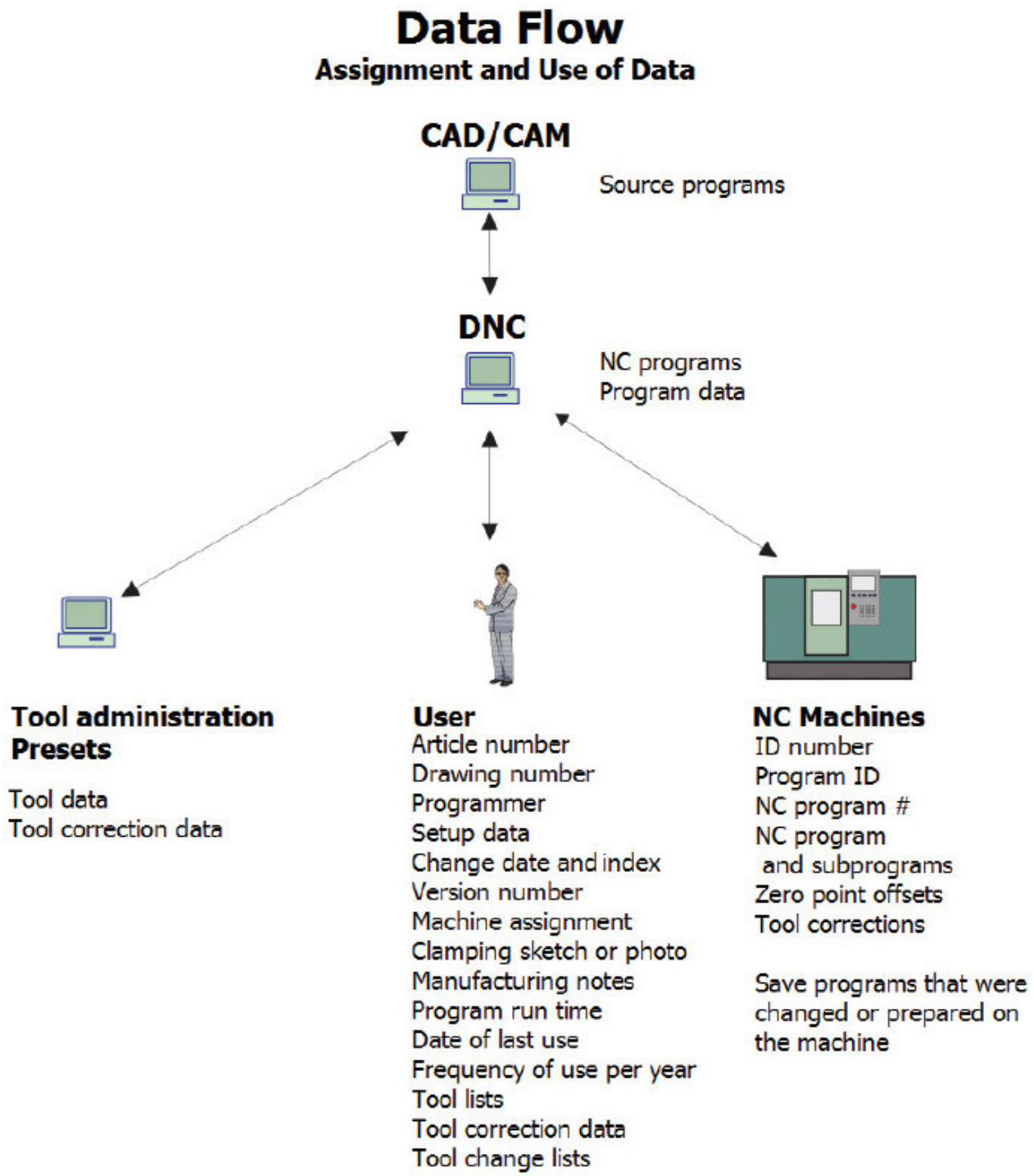

FIGURE 28.6 Distinction of data and their assignment and use for production.

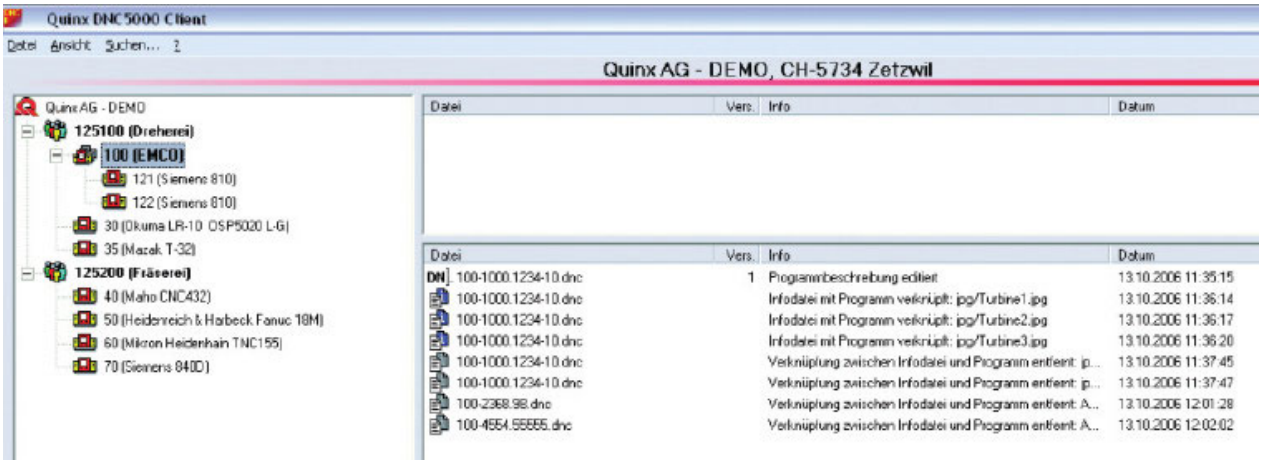

FIGURE 28.7 Machine overview ongoing transfers

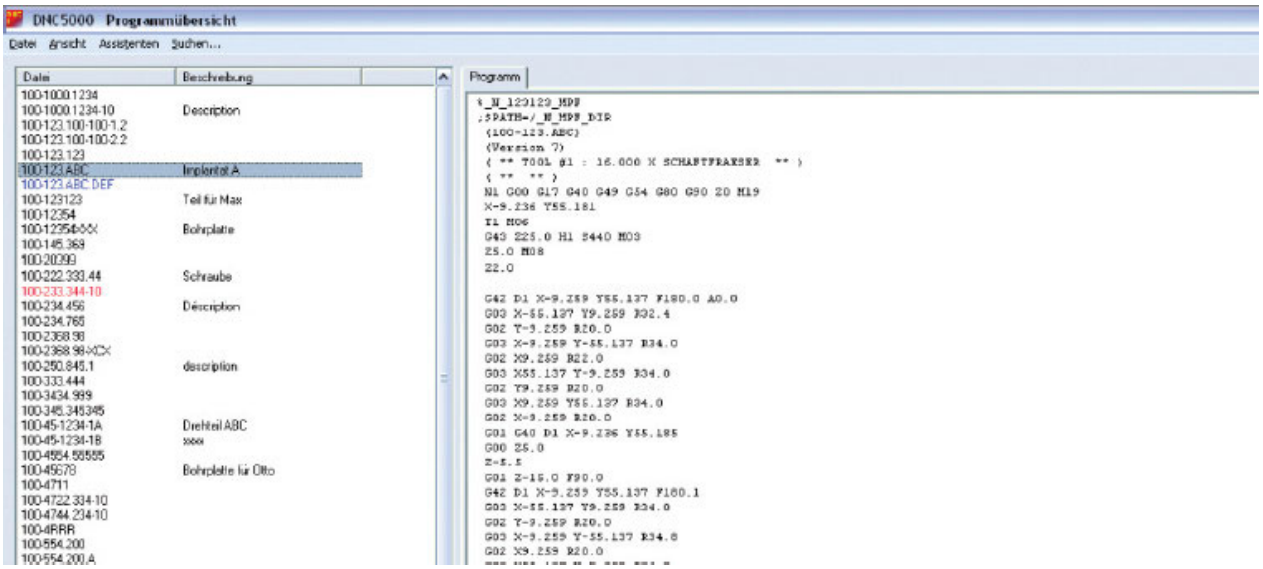

FIGURE 28.8 Machine log and file details.

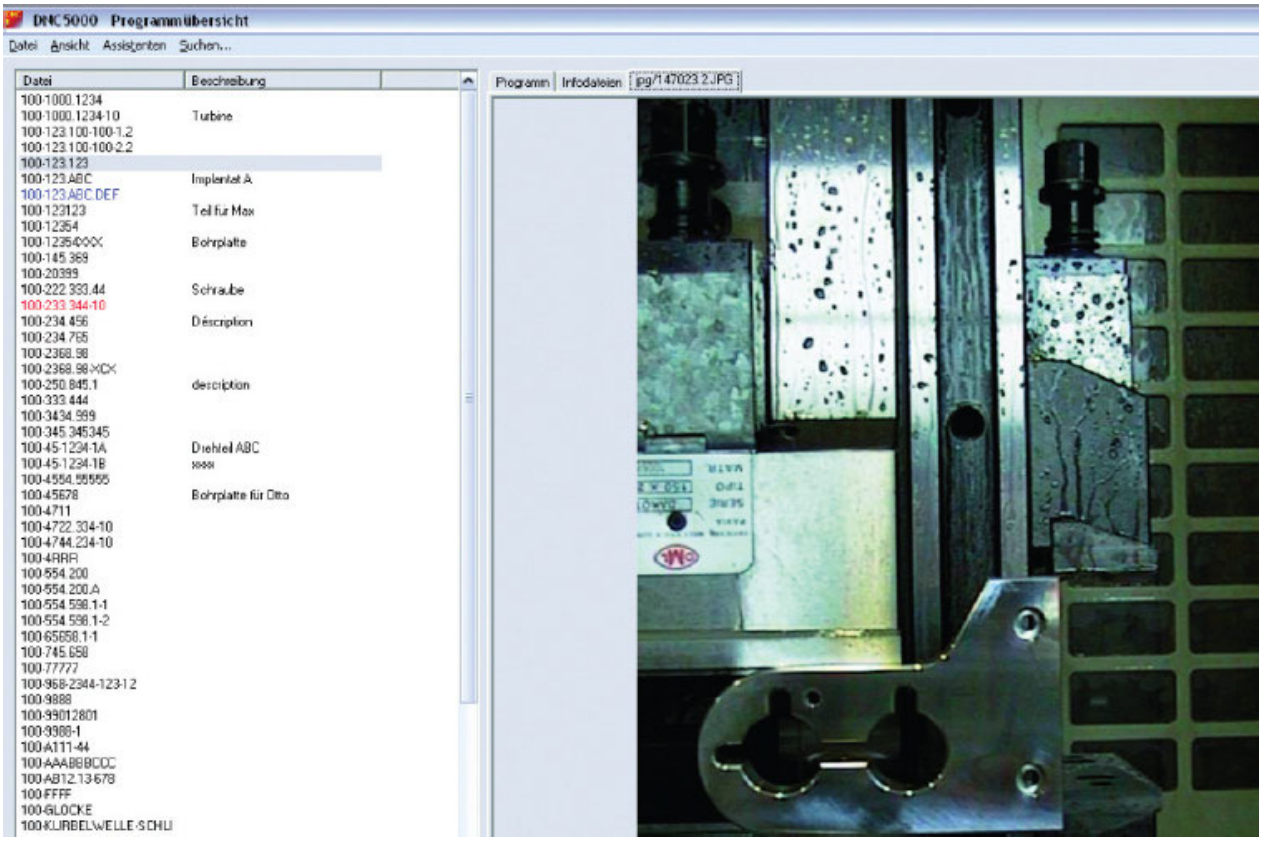

FIGURE 28.9 Production data for marked NC program: photo of a clamping situation.

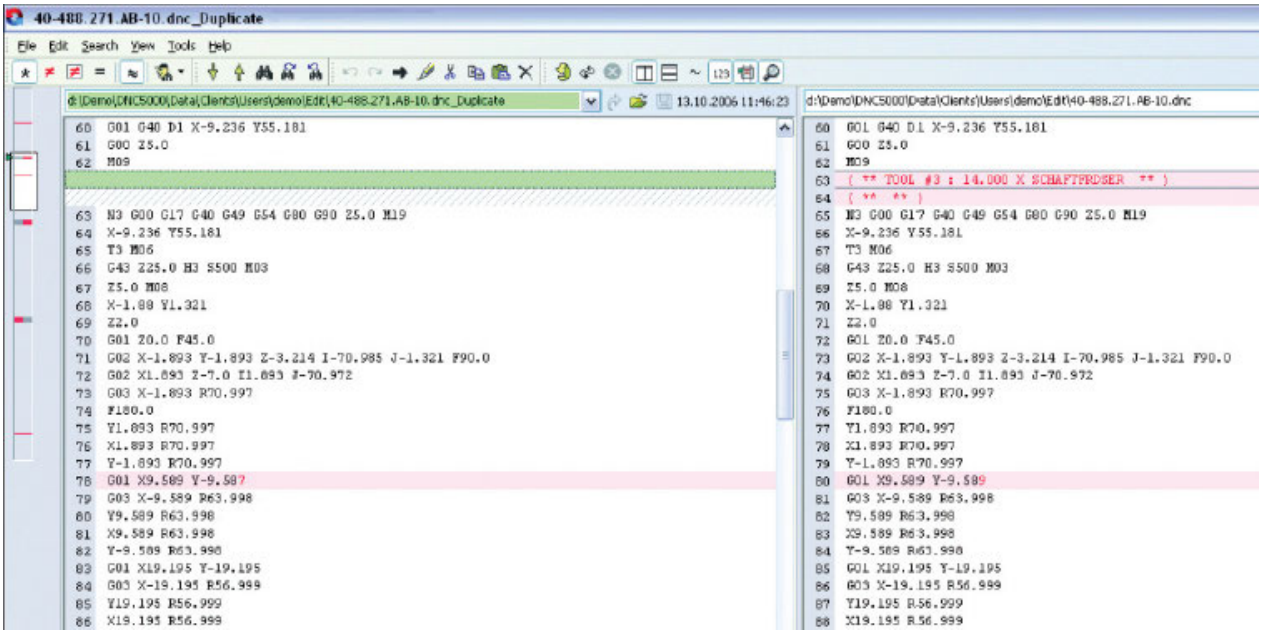

FIGURE 28.10 Automated program comparison.

ADVANTAGES OF DNC OPERATION

Introduction of a DNC system provides the following advantages:

- Higher productivity thanks to shorter changeover times
- Absolute reliability of data transfer over long distances
- Program read-in at maximum speed
- Simplified data management
- Reduction of tedious, routine work that is performed by the person responsible for the programs
- Traceability with detailed transfer logs (ISO 9001, DIN EN ISO 13485:2003)
- Absolute safety from mix-up of data media
- Error-free data entry even at maximum transfer speeds, for example, during operation of high-speed cutting (HSC) machines
- Guaranteed use of the most current program
- Simple, automatic, clearly structured program management

■ Quicker availability of programs and compensation values

■ No machine downtime due to missing programs

■ Trouble-free availability of tool data and compensation values

■ Avoidance of extensive libraries of punch tapes or disks, including the associated cabinets

For systems with an expanded scope of functions, advantages include:

■ Better utilization of tool service lives thanks to a closed data circuit

■ Minimization of tool changes when the program is changed

■ Better transparency of information, especially with a view to interlinked production systems

■ Operation of NC machines that is generally more flexible and fully automated

■ Greater use of machine times

COST-EFFECTIVENESS OF DNC

The total cost of a DNC system today ranges from about $1,000 to $5,000 per machine depending on the manufacturer, the CNC systems to be connected, and their interfaces. Given an hourly operation cost of $150 per machine and an increase in productivity of only 2% for 2,875 hours, a total investment of $15,000 will be returned in only two years in a two-shift operation.

Each buyer must calculate the cost-effectiveness based on the actual situation. The inexperienced user should seek an entry-level DNC system that is easy to expand if the user experience is positive.

The most important consideration is compatibility with existing equipment and the portability of custom software that may have been created previously.

The following criteria can be used to evaluate a DNC system:

■ *DNC* Not all manufacturers' products are able to withstand tough manufacturing environments (e.g., interference, temperature changes, mechanical shocks, continuous operation, and atmosphere). The computer should have a standard operating system, and the electronic devices (i.e., network adapters, terminals, etc.) should be in compliance with Federal Communication Commission (FCC) specs.

■ *DNC* This should be modularly expandable, service proven, and error free, and above all, it should fulfill the written requirements.

■ *Transmission* For example, coaxial cable, twisted pair, fiber-optic, etc.

■ This should be standardized if possible, such as Ethernet with TCP/IP.

■ *Manufacturer or* The company should have sufficient experience, its own development department, a well-thought-out product, a stock of spare parts, and adequate service support.

■ This should be appropriate for a quality product, which is a precondition for a short payback period.

■ *Emergency contingent* These should be in place in the event of failure of the DNC computer, the transmission line, or the connection terminal.

CURRENT STATE AND TRENDS

Today, DNC systems are an integral component of industrial information technology (IT). They supply the CNC machines and personnel with all the data related to production. They use high-performance industrial computers as a universal management and distribution system for all manufacturing data. Their scope of functions has been expanded considerably compared with earlier DNC systems. Reliability and speed also have increased. For use in flexible manufacturing systems, there is an option that allows access to all the manufacturing-related data.

The objective for the coming years is *digital* This means that data generated with a CAD system are processed into NC programs with the aid of computers and can be passed on to the CNC machine with no errors via a DNC system. New technologies such as HSC, rapid prototyping, and laser applications require large amounts of data and very high transfer rates. The punched tape of old is completely inadequate for this. Electronic data media such as magnetic tape and floppy disks are unsuitable for use in production shops and are not economical because they require reading devices. The best solution is a network-based DNC system.

Upcoming DNC systems therefore include the latest developments in the field of IT, that is, network technology, Internet, Intranet, etc., but they also meet the requirements of existing older machines and CNC systems. In most DNC

installations, it is necessary to connect at least some older NC machines.

Modern CNC systems are equipped with universal data communication functions and standardized LAN interfaces. This means that, as with other network devices (e.g., CAD, PPS, tool management, NC programming, etc.), they can easily be integrated into the flow of information within the company.

There will be a market for DNC systems in the future because these systems will be required for a long time, even if new machines come with their own network connections. DNC systems and the network are already provided for during the planning process for new installations.

The path to DNC is already clearly marked in shops with many NC machines present or planned. The same applies for the installation of new technologies, even for only a few machines. DNC systems are absolutely indispensable for flexible manufacturing systems. Flexibility can only be attained if fast changes in machining are supported by the equally fast availability of NC programs, tools and tool data, compensation values, and zero-point tables. Pictures of the workpieces in various clamping positions also help operating personnel to become familiar with new workpieces more quickly.

SUMMARY

DNC systems have three main tasks:

■ Management of NC programs for all the connected CNC machines

■ Timely transmission of NC programs to the CNC machines

■ Activation of data transmission:

●Manually from a central location

●Automatically or manually from the CNC machine

This means that it must be possible to make the data request for transfer of an NC program to a specific CNC system either from the computer or from the CNC system. The DNC computer does not perform or replace any of the functions of the CNC system. Even in flexible manufacturing systems, in which all CNC machines are supplied with data via the DNC, CNC systems still retain all their control functions. Each CNC system has a DNC connection for automatic data exchange with the DNC computer. Today, this is generally an Ethernet interface. If several machines request programs from the DNC system simultaneously, the transmission sequence has to take place according to specified priorities.

Computers have been given more and more tasks over time because of the high performance of DNC systems. For example, in addition to transmitting NC programs, it is also necessary to transmit the programs for the workpiece-handling devices and any measuring programs that are necessary for in-process measurements. Additionally, there are the current compensation values for the length and/or diameter of the tools, tool wear, necessary zero-point offsets, operator notices, and clamping plans.

For protection against incorrect program transfers, additional information is necessary, such as:

■ Checking whether the program number is enabled for this machine

■ Operator, time, and date of call-up

■ Enabling the new program for activation and processing of the parts

■ Comparison of the required tools with the tools present in the tool magazine and issuing a “Tool XXX missing” message to the operator

Another very important task is automatic transfer of the MDA/PDA data from the CNC system to the central computer. This comprises the following:

- Run times and downtimes of the machine
- Production count, reject messages
- Interruptions of production with causes
- Machine downtimes with causes
- Error messages generated for statistical analysis
- Maintenance notes and monitoring of execution

For purposes of operator control, it is also important whether the communication between the CNC system and the DNC computer takes place via the keyboard integrated into the CNC system or an additional DNC terminal. Today, it is more economical and more common to use the operator panel of the CNC system, but this requires an interface adapter for each brand of CNC and possibly involves different operator control inputs. Using DNC terminals at the machines has the advantage that the operator controls are largely identical.

Last but not least, the type and speed of data transfer are important. The transmission speed should be as high as possible to prevent data transfer from becoming a bottleneck, and it also should be absolutely error-free. Today, both of these requirements are fulfilled by Ethernet connections. Systems with wireless transmission are also available.

IMPORTANT POINTS TO REMEMBER

1. The present meaning of DNC is "distributed numerical control," and it expresses the idea that the scope of DNC functions can be distributed among several computers that communicate over a LAN.

2. Modern DNC systems have clearly defined jobs:

a. Supplying the connected machines and automation equipment with NC part programs and other manufacturing-related data in a timely manner

b. Reducing wait times for NC programs and other manufacturing data

c. Introducing a system of data organization with the help of meaningful program identifiers

d. Replacing portable data media with all their disadvantages, such as storage and management, damage, loss of data, and cumbersome handling on the machines

e. Managing any required number of NC part programs and amounts of manufacturing information in the DNC computer

f. Returning corrected NC programs from the machines to the DNC system with indication of the changes

g. Better information for operators at the machines

3. There are several options available for bidirectional data transfer:

- Star connections from the computer to each device via a multiple-interface card

- LAN with the advantages of absolute data reliability and high transmission rate

- Wireless transmission to and from the machines is also possible.

4. The CNC systems connected to the DNC do not require any data-reading devices. This eliminates downtimes for maintenance work and the cost of keeping spares available.

5. A choice of various systems is available as the transmission medium. LAN interfaces, such as for Ethernet with the TCP/IP, are recommended.

6. Modern CNC systems must in any case have an integrated LAN connection.

7. In the case of extra long NC programs, uninterrupted operation is possible through the automatic loading of multiple program sections.

8. The master data or header data of NC programs serve the following purposes:

a. Better management, identification, and labeling

b. Prevention of improper use

c. Providing information to the operator

9. MDA and PDA are not DNC expansions but rather separate function modules that use the existing DNC hardware and software.

10. DNC systems have a clearly delineated range of functions and, for example, do not include any FMS process-control functions.

11. The cost-effectiveness of DNC systems is indisputable.

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INTRODUCTION

The computers and computerized numerical control (CNC) systems that are used in the various computer-aided technologies (e.g., CAD, CAM, CAQ, CAR, CAI, and CAE) are data-generating and data-processing systems. As more of these devices are installed, it becomes increasingly important for them to be capable of exchanging data with one another. This happens in the company's internal data network

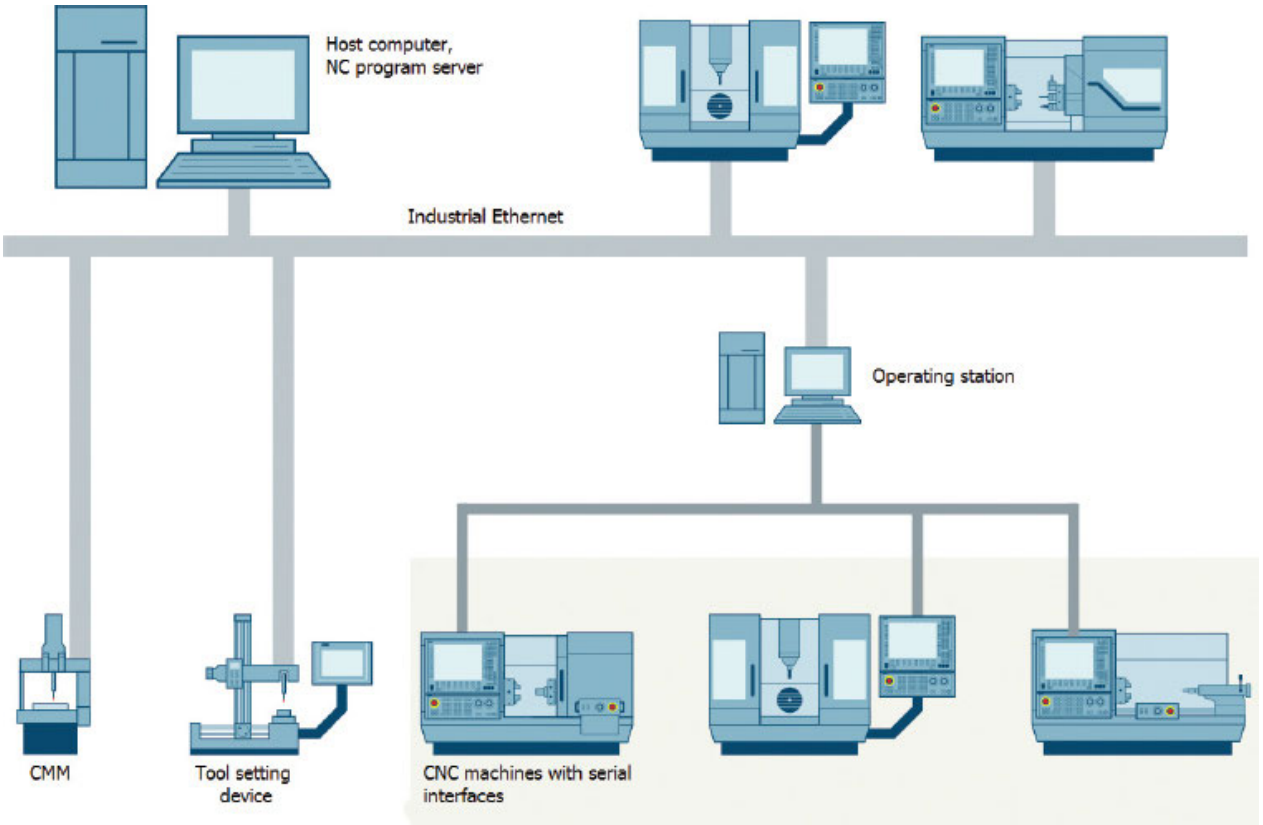

FIGURE 29.1 Communication of CNC machines and peripherals with a DNC computer within a LAN or serial interface.

Broadband cables and networks transmit multiple types of information simultaneously between various transmitters and receivers. Broadband networks of this type are comparable with familiar cable television networks. These cables also carry multiple television and radio programs simultaneously, in addition to videotext. From this multitude of information, each receiver extracts only the program to which it is tuned. However, this requires a cable tuner that converts the programs from the cable frequency to the standard input frequency of the devices. There are three modes of operation:

Traffic flows in one direction only, from the transmitter to the receiver.

Information from the cable television use is sent back to the central office during television programs.

Only one participant can transmit at a time

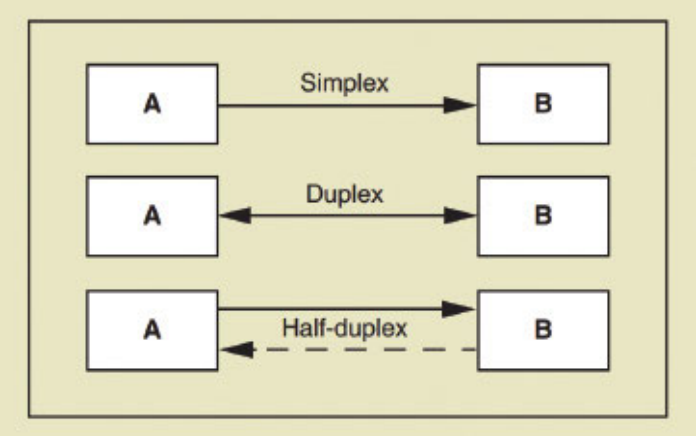

FIGURE 29.2 Simplex, duplex, and half-duplex transmission principles.

One critical difference between LANs and cable television networks is that the individual customers on a cable television network cannot

communicate with each other.

LOCAL-AREA NETWORKS (LANs)

LANs are data networks that are limited to a particular geographic area. LANs do not expand beyond the company's premise and thus are free of any regulation by public authorities. Figure 29.3 provides an overview of the range of communication options. A connection between computers located far apart is called a *wide-area network* and requires publicly available facilities such as telephone cables, ISDN or DATEX-P, or a *direct subscriber line*

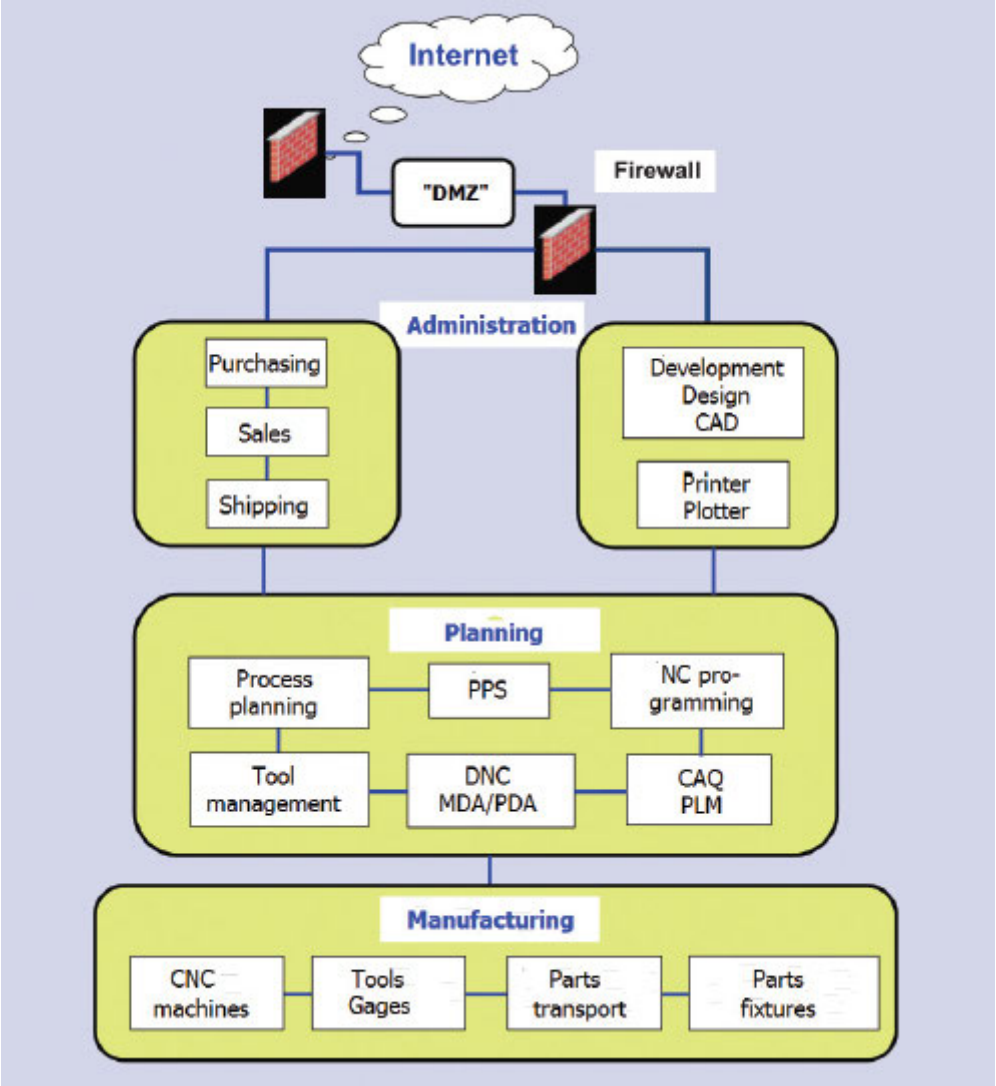

FIGURE 29.3 Schematic of communication between the internet and the company intranet. DMZ stands for "demilitarized zone," that is, a high degree of protection with two routers, two different IP addresses, and two firewalls.

WHAT IS INFORMATION?

Information can take the form of data, images, drawings, or control programs. Information processing involves the control and documentation of processes and relationships in various areas within a company. Information is used to regulate inventory management and production (in production planning systems), to control NC machines and robots (DNC, CNC), to log production data and breakdowns (MDA/PDA), and to reduce unnecessary downtimes (CAQ, diagnosis, maintenance), thus increasing the profitability of a manufacturing operation. This is also the reason for the increasing interest in data networking within companies.

What does a company need to do to gather and distribute information more quickly and then use it to carefully control manufacturing?

■ The most important requirement is the use of computers and peripheral devices, databases, and suitable software tools so that information can be generated, stored, and distributed.

■ IT is absolutely essential to build an information network that allows all users to access all the information they need. As automation increases, more and more locations in the production environment will use this information and feedback results. These data networks therefore must be reliable, fast, expandable, and secure.

■ The devices connected to the network must be equipped with data interfaces that allow them to communicate with each other across the data network. The hardware and software involved in these interfaces must be adapted to the common data network.

CHARACTERISTICS AND FEATURES OF LANs

A number of different LAN systems exist today. Although their basic task is always the same, there are significant differences in features. These differences lie within the following seven areas:

- Transmission technology
- Transmission media
- Network topology
- Access methods
- Protocols
- Transmission speed
- Maximum number of devices

Transmission Technology

Local data networks employ two different methods of transmission depending on the requirements of the situation at hand:

- The baseband method
- The broadband method

Baseband technology makes use of a single transmission channel that is made available to each participant for communication for only a short time. This method is called *time-division* Because it does not require any costly modulation/demodulation devices, this principle is more affordable than broadband technology.

In broadband technology, each channel uses only its own limited portion of the available broadband frequencies. For this reason, this method is also known as *frequency-division* Each method has its own advantages and disadvantages.

The information that is transmitted by either of these methods is electronically "compressed" to improve the integrity of the data transmission. The transmission is so fast that the data cannot be read directly but must be made readable for the receiver by a so-called converter.

Transmission Medium

In information technology (IT), the term *transmission medium* is specified as:

■ Wired transmission (e.g., LAN or WAN):

● Twisted-pair cable as unshielded multitwisted pair or as shielded pair with shielding of the individual pairs

● Coaxial cables, two-pole cables with concentric design

● Optical waveguides such as fiber-optic cables, polymer optical cables, or polymer-clad silica cables

■ Wireless transmission (e.g., WLAN):

- Radio technology
- Infrared
- Bluetooth

Single-twisted pairs, shielded multitwisted pairs, coaxial cables, or fiber-optic cables may be used for data transmission. The choice depends on the frequencies that are transmitted, which may range from 500 kHz to 10 GHz. Fiber-optic cables offer the highest protection against possible interference, but they require more expensive modems for modulating and demodulating the transmitted data

TABLE 29.1 Transmission Media and Their Capacities

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Cable Lengths

The possible cable lengths for Ethernet LAN cannot be generalized. For up to 1 Gb/s, one can assume a length of 100 m, including patch cables with plugs/sockets. This presumes 90 m of cable length plus 10 m of patch cable as a connection between wall socket and computer.

For up to 10 Gb/s networks, the length depends on the cables used. For a 100-m transmission, cables of certain categories, such as Cat-6 shielded or Cat-6A, must be used; otherwise, only 45 m or even less can be reached. The installation effort is significantly higher and is not suitable for common workplace networking. Transmission speeds of 40 or 100 Gb/s cannot be reached with copper cables but require fiber-optic cables. The maximum cable length depends on several factors and must be determined based on local conditions.

Network Topology

The current standards for LANs are bus, ring, star, or tree structures 29.4 and In bus networks, all devices are connected to a common line. Bus networks are characterized by short, simple wiring schemes for the overall network. The data are always transmitted along a direct path from sender to receiver. In ring networks, all stations are connected to a ring line, meaning that each station is connected to at least two adjacent stations. The data pass through the ring in a predefined direction and return to the starting point.

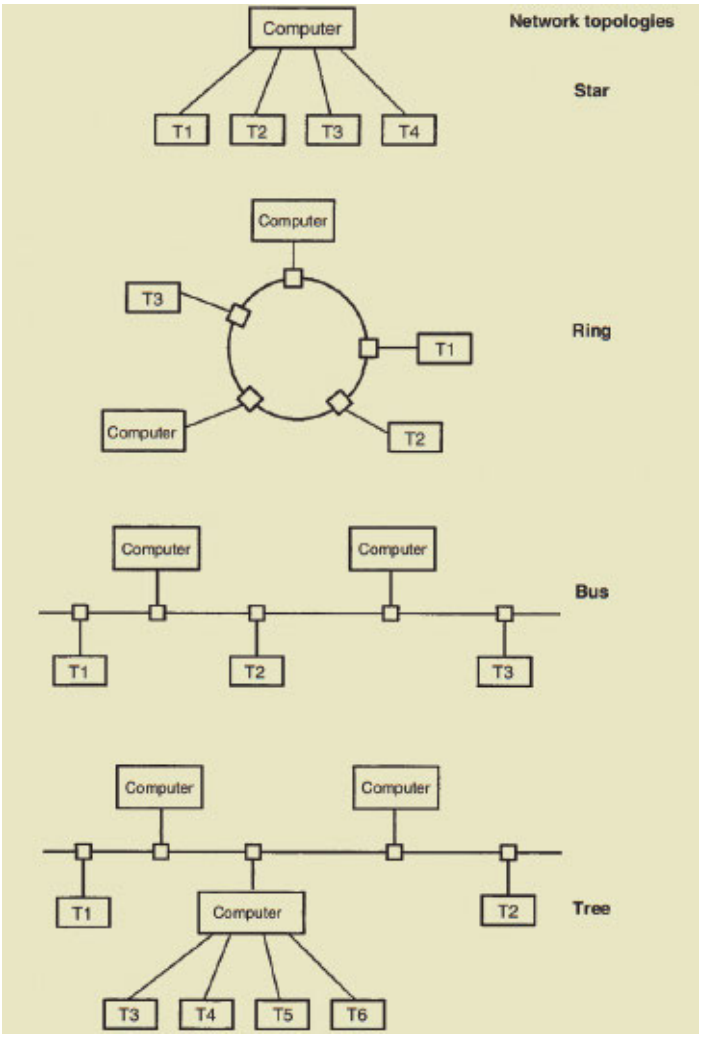
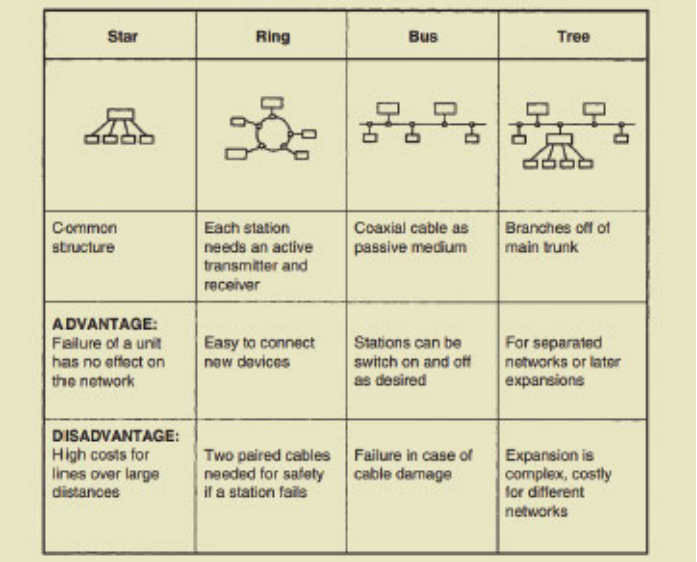


FIGURE 29.4 Star, ring, bus, and tree structures of local networks ..., = devices 1 to 6).



Star	Ring	Bus	Tree
Common structure	Each station needs an active transmitter and receiver	Coaxial cable as passive medium	Branches off of main trunk
ADVANTAGE: Failure of a unit has no effect on the network	Easy to connect new devices	Stations can be switch on and off as desired	For separated networks or later expansions
DISADVANTAGE: High costs for lines over large distances	Two paired cables needed for safety if a station fails	Failure in case of cable damage	Expansion is complex, costly for different networks

FIGURE 29.5 Topologic structure of networks and their advantages/disadvantages.

To prevent a break in the ring from causing a total breakdown in data transmission, the token ring network employs a redundant wiring scheme involving twisted pairs. Malfunctioning lines or devices can be bypassed by automatically or manually creating a short circuit in either the outgoing or return line.

The simplest form of data transmission from the DNC computer to the CNC system is accomplished by means of direct cable connections. In such a star network, all devices are connected to a central station. They cannot communicate with each other directly but only via the central station. Because each connection uses one interface on the computer, this type of network configuration is suitable only for connecting a small number of devices. The tree structure is a combination of the above-mentioned topologies.

Access Methods

The access method determines which station may send information and how the receiving station will recognize the message intended for it. A distinction is made here between methods that are collision free and those that allow collisions to occur as the data network is accessed.

In principle, the following access methods are used:

- Master-slave procedure (Interbus-S)
- Token ring (Token Ring protocol)
- Token passing (Profi-Bus)

It is an important principle to detect and prevent collisions. A collision takes place when two (or more) signals are simultaneously on a common line. In this case, the two electrical signals overlap to a common voltage level with the consequence that the receiver can no longer distinguish the electrical signal according to the individual logical signals (bits).

- *Carrier Sense Multiple Access with Collision Detection (CSMA/CD)*
- *Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)*

With CSMA/CD with arbitration in case of collision (i.e., the subscriber with the higher priority continues to transmit), the subscriber with the lower address has the higher priority. This means

that the subscriber with the lowest address has the highest priority and thus real-time capability.

In the master-slave procedure, one participant is master; all others are slaves. The master is the only one who has the right to access the common resource without being asked. The slave cannot access the bus on its own; it must wait until it is asked by the master, called

The main advantage is that only the master controls the access, which prevents collisions. The disadvantage is that communication between slaves is not possible. In addition, the polling of the slaves by the master is inefficient.

The problem of communication between slaves can be reduced by the process of *accelerated data* Here the master transmits to slave 1 the command "Receive data." Slave 2 receives from the master the command "Send data," whereupon slave 2 begins the data transfer.

If slave 1 receives the data including an "End of message" sign correctly, it in turn sends an "End of message" sign to the master. This requires a slightly higher intelligence from the slaves, which, however, also affects the price of the hardware.

Master-slave architectures can also be combined with the token bus, where only the master can pass on the token. The token principle means that a special pattern of bits, the constantly circles around the It is passed on like a relay baton from one active device to the next. In order to transmit, a station must possess the token. To do this, the station that is ready to transmit must wait until the

arriving token indicates that it is "free." The station then changes the status of the token to "busy" on the fly, adds the source and destination addresses, and attaches the data to be transmitted. The destination station recognizes its address, copies the data into its input buffer, and sets the "copied" bit as a flag. The entire data stream eventually returns to the transmitting station. Just to be sure, the transmitting station compares these data with the transmitted data for verification, removes them, and sends a "free" token along the ring. This prevents data collisions. Token passing is a hybrid access method of token ring and master-slave. The basis of token passing is that the token in a network is passed on from a master station to the adjacent master station in a logical ring topology.

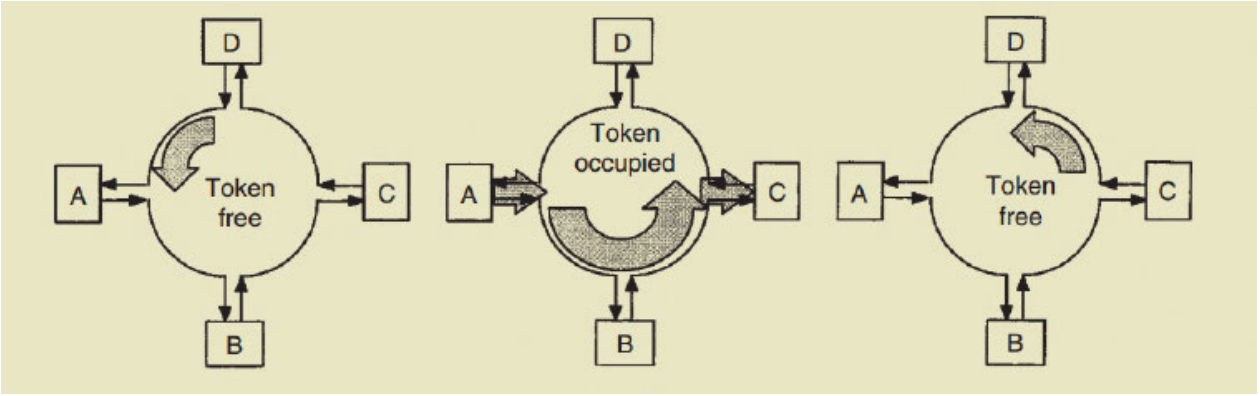


FIGURE 29.6 Token ring principle (sending from *A* to

The term *Carrier-Sense Multiple Access/Collision Detection* (CSMA/CD) refers to an asynchronous media access protocol that regulates the access of different stations to a common transmission medium. If several stations want to use the bus at the same time, collisions may occur that will render the transmitted signals unusable. To effectively prevent this, the CSMA/CD protocol is used to detect collisions, react to occurring collisions, and prevent them from repeating.

Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) is a principle for collision avoidance when several users access the same bus. It is also used in a modified form in communication methods such as Integrated Services Digital Network (ISDN) or in many communication networks where multiple clients put data on a bus and collisions must not occur. This problem does not happen in centrally coordinated communication networks.

In cases of collision-prone access, each station can send at any given time. Possible data collisions are deliberately accepted and lead to the immediate termination of the ongoing transmission. After a random waiting period, the transmission restarts, and the first transmitting station blocks access for all other stations. This procedure is called *Carrier Sense Multiple Access/Collision Detection* (CSMA/CD) and is known under the trade name Today it is the most widely used LAN.

Protocols

The term *protocol* refers to established conditions, rules, and conventions that are intended to provide a reliable exchange of information between two or more communicating systems or system components. A protocol is the set of rules governing the communications in a data-transmission system. The protocol provides the code, method, direction, and format of the transmission and the establishment and termination of the connection. An example might be the human language and its rules. People who converse in the same language can engage in a two-way exchange of information by using their mouths and ears (= Language, as a means of communication, is defined by words and their meanings, a grammar, and pronunciation (=

If, by contrast, each person understands only one language and this language is different from that of the other person, no communication will be possible, even if each party can do both, speak (transmit) and hear (receive). In order for data transmission to function properly, the interfaces and protocols of all participants must be either identical or capable of being made compatible by converters. This is to say, they must speak and understand the same language, or they need an interpreter. Furthermore, it is important that transmitting and receiving speeds match.

Transmission Speed

The transmission speed must be as high as possible in order to transmit as much data per second as possible and to avoid wait time Transmission speed and data rate are the same thing. In the context of digital signals, one speaks of meaning the available capacity per transmission step. As a rule, it is expressed in bits per second (b/s), kilobits per second (kb/s), megabits per second (Mb/s), or gigabits per second (Gb/s). The units bytes per second, B/s, kB/s, MB/s, and GB/s, by contrast, are uncommon. The expression for transmission speed in bauds is mostly wrong because a baud is defined as a unit for the step speed (baud rate). If only two different voltages are used, such as 0 and 1 in RS-232, then one bit is transmitted in one step, meaning at 9,600 baud, 9,600 b/s are transmitted. But if several different voltage levels are used, then several bits per baud are transmitted.

TABLE 29.2 Transmission Speeds in Comparison

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If the CNC machines in a data network have a limited download speed, then a converter must be placed between the LAN and the CNC. It puts the data that are arriving at a higher speed into a data buffer and sends them to the CNC machine with the correct reading speed. Most CNC machines have fast data interfaces. Although data are flowing past all participants, they must only be delivered to the particular participant with the correct address. For this reason, the converter also has the job of filtering and unpacking of the information

Maximum Number of Devices

A maximum of 1,024 stations can be connected to an Ethernet network with a length of the network of up to 2,500 m, not including gateways or routers. Standard Ethernet has a transmission speed of 10 Mb/s, Fast Ethernet 100 Mb/s, and Gigabit Ethernet 1,000 Mb/s. Fast Ethernet and Gigabit Ethernet require twisted-pair or fiber-optic cables because coaxial cables do not allow these high frequencies.

The performance data of field buses CAN, InterBus-S, and Profi-Bus are practically identical because they are physically based on serial interface type RS485. Differences exist, however, with regard to the bus access procedures, the security mechanisms, and the transfer protocols.

The CAN bus is based on CSMA/CA; thus the maximum cable length is not easy to calculate. It is about 1 km at a transfer rate of 50 kb/s. The maximum number of devices is limited to 64 (or 128 with restrictions). Interbus-S can transmit 500 kb/s between two parties to up to 256 at ranges up to 40 m. Profi-Bus can serve 32 devices and with the use of repeaters up to 127 devices. Between two communicating participants there may only be three repeaters or fewer. The transfer rate at a range of 200 m is 500 kb/s; at 1,200 m, it drops to 93 kb/s.

GATEWAYS AND BRIDGES

The purpose of data communications is to provide information at the desired location, no matter where that location may be. Local networks are actually incompatible with this objective because they are restricted to a certain building or department, as mentioned earlier. Thus it is possible for multiple LANs to exist within a single company. This created the need for devices that can carry information from one LAN to another network. These devices are called *bridges* or *gateways*

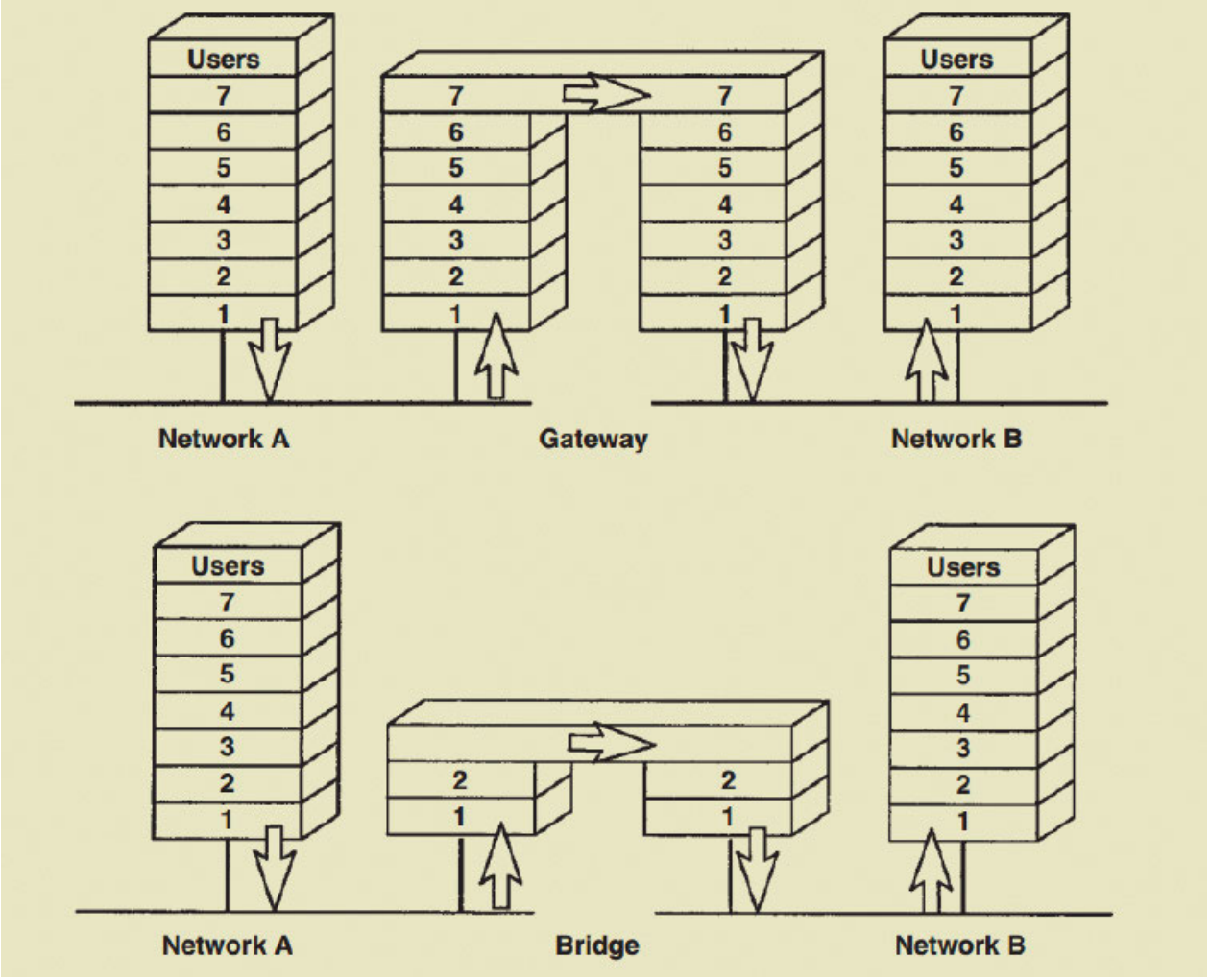

FIGURE 29.7 Gateway for connecting dissimilar data networks; bridge for connecting similar data networks.

The term *bridge* refers to a device, usually a computer with accompanying software, that makes it possible to connect similar LANs and provide communication between the stations of these similar networks. Because, by definition, the connected networks are identical in type, the bridge does not provide conversion between protocols. However, the bridge must recognize the address of each data packet as it arrives and determine whether its intended recipient resides in the other network. Only then will the bridge direct this packet to the other network. This prevents unnecessary overloading of the networks. Bridges also can be used as amplifiers in order to extend the otherwise restricted length of a network.

Gateways, by contrast, serve to connect dissimilar networks. It is evident that a gateway can be a rather complex device because it must assume a wide variety of additional tasks such as protocol conversion, formatting, and matching.

CRITERIA FOR SELECTING A SUITABLE LAN

When selecting a LAN, the buyer must consider a number of essential criteria:

1. Maximum transmission speed in bits per second

2. Maximum quantity of data expected to be transmitted

number of devices that can be connected without problems

4. The issue of transmitting data to all devices in simplex, duplex, or half-duplex operation

5. Protection against failure of a single device or node because data transmission must not be compromised

6. Maximum allowable line length without intermediate repeaters

7. Number of conductors in the cable and the type of cable, such as shielded, twisted, coaxial, or fiber-optic

8. Minimum bending radius of the cable because this is relevant for purposes of installing cables in ducts

9. Installation conditions, for example, whether cables are installed together with power cables, in the presence of interfering

electromagnetic radiation, or severe network disruptions

10. Price, consisting of:

a. The base price for the LAN

b. The price per device connection

INTERFACES

The transmitted data must be capable of being entered into any of the connected systems. This is accomplished with the device interface. An *interface* is the precisely defined boundary between two hardware systems, such as computers, printers, CNC systems, or two software programs within one computer. It also can be defined in a broader sense as the "point where responsibilities are transferred," for example, from a cable television network to the service line of a particular house.

An interface can serve to connect two similar or dissimilar systems, for example, two identical computers, two different computers, a computer and a printer, a computer and a CNC system, a DNC system and a CNC system, or a person and a computer, in which case keyboard and display form the interface. The following considerations are restricted to interfaces that pertain directly to the CNC systems of machines, as in computer-aided manufacturing (CAM). These primarily include the interfaces that are used to transmit data to the machines, robots, transport systems, tool-management systems, measuring machines, and other devices. Figure 29.8 shows how interfaces are classified.

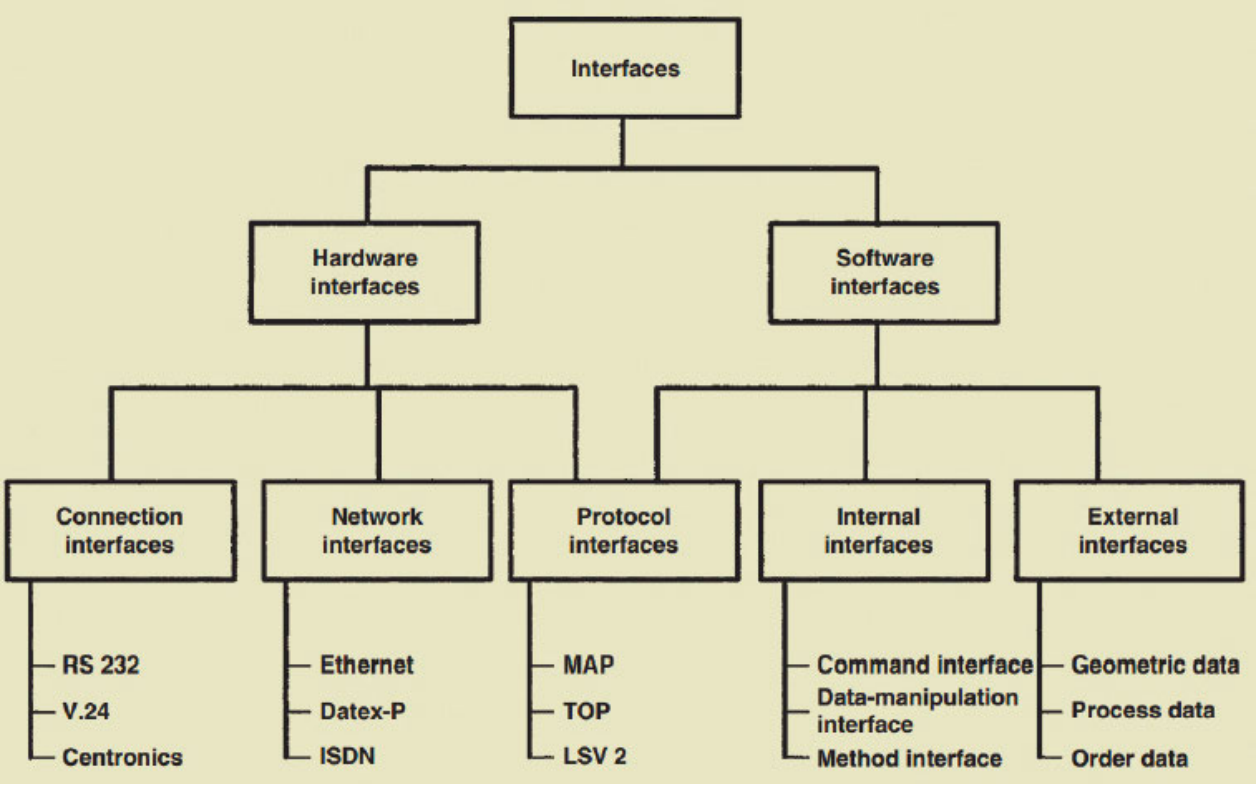

FIGURE 29.8 Classification of interfaces.

Hardware Interfaces

This term refers to the hardware-related specification of a device interface. For example, the hardware interface defines how many wires are used for transmitting, receiving, control functions, messages, clocking, and so on, as well as the design of the plug being used and its pin assignments. Hardware interfaces also can be described as device-connection mechanisms through which all information must pass when flowing into or out of a device. A distinction is made between bit-serial and bit-parallel interfaces.

In the case of *bit-serial* the information is transmitted in a certain chronologic sequence in a single line. For this reason, this type of transmission is slower than *bit-parallel* in which the individual bits of a given character are carried simultaneously on multiple lines. Parallel interfaces have some serious drawbacks, however:

- At least nine lines are required for 8-bit characters.

- The interfaces are technically complex.

- The cable length is limited to 1 to 3 m.

- Examples include Centronics and IEC-bus.

Because of the general preference for the use of bit-serial interfaces in data transmission, the most commonly used interfaces are examined in greater detail next.

The V.24 interface is a list that summarizes all the lines that might be significant for an interface and describes the functions of these lines. These include a total of 25 lines for transmitting, receiving, control, messages, and so on. Only seven of these lines are actually used, however.

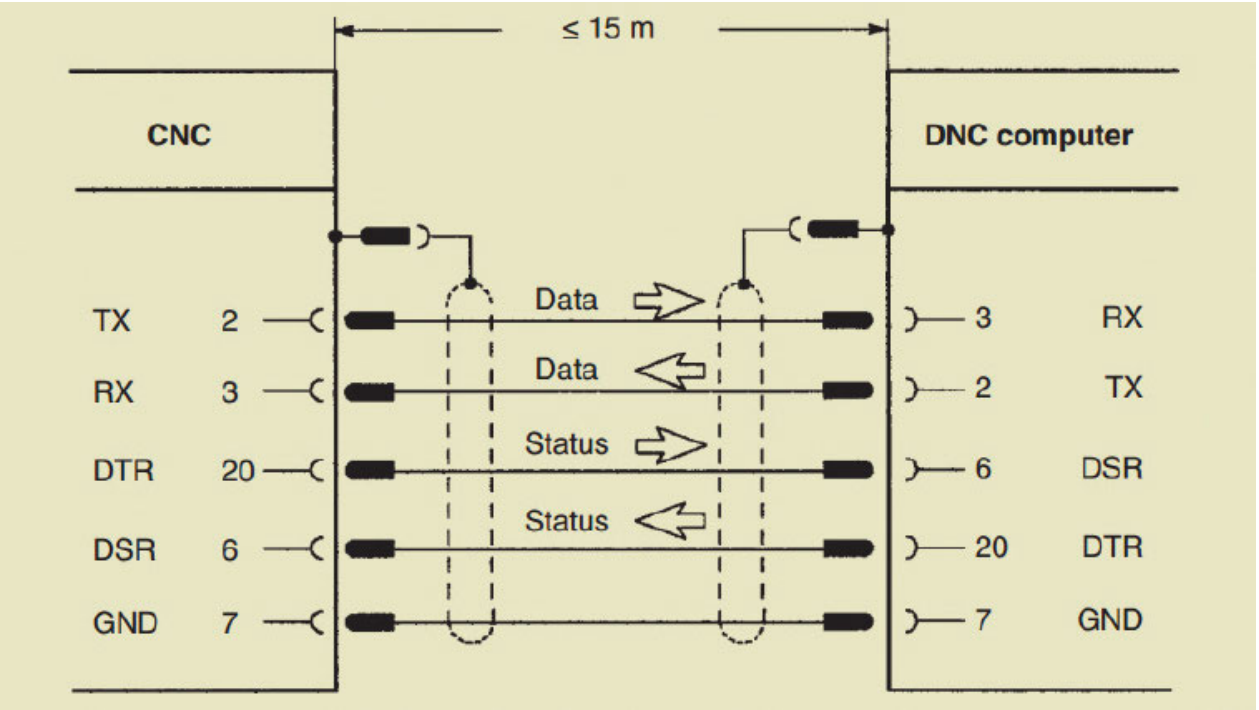

FIGURE 29.9 V.24 interface.

Handshakes

This is the procedure for controlling data transmission between two devices. In a start/stop operation, handshaking controls data transmission by allowing the receiving station to accept the transmitted data. If this becomes temporarily impossible, the receiver will issue a predefined signal to stop the transmitter until it is ready to receive again. A distinction is made here between software handshake and hardware handshake

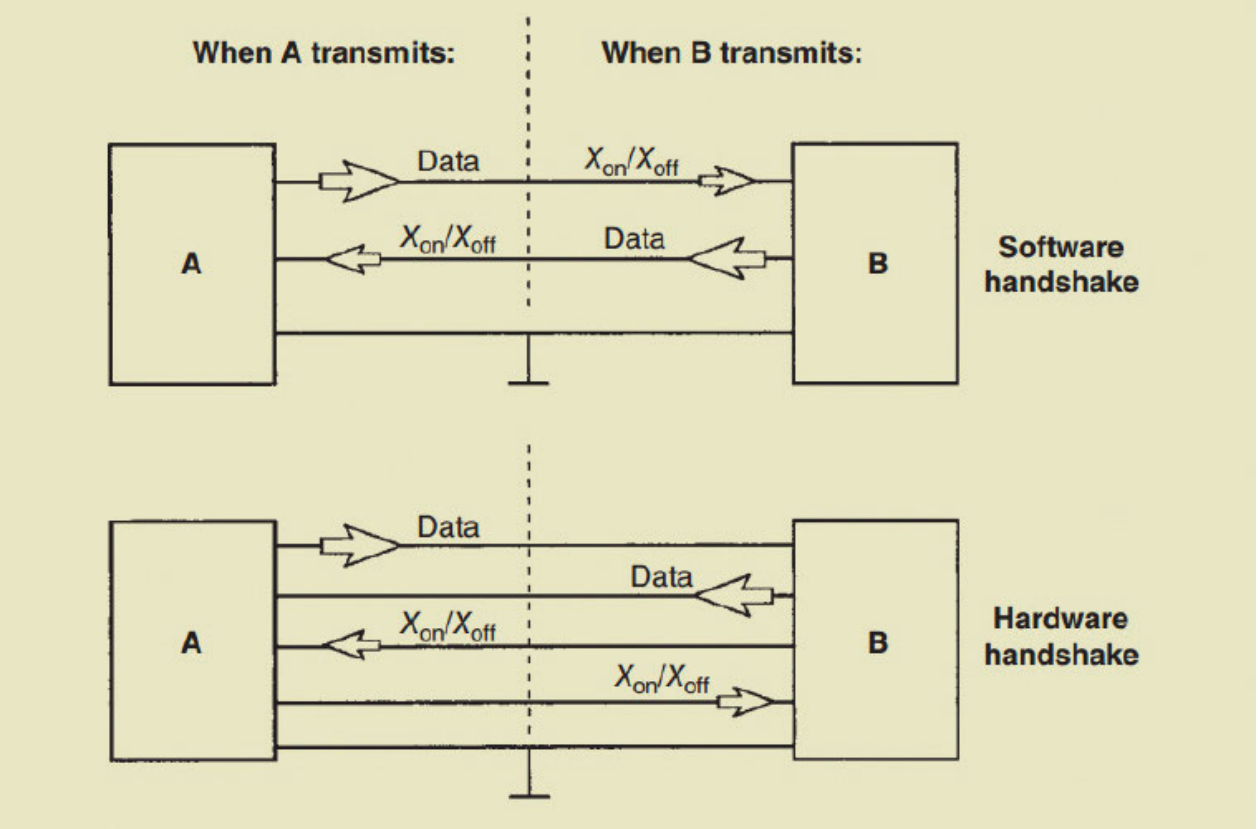

FIGURE 29.10 Principles of software and hardware handshakes.

The principles of these two types of handshakes differ only as to:

- The number of lines required
- The assignment of data and control lines

In hardware handshaking, two separate lines are defined for data signals and two for control signals. Software handshaking requires only two data lines. The function of the respective data lines varies according to the direction of transmission.

Software Interfaces

A software interface is a predefined point at which data are transferred from one software package to another (e.g., within a computer). The purpose and design of the interface are defined, as are the types of data that can be transmitted across it, such as:

- Product-defining data (CAD)
- Process-defining data (NC programs)
- CL-DATA in the postprocessor
- Order data (PPS)
- Examples: IGES, LSV 2, MAP, TOP

Synchronous and Asynchronous Transmission

Data transmission requires coordination of the timing between the transmitting and receiving stations. *Synchronous transmission* is a form of block synchronization; that is, the transmitter and receiver are synchronized with one another by means of a separate clock signal for the entire duration of the transmission of a data block. In *asynchronous transmission,* also known as the *start/stop* synchronization is performed by means of START and STOP bits and lasts only during the transmission of a single data word (e.g., V.24).

SUMMARY

The field of LANs, protocols, and interfaces is very broad and complex and typically the realm of specialists, as is the installation of a LAN. A company that plans to use a data network in the future therefore should begin training its own skilled help early on. It is also advisable to seek the advice of experienced specialists until the company has built up its own know-how. The purchaser should at least be able to specify the requirements in technical terms in order to prevent unpleasant surprises and additional costs later.

There is a widespread belief that a company needs to commit itself to a single type of LAN that is fully integrated from the top down to solve all its future data transmission problems. This is false for the following reasons:

- LANs are subject to a variety of different requirements with respect to the quantity of data being transmitted and the transmission rates

- Most manufacturers provide Ethernet interfaces as standard.

- Besides the choice of technology, the cost of an overall system plays an important role.

- Several of the available data-transmission systems can be recommended and are easy to implement. The purchaser is well advised to accept the supplier's recommendation.

■ The use of separate LANs will not necessarily be an obstacle to implementing a computer-integrated manufacturing (CIM) system in the future.

■ A general trend in future networking could be to set up several small, self-contained, easily managed networks and then connect them by means of bridges or gateways. But this approach should be adopted only under specific conditions.

■ The expanding field of local networks is subject to continuous change and development. At this time, Ethernet appears to be the most widely used standard with the greatest acceptance and the largest body of experience.

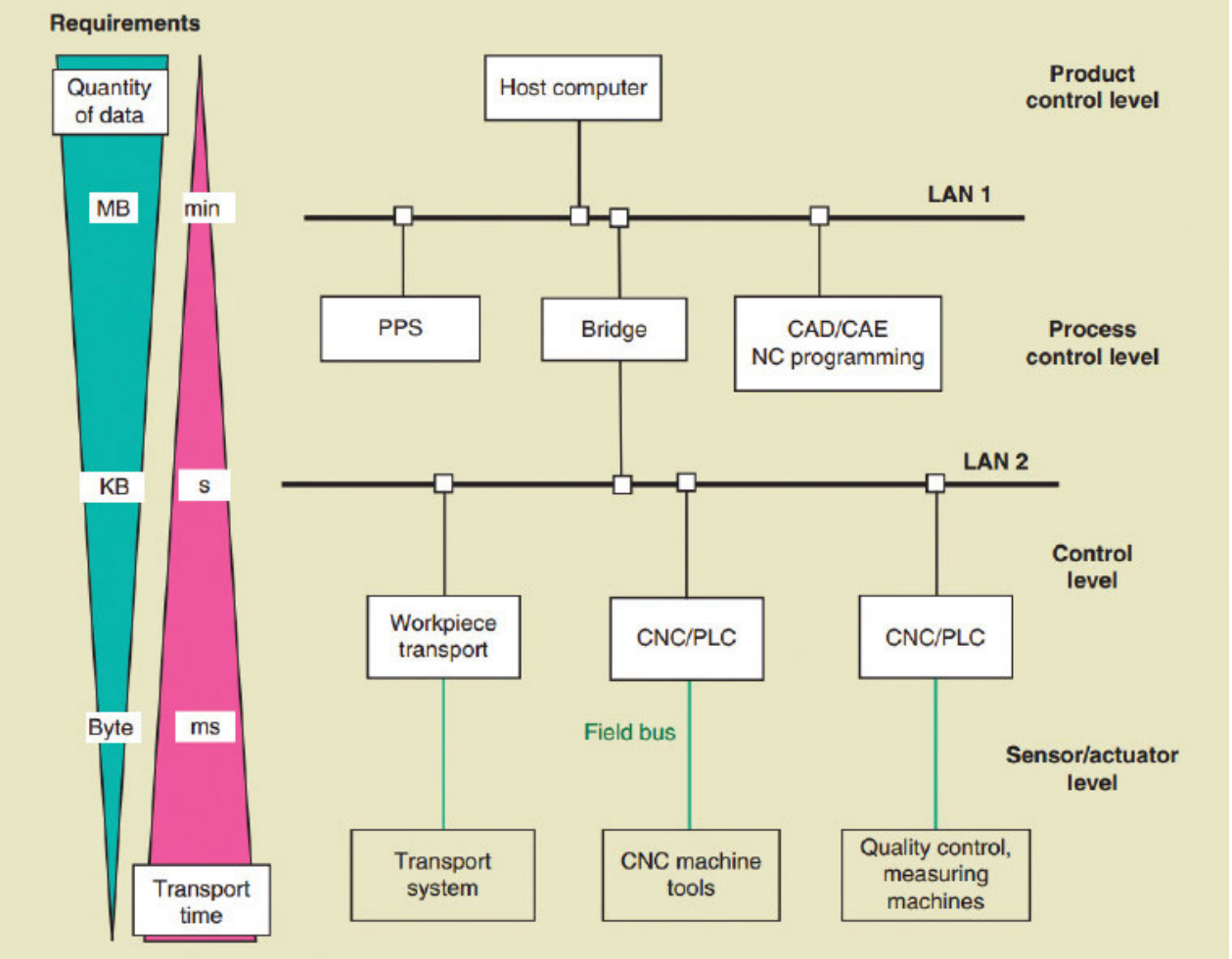

FIGURE 29.11 Requirements for information networking with regard to the quantities of data to be transmitted and transmission wait times in the four hierarchical levels of a company.

IMPORTANT POINTS TO REMEMBER

1. LAN refers to a standardized local data-transmission network that allows communications between different data processing devices within a company.

2. There are several LAN brands available with specially designed transfer and deployment priorities. The choice must be made by the buyer.

3. Although the task of LANs is in principle always the same, it can differ in several ways, such as:

a. Transmission technology

b. Transmission medium

c. Network topology

d. Access methods

e. Protocol

f. Maximum number of devices

g. Transmission speed

4. Bridges facilitate the connection of similar LANs; gateways are used for dissimilar networks.

5. The number of participants in a LAN is limited. For many different participants in different hierarchies, it is advisable to select the most suitable LAN and connect the networks only when necessary.

6. The most commonly used LAN is Ethernet.

7. Before a company decides on a particular LAN, the question of available interfaces on the devices should also be addressed.

8. The future use of CIM with separate and different LANs is not blocked but difficult and time consuming.

9. Considerations to install a LAN begin either with the networking of the administrative computers or with the installation of the first DNC system.

10. A basic distinction is made between LANs operating with baseband technology (i.e., signal transmission without modulation) and those operating with broadband technology (i.e., transmission with modulated carrier frequencies).

11. Access control in a LAN is usually accomplished with the CSMA/CD or token passing method.

12. A protocol is the rules for the exchange of information between computers or participants in communication networks.

13. Field bus systems have the task of transferring small amounts of data between the CNC and the sensor/actuator system in quick succession. Examples include CAN, Interbus-S, Profi-Bus-DP.

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INTRODUCTION

Industry in general, including the predominantly metal-working segments, is under pressure from globalization. This means, on the one hand, that there are many new competitors in open markets with different conditions and, on the other hand, that there are many new consumers with their own product requirements and purchasing habits. To be successful, companies have to take all these factors into account. New product variants, an increasing pace of innovation in all technological fields, and continuous measures to increase productivity are forcing industries to make extreme efforts to improve their processes, to automate their production, and to communicate worldwide.

In this framework, the fields of development, design engineering, production planning, and production itself all have undergone a transformation. The previous practice in which development, design, and production took place in seclusion has given way to the management of ideas, requirements, variants, manufacturing capabilities, and market opportunities. Design engineering of components has been subsumed by digital product definition. Downstream company departments such as testing, analysis, production planning, and production have to be brought in as early as possible. Development and manufacturing can only be successful if these areas maintain a continuous exchange with all areas of the company

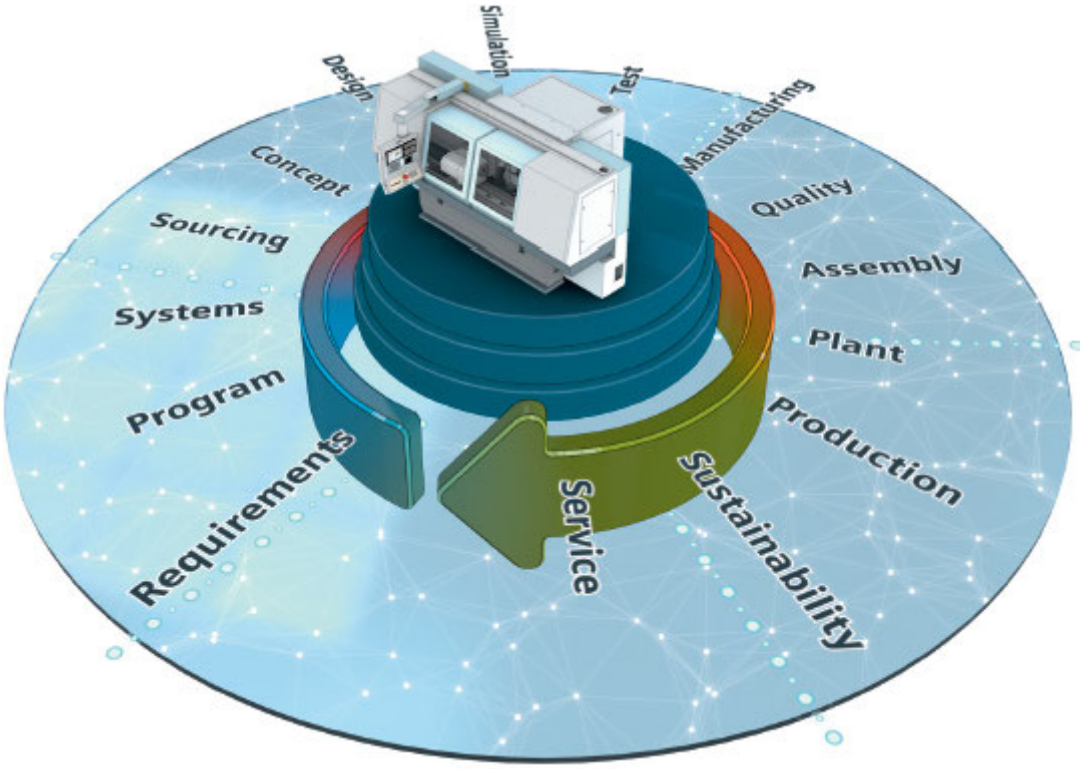

FIGURE 30.1 Product lifecycle management integrates digital product development and production into a total concept for all areas of a company.

Today, this exchange takes place electronically on the basis of internet technologies. E-mail programs and browsers have almost completely replaced earlier CAD/CAM concepts (see below) and computer-integrated manufacturing (CIM) concepts. The digital 3D product model has served as a catalyst, offering a wide range of potential uses in simulation and visualization, production planning and testing, production and logistics, spare-parts management, and service. Software systems for product data management (PDM) ensure seamless management, distribution, and use of this information. These systems store knowledge that is a type of working capital that is kept up-to-date in product lifecycle management (PLM) concepts and put to use in all areas of the company.

TERMINOLOGY AND HISTORY

Computer-Aided Drafting

Computer-aided drafting (CAD) initially meant the computer-based creation of design drawings. It saved design engineers from time-consuming work in applying templates, hatching, filling in drawing headers, and creating various views and modifications. Later the term evolved into *computer-aided* The first generation of modeling systems defined irregular surface characteristics that could no longer be calculated from points, lines, angles, and control bodies with the help of two-dimensional (2D) CAD. They represent the roots of 3D CAD. The most important ones, however, developed with solid modelers for definition of components in 3D space. They contain all the geometric information with regard to intersections and penetration of bodies that are relevant in subsequent process steps such as visualization, simulation, depiction of assemblies, prototyping, and manufacturing. Parametrics is an additional state of development that makes it possible to influence these models using numerical values (parameters), thus making it easier to implement change processes, creation of variants, and repeated use of similar models. Hybrid modeling combines functions for the design of complex surfaces with those for volumes. This is the standard today. Object-oriented programming methods allow automatic creation of components, wizards, and other artificial intelligence (AI)– and knowledge-based design applications. The history of the creation of the components that is kept in the design system provides additional options for influencing the model, including associative links. These define how changes in one object, such as a feature, component, or module,

affect another object. This property can be used for work with assemblies as well as for CAD/CAM integration

Because parametric design in most companies is not subject to strict guidelines, their models are difficult to modify at a later time due to possible dependencies. Also, parametric models lose their intelligence in *standard-interface transmission*

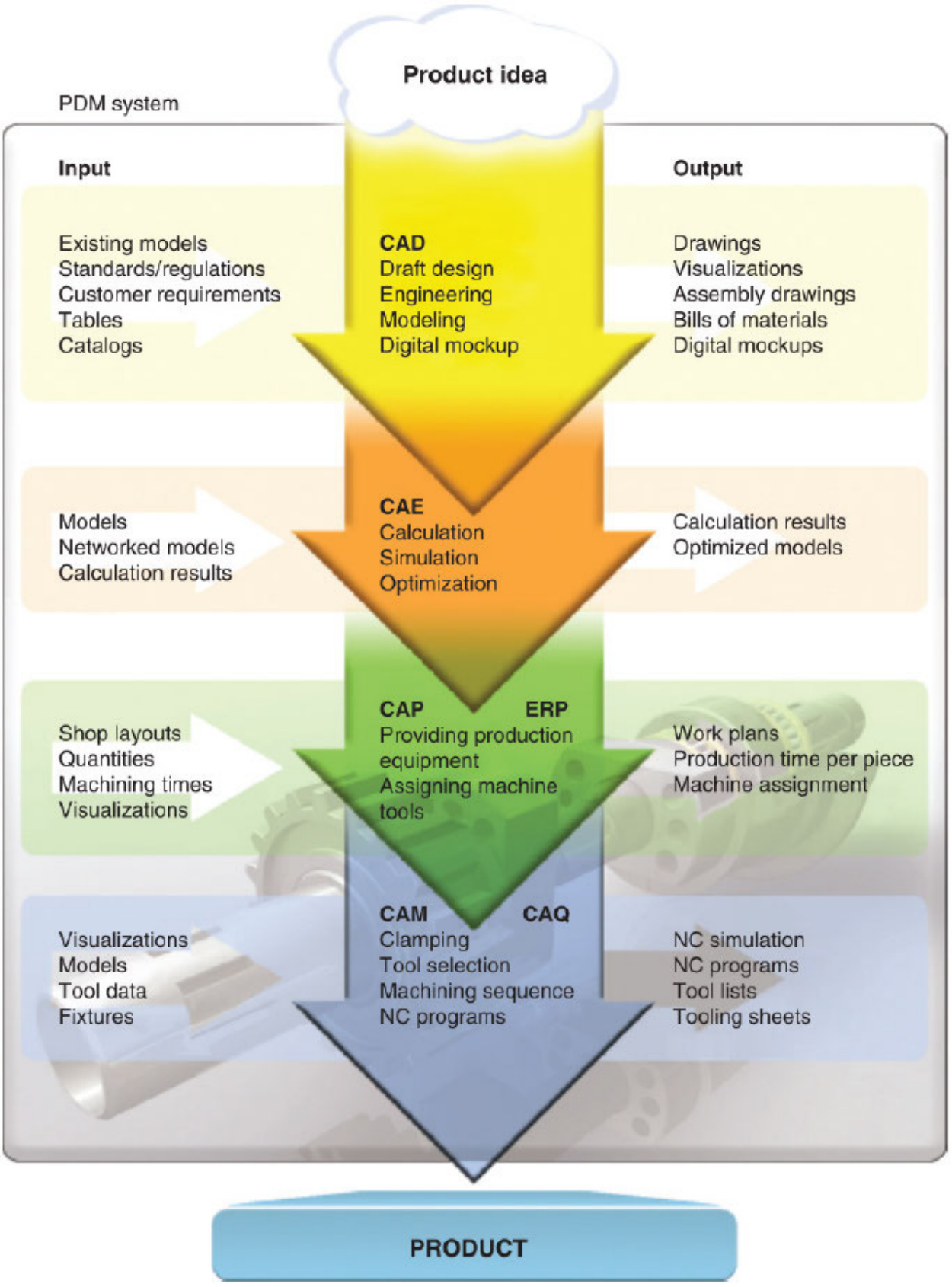

FIGURE 30.2 Computer-aided technologies in the information network. The depiction V shows the principal interactions between networked

computer-aided systems.

Therefore, some CAD systems also offer the option of direct modeling. The geometry is simply adjusted to the requirements by moving, enlarging, and so on and is thus also very well suited for adaptation of models for production (see Figure

Product Manufacturing Information

Product manufacturing information (PMI) includes all production-relevant information directly on the 3D model. These are primarily dimensions, tolerances, fits, and surface characteristics. PMIs can be used in knowledge-based CAM systems to automatically assign the rules that are required to achieve the required quality Example:

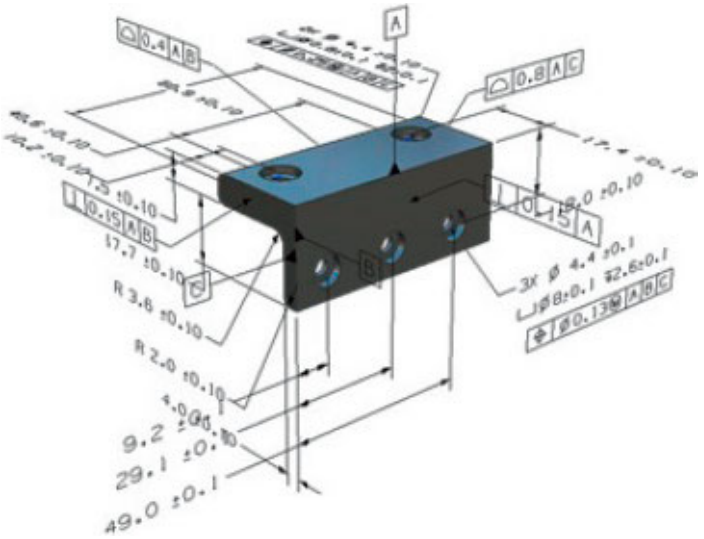

FIGURE 30.3 3D Model with PMI, such as dimensions, fits, and tolerances.

Normal hole = spot drill, drill
Fit = spot drill, smaller drill plus use of required reaming tool

Computer-Aided Manufacturing

Computer-aided manufacturing (CAM) programming creates a program for CNC machines, whether with or without the use of CAD data from 2D or 3D systems. It also generates a graphical simulation on a computer screen of the design computer. The system also can create machining, clamping, and tool plans; management of the tool data and tools; clamping equipment and fixtures; and distributed numerical control (DNC), that is, the direct transfer of NC programs to the CNC systems of the machine tools via a network.

A CAM system can do the following, with or without CAD data from 2D or 3D systems:

■ Graphically simulate the generated machine and tool motions on a computer screen

■ Create machining, clamping, and tool plans

■ Manage tool data, tools, clamping devices, and fixtures

■ Direct transfer of NC programs to the CNC system of the machine tools via a network

In addition to stand-alone CAD and CAM systems, combined CAD/CAM systems have appeared on the market. The purpose of these was to use internal connections of the two functional areas on the basis of a common data model to ensure that the data generated with CAD systems could be used for NC programming as directly as possible. The intention was to eliminate the cumbersome

use of interfaces, which often involve additional work and data repairs, thus enabling seamless sequences and error-free processes. Initially, these objectives could only be achieved to a very limited extent. Often the various requirements of the functional areas were not adequately met. Progress in these fields led to modern high-performance CAD/CAM systems with various options for CAD/CAM integration and numerous 3D data formats that can be used easily in CAM systems. All these formats can accommodate a wide range of requirements. The organization of the processes is performed by PDM systems.

Computer-Aided Engineering

After computer-intensive beginnings with calculations according to the finite-element method (FEM), computer-aided engineering (CAE) found its way into practical use 30.4 and After adopting a 3D model and the process of meshing, components and assemblies are analyzed in a solver for numerous properties in mechanics, acoustics, and thermal and other fields. Feedback to the CAD model is used to perform numerous optimization loops in a short time—long before the first component is manufactured or the first prototype is created. Originally, CAE was in the domain of specialists or entities with major computing power, but today digital simulation and analysis have become standard in development departments.

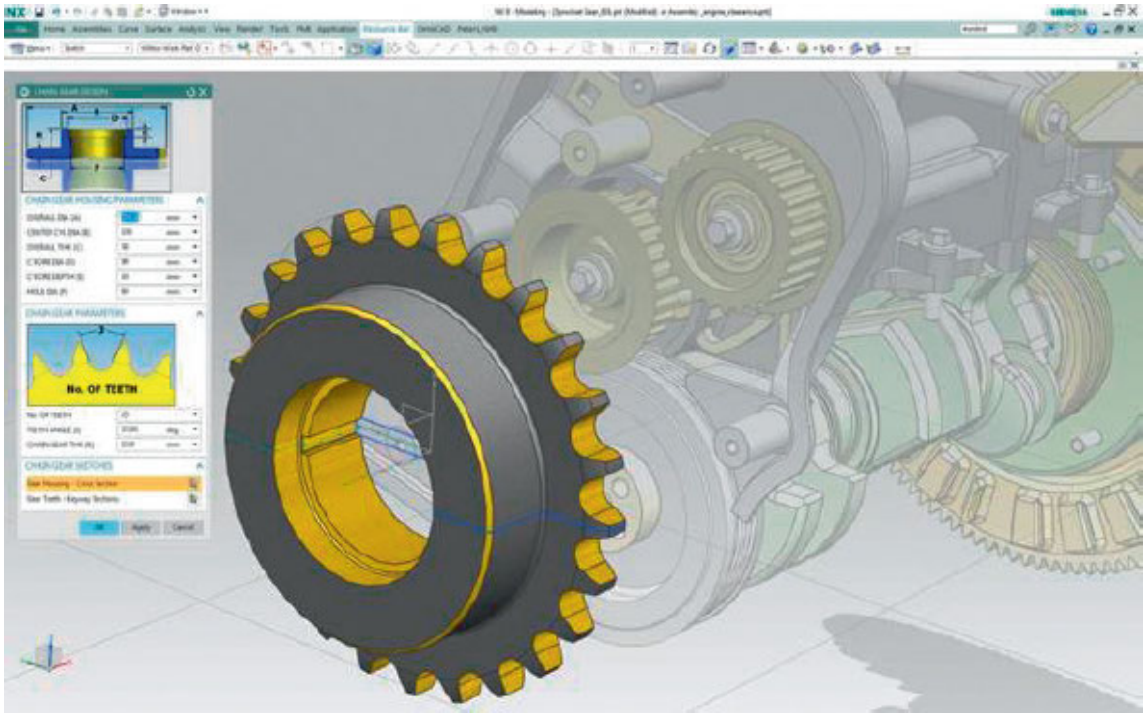

FIGURE 30.4 Knowledge-based engineering design with integrated template technology. Given formulas determine the dimensioning for entire assemblies; the stored development knowledge is applied quickly and without error.

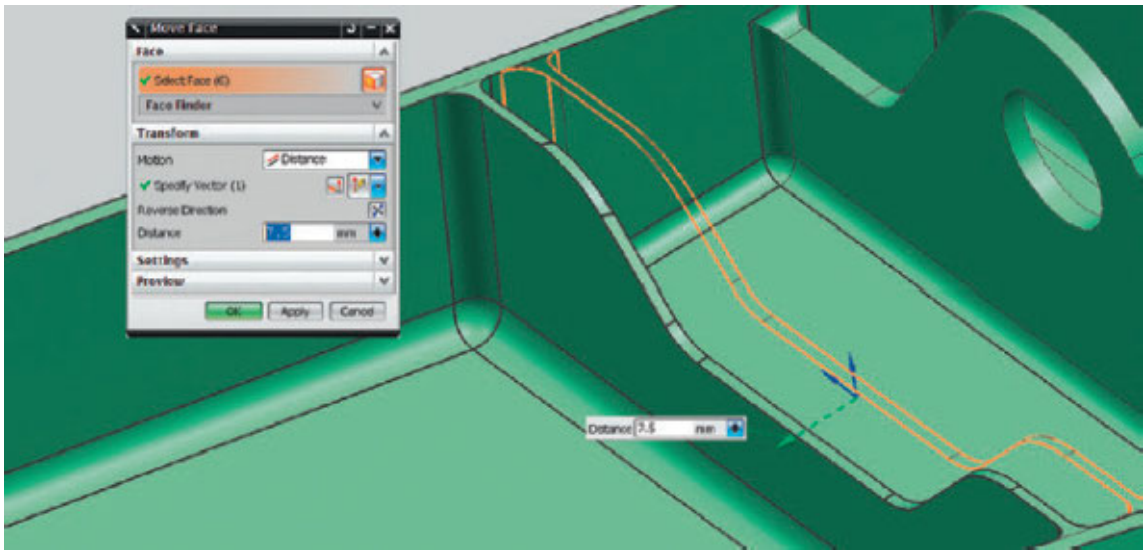

FIGURE 30.5 Simple changes in direct modeling: select object and move a given distance.

The term *digital product definition* better summarizes the three historically separate areas CAD, CAM, and CAE: the computer has changed from being an aide to a stand-alone workstation. The work areas are interwoven and overlap. Development and manufacturing processes should not be understood as linear; rather, they each run in concentric circles, influencing each other continuously.

Computer-Aided Process Planning

Computer-aided process planning (CAP) summarizes the planning activities for new production jobs During the investment stage, fabrication plans are made for a new component based on the CAD model; CNC programs are simulated; and optimal work sequences, fixtures, and tools are planned. Flexible manufacturing cells can be retrofitted for new components more quickly, complete processes in interlinked production lines can be meticulously planned, and the material flow can be simulated. These are important steps toward the *digital* For day-to-day production planning, manufacturing execution systems (MESs) are the better tool than previously used PPSs. They plan appointments, machine load, production equipment, and employees and are in communication with enterprise resource planning (ERP) systems.

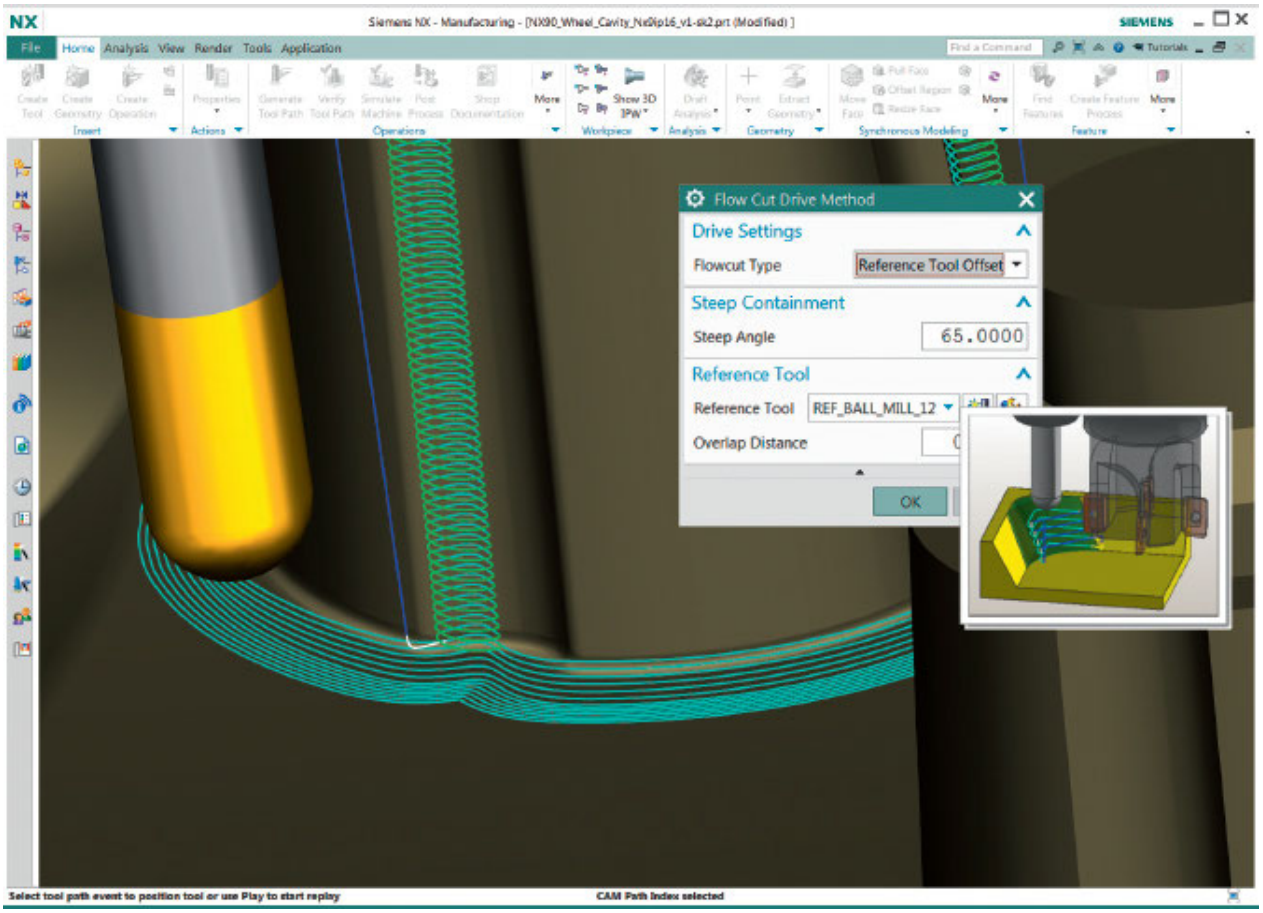

FIGURE 30.6 Display of the tool paths on a 3D model in a CAM module.

Product Definition Management

Product definition management (PDM) extends far beyond its origins of drawing management or product and engineering data management (EDM). Using modern database systems, all product-related data from the various departments are stored and managed. Databases that are distributed worldwide with daily replication, extensive provisions for granting access rights and other security precautions, and company- or role-specific menu systems in browsers offer not just 24-hour access to all relevant manufacturing data, but they also contain service-proven processes typical for specific branches of an industry. They cover the basic routings of all

manufacturing companies: manufacturing release and changes, reuse of files and the quick and efficient organization of prints. Modern work methods thus can be organized flawlessly, including concurrent engineering, the simultaneous development and engineering of different but related components at multiple sites, and simultaneous processing of the same components at different sites.

Product Lifecycle Management

Product lifecycle management (PLM) is not a description of new software but rather the best possible use a company can extract from available technologies. PLM encompasses error-free and efficiently run processes, from the phase of product emergence through all stages of the process chains in development, production, installation, and customer service—and all using the same database and proven processes. This involves all areas of the enterprise: marketing and sales, training and service. Manufacturing companies use the PLM concepts to answer the challenges of the world economy that were described earlier.

DIGITAL PRODUCT DEVELOPMENT

Draft Designs

Although the industry still uses 2D CAD systems, these are being supplanted by 3D modeling, also called *solid* 3D modeling has built-in 2D functions for production blue prints. In the early design phases, high-performance drafting programs provide new ways to quickly make a record of a new idea. Existing 3D objects can be imported and modified

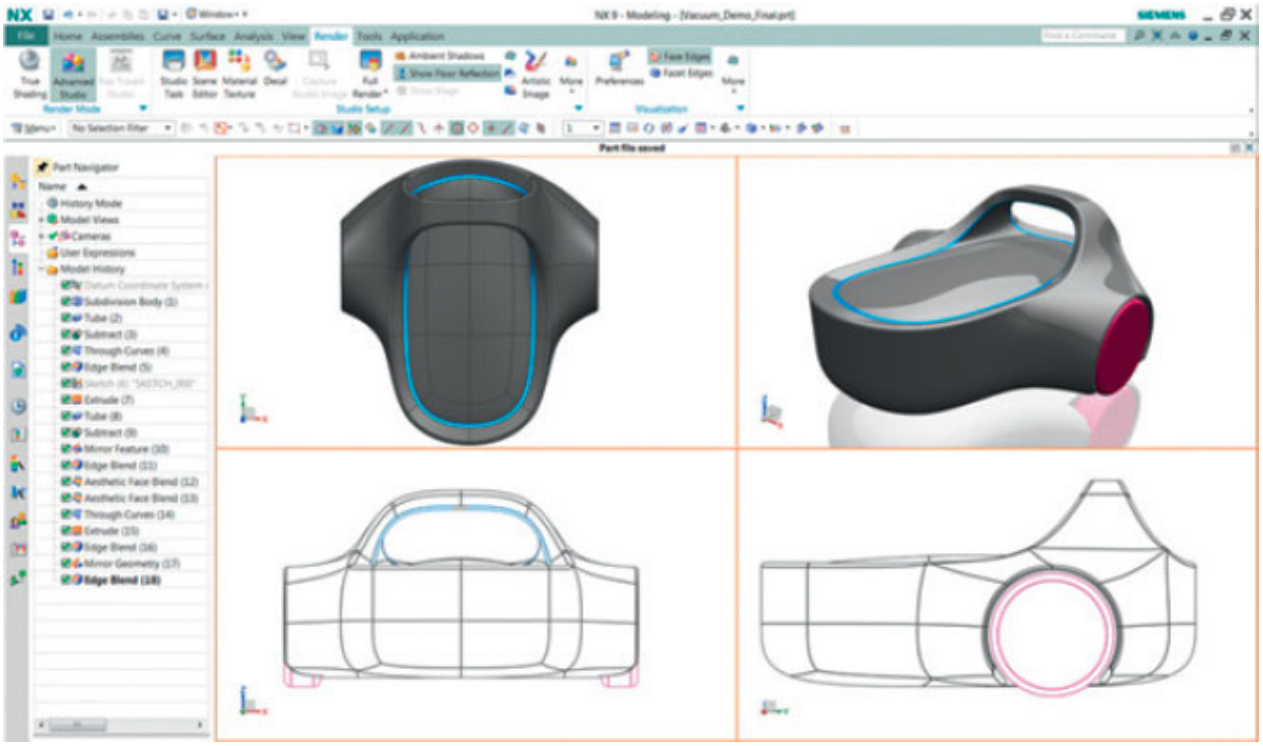

FIGURE 30.7 Modern 3D systems support the concept phase with their powerful sketcher tool that incorporates existing 3D models.

Component Design

Previously, new components could be designed by selecting standard bodies that were placed in planes, given dimensions, mirrored, rotated, copied, and cut or joined using surfaces or lines. Modern high-performance 3D CAD systems, however, cover a much wider scope. The selection of standardized parts from catalogs, parameter-controlled modification of existing components, automatic geometry generation based on specified parameters, and many other techniques provide an efficient method for any task. In addition to the purely geometric description of a component, the models are enhanced with a great deal of further PMI that is stored in assigned data sets such as surface quality, fits, tolerances, material, weight, mounting orientation, and many other characteristics that can be appended here. This information will be needed in later process steps

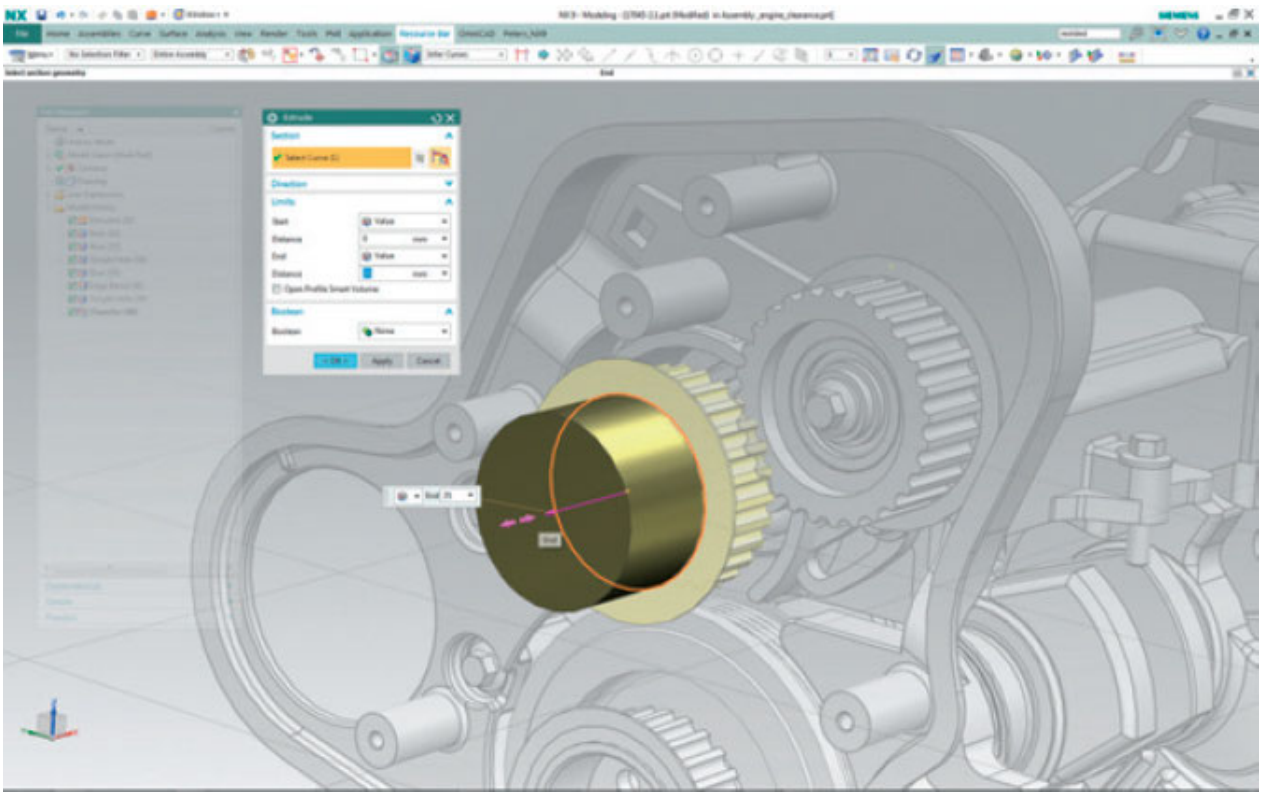

FIGURE 30.8 The tools in modern design are diverse. In this image, a cylindrical body is extruded.

Assemblies

The capabilities of systems today generally are sufficient to edit even large assemblies on the computer display. At the least, it is possible to design subsystems of products in relation to the assembly and to relocate component parts virtually. This makes it possible to immediately verify the accuracy of fits, tolerances, assembly options, or interference geometries It is still problematic to handle large assemblies, for example, complete machine units. Working on complex 3D models can involve significant wait and regenerate times, particularly in connection database inquiries.

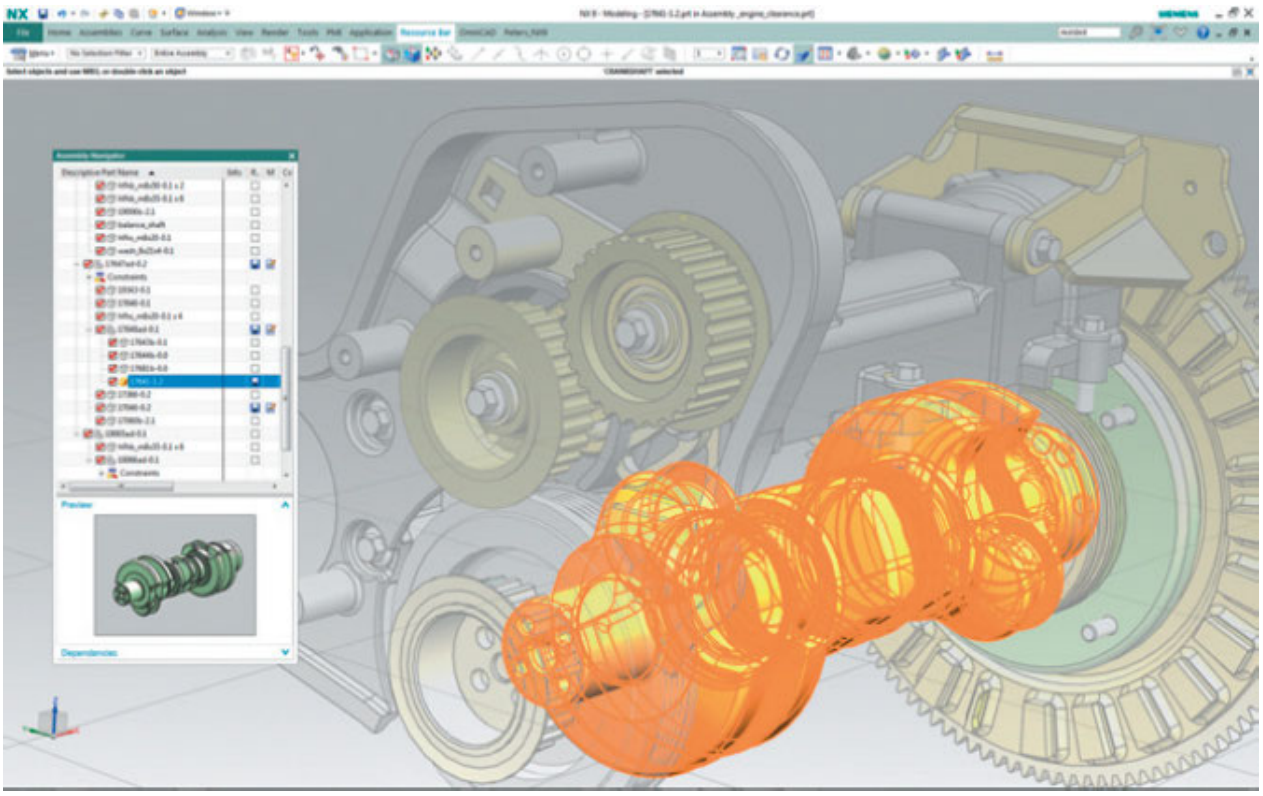

FIGURE 30.9 Modern product development in the context of all subassemblies (Jaguar transmission).

Simulation

Many properties of components and assemblies can be checked directly in the development process using FEM analysis. Although weight and center of mass are already part of the model information from the CAD system, tensile strength, bearing strength, thermal and vibration characteristics, and acoustic effects are calculated using CAE software. This is done by exporting models from CAD, networking them, and subjecting them to analysis. Associative links between CAD and FEM models make it possible to abbreviate the change loops needed to achieve the optimal model. These analyses are performed earlier in the development process than real tests and cost less time and money. The development results are verified at an early stage, allowing other areas to build on them.

Additive Manufacturing

Models made of wood, paper, and, more recently, high-strength metals can also be made. This method is mostly used in prototype fabrication and small-batch series, including mold making.

Additive manufacturing, formerly called *rapid* converts 3D models to facets, usually in the stereolithography (STL) format. Next, the body is divided into individual superimposed layers that can be produced using various processes. Functional models made of plastic thus can be created right in the design department.

Visualization and Digital Mockup

Visualization and digital mockup (DMU) of 3D models are used to check components, assemblies, and whole products at an early stage. There are many ways to do this. CAD systems read and generate compressed data formats for the internet. Special visualization software compresses data, reads common formats, and provides

functions for revision; marking and commenting are likely to be the most common. These features are also offered by PDM systems. The DIN standardized data format JT plays an important role in the presentation and testing of 3D data from different CAD systems. It supplies standardized component information from many CAD systems in a small size data format with accuracies that allow testing of assemblies and installation spaces, collision and tolerance tests, and other investigations as part of a complete DMU representation of geometric data. DMU finds its most spectacular application in the automotive industry: long before the first model is manufactured, various projections can be condensed into a wire cage in a 3D model that can be viewed from all sides. The virtual automobile can be used to examine the inside and outside features such as doors, trunk lids, and so on. This creates a realistic overall impression.

2D Drafting

With the increased use of 3D CAD, the digital product model supersedes the drawing as the central carrier of development information, at least for mass-produced items. Drawings are still not superfluous, however. Sets of drawings for production are still standard alongside setup and tool information and NC programs, even when they are supplemented with 3D visualizations in many places. A 2D draft is an important and efficient output of a 3D CAD system and can be automated to a large degree. It is still possible to create sections, fill in drawing headers, and select views manually. Often drawings are generated automatically, whenever necessary, together with an assembly drawing, transferred as TIF files and archived for reasons of product liability and warranty. PDM systems perform the task of feeding drawing data to the specifically intended uses with minimal effort

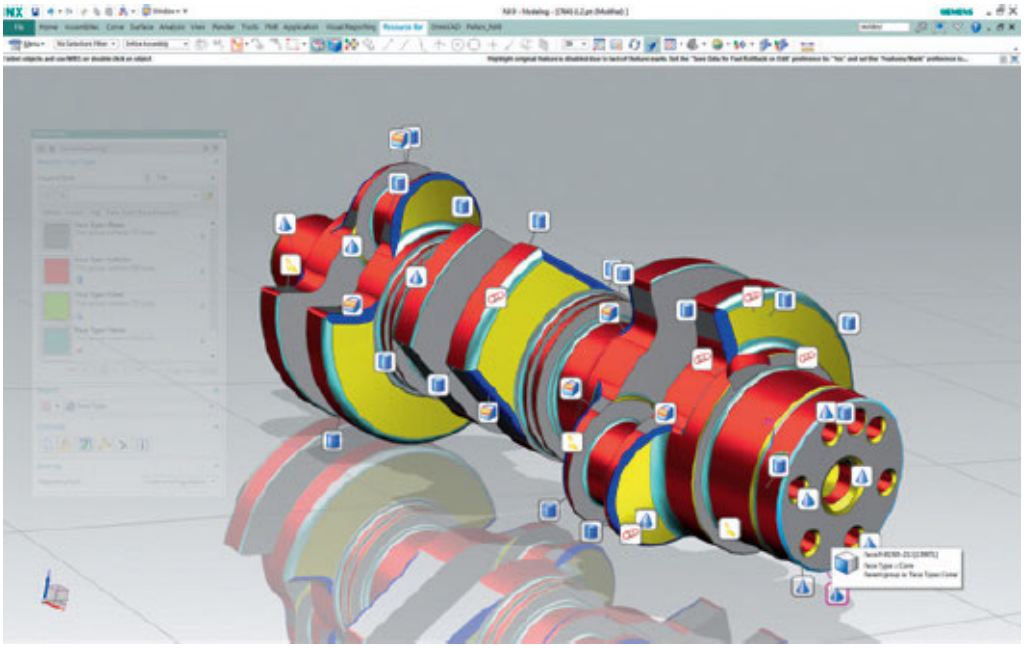

FIGURE 30.10 Information can be called up on a 3D model with a mouse click for a quick analysis.

Product Data Management

Once the number of CAD workstations reaches five or more, it is no longer possible to handle engineering data without the use of intelligent management functions that go beyond the capabilities of the directory structure of a computer's operating system. But this is no longer the main reason for the rapid expansion of product data management (PDM) systems on the market. The capabilities of even simple PDM systems today extend far beyond classical functions for structured data storage, assignment of number ranges, compilation of bills of materials, or drawing management. Additionally, for a long time, PDM systems have provided intelligent referencing and search functions and the opportunity to define processes and permanently assign access rights. Professional work methods especially are based on the management of change states, internal company processes such as development releases and production releases, and support

for the compilation and transfer of all the pertinent data to the downstream departments and processes.

PDM as an Integration Platform for CAD Systems

Anyone who develops complex products with numerous subassemblies, who works with multiple suppliers, or who serves various customers with semifinished products will not be able to maintain a single CAD standard, desirable though that may be from a cost standpoint. This is where PDM takes on a central role: Regardless of the source of data, it is essential to establish uniform access rules, processes, and higher-level management functions. PDM systems can provide these functions with multi-CAD/PDM. System-specific CAD managers emulate the familiar interface of the different CAD software systems. The user interface is merely augmented with PDM functions.

The original file management of the CAD application is replaced by centralized database operation. The management of subassemblies from various sources can be facilitated with one product. Attributes, relations, and documents of various kinds can be assigned to the geometry data. If one works with several CAD programs, it makes sense to autosave 3D data in the PDM system in addition to the original format and also as a neutral format using the industry standard JT. This allows cross-CAD representation and analysis.

PDM as a Key to Information Distribution

Just as the use of 3D CAD systems has turned the digital model into a catalyst for product development, internet technology in the same way has allowed PDM systems to become communication platforms in all areas of product development. Thanks to the use of internet technologies and standards such as J2EE, all locations of a

particular company can use the same data. Development teams spread all over the world can work simultaneously on a common set of data that is administered and stored at a central location. Single sourcing of product data makes it easy to find the most current development version, even if globally distributed teams collaborate simultaneously.

PDM as the Basis for Product Lifecycle Management (PLM)

PDM systems store knowledge from the development departments, distribute it to all areas of the company, and ensure that it can be used many years after conclusion of the actual development phase. These capabilities make use of concepts from product lifecycle management (PLM) to achieve concrete economic objectives: shorter development times, higher product quality, shorter innovation cycles, and production at locations distributed all over the world. Thus they make an important contribution to industry's ability to deal with today's challenges.

DIGITAL MANUFACTURING

In the interaction between CAD and CAM systems, three principal combinations have developed in recent years:

- Stand-alone CAM systems independent of CAD

- CAM systems that optionally can be integrated into the user interfaces of CAD systems

- Complete CAD/CAM integration

Each of these is oriented toward a particular method of work organization in a company and range of parts being produced. Component suppliers without their own design department will need different systems than manufacturers that perform their own product development

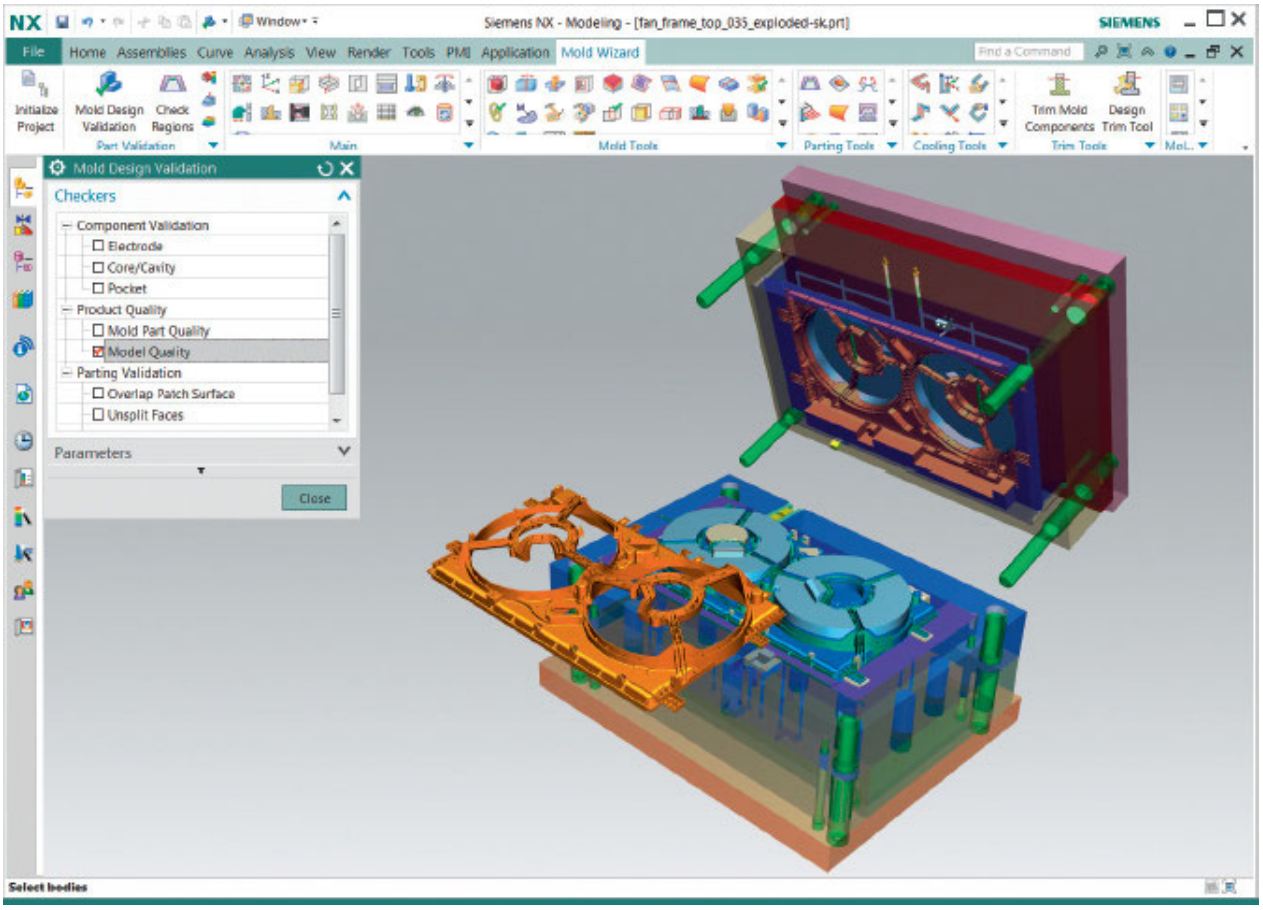

FIGURE 30.11 Mold design with knowledge-based design technology is largely automated.

2½D Programming Systems

For many years, CAM systems that were independent of CAD were typical for component suppliers and series-production manufacturers that had to make a spectrum of products in the 2½D range, that is, components comprised of ruled surfaces and standard geometries. Data transfer from 2D CAD systems via DXF, the Initial Graphics Exchange Specification (IGES), and other standard interfaces was in practice generally more labor intensive and costly than creating the desired components using the capabilities of the NC programming system. The component was subtracted from a fictitious blank based on the manufacturing drawings, dimensions, and material properties. The utility of 2½D programming systems was based on the difficulty

of communication with the CNC system of the machine tools. CNC machines for turning, milling, EDM, and laser cutting require different data formats, and the scope of their commands goes beyond the standardized language defined in the DIN 66025/ISO 6938 standard, which only covers a basic vocabulary of necessary work instructions.

3D CAM Systems

In addition to the main aspect already described, 3D CAM systems also exist for individual operations at the shop-floor level, especially for demanding manufacturing tasks in single-piece and small-series production, for example, in tool and die making. These systems naturally can receive data in the common 3D formats, allow the definition of blank contours, and then propose predefined strategies for roughing, finishing, pocket milling, and many other specialized machining options. They generate very complex NC programs for various machining sequences that often depend on each other, such as 3D milling and die-sinking EDM. However, the results of this process in most cases cannot be returned to the 3D CAD system. It often becomes evident after the data transfer that the models provided do not comply with the requirements of 3D milling, and as a result, surfaces must be repaired, and chamfers and rounded areas have to be reworked or repaired

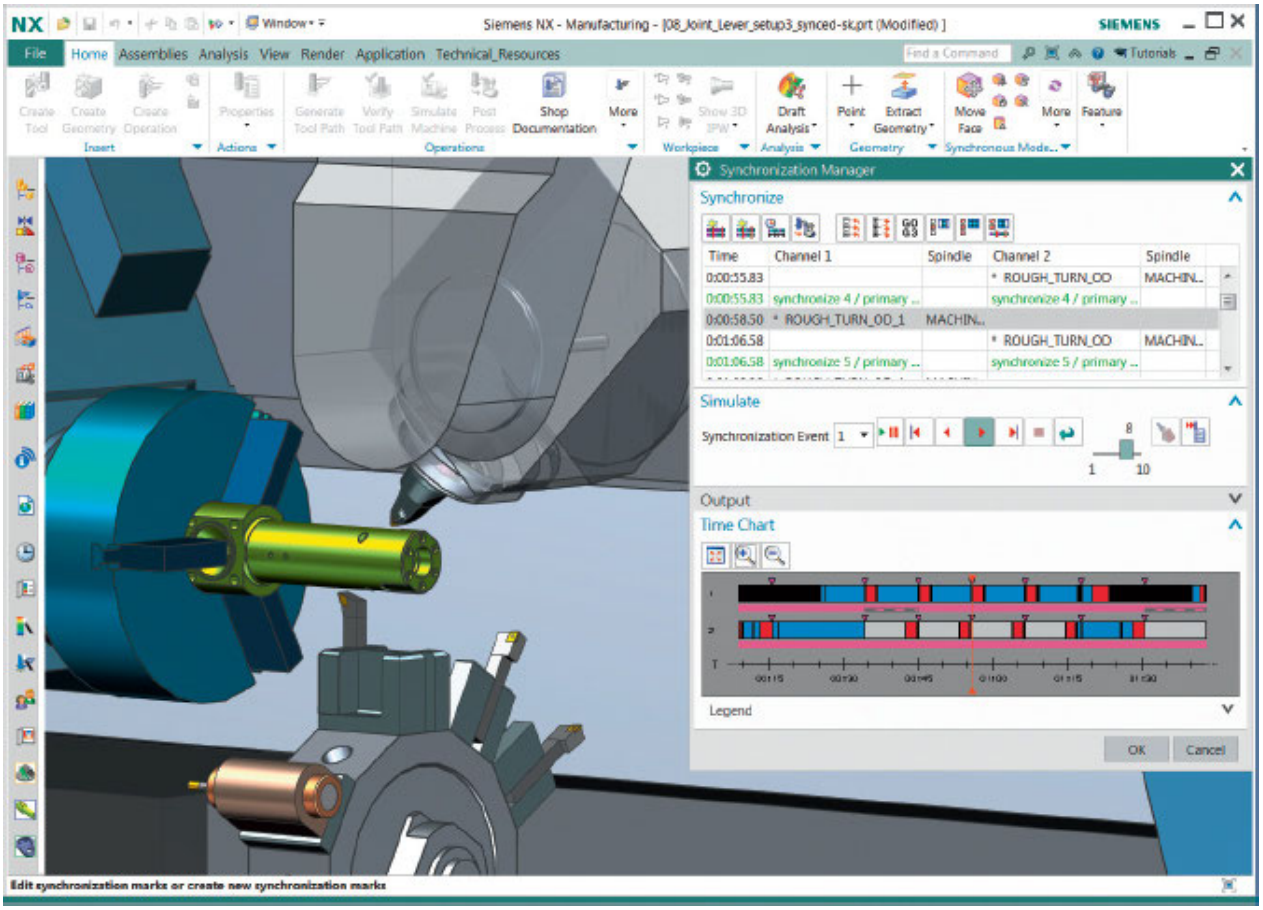

FIGURE 30.12 Modern CNC machines with live tools place high requirements on programming and simulation.

3D CAM Systems as a Plug-In

CAM systems can be acquired as a standalone programming system or as a plug-in for one or more 3D CAD systems. The advantages of this variant, which is closely linked with midrange 3D CAM systems, lie in their uniform menu system and optimized data transfer. Training and familiarization are less costly, and data consistency is automatically improved because the geometries that are used are based on one of the common kernels and do not lose most of their information when passed through a translator. The calculated tool paths are stored in a part file with the 3D model. All manufacturing information is automatically taken from the solid model, thus largely eliminating input errors. After the component has been clamped, it is

easy to assign individual features, reducing the number of mouse clicks and keyboard entries. Complete association between solid model and machining process allows quick modifications and avoids errors when the model is changed. In addition, once machining strategies have been defined, they can be quickly assigned to other members of groups of related parts that have been generated parametrically.

Integrated CAD/CAM Systems

As described earlier, improved design engineering methods represent only a small part of the utility of solid modeling. The capital value of 3D data is only truly exploited through the superimposition in time of all product-emergence processes, collaboration of distributed teams on the same component, and the complete documentation of all process steps. This basic concept is best embodied in the form of seamlessly integrated CAD/CAM systems.

The CAM module itself provides integrated access to all product-development and manufacturing functions. This is helpful for data transfer and repair of models from external systems, the design of tooling, and the optimization of geometries that otherwise would be impossible to mill.

The mutually associative linking of all design engineering and manufacturing data brings the functional areas close together.

Subsequent changes to the 3D model take effect immediately in the CAM area, resulting in the quick updating of the NC program. Each step remains fully traceable; tool selection, clamping fixtures, and documentation are also updated at the same time.

Controlled Change Process

An integrated CAD/CAM system in combination with an integrated PDM system supports controlled change processes, reducing the effort in a very safe manner. Figure 30.13 illustrates the method:

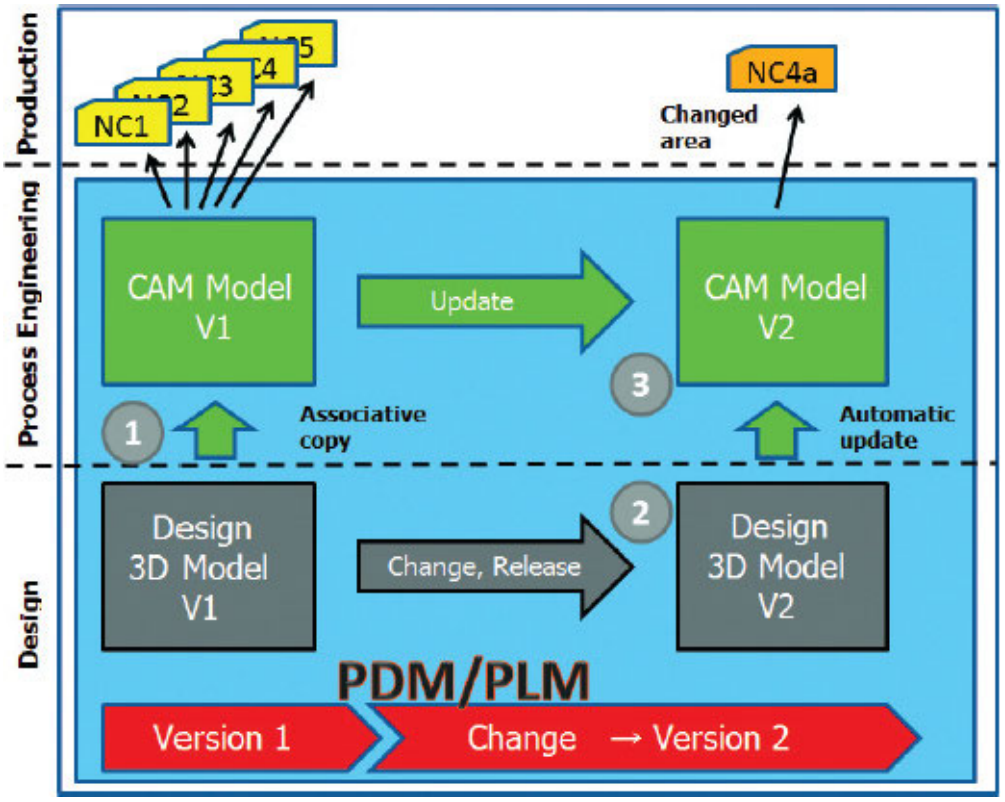

FIGURE 30.13 Master model (quick and safe changes through integrated CAD/CAM in the context of PDM).

1. The designer releases a design. This locks the model for changes.

2. Production planning (PP) creates NC programs based on an associated copy.

3. If the designer releases a new change, PP receives an update, and the changed geometry is reflected in the associated copy.

4. The CAM module displays the changes, and PP creates the pertinent NC programs.

Knowledge-Based CAM

Late-generation CAM systems can detect and analyze form elements in the 3D model and use this geometric information for automated production. This technology of feature-based machining (FBM) uses engineering knowledge in the form of rules and formulas, also called *knowledge-based engineering* This increases process reliability and reduces programming time by up to 90 percent. The CAM system controls and generates the NC paths and selects the tools and the manufacturing strategy. The field of drilling operations, in particular, can be automated completely in a knowledge-based manner using modern CAD/CAM systems. The CAM module detects holes and automatically proposes processes such as spot drilling, drilling, and subsequent thread cutting and optimizes tool paths and tool changes. Special knowledge-based modules, for example for tool and die making, enhance the capabilities greatly

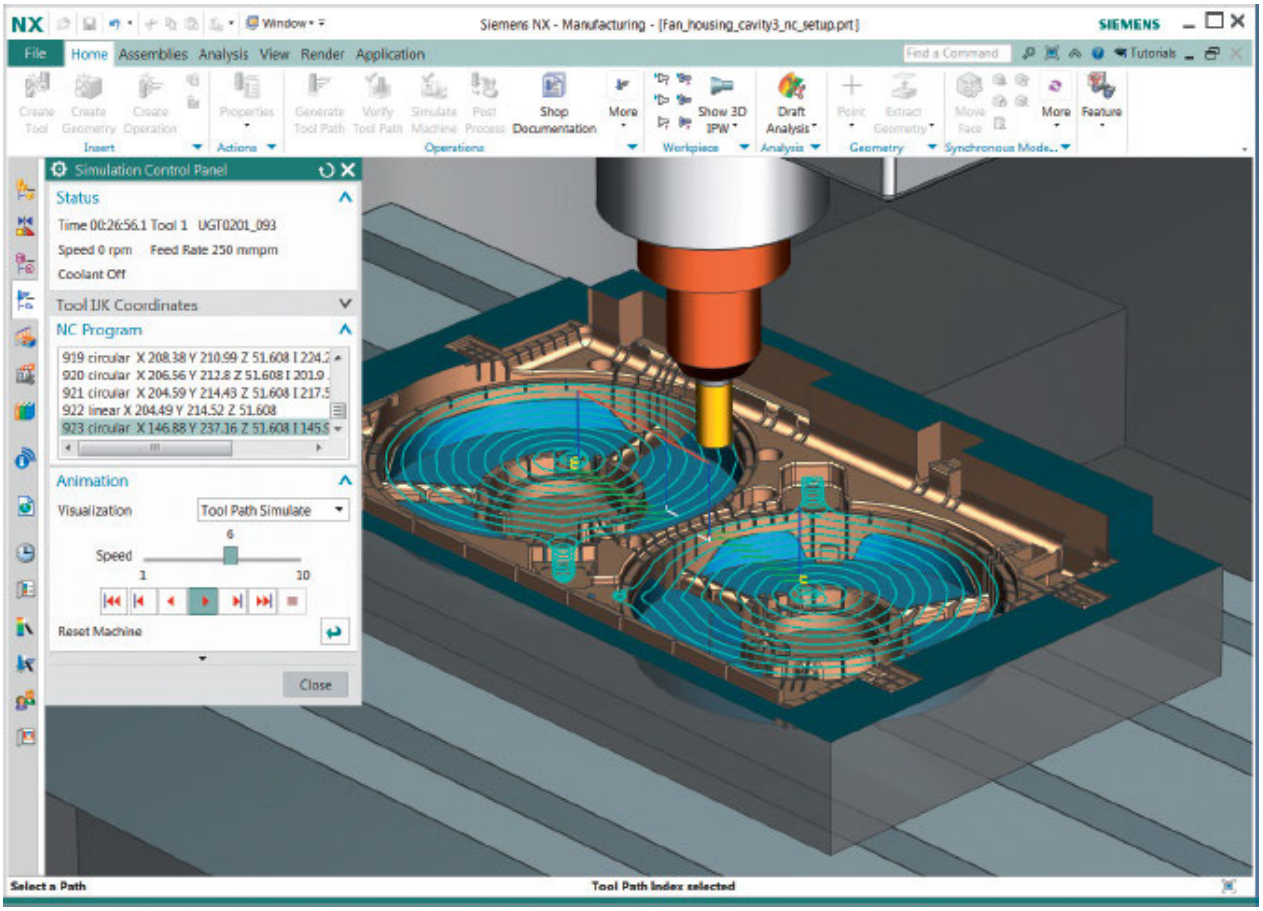

FIGURE 30.14 The mold section remains linked to the underlying 3D model of the plastic part. Later changes are automatically taken into account in the CAM module.

Simulation of the Machining Process

The graphical simulation of the machining process on the computer screen generally represents the conclusion of NC programming in the office see also Figure Collisions and damage to the workpiece contour, tools, holders, and spindles are detected at an early stage by suitable simulation technology. User-friendly systems can simulate the tool paths in real time within the programming environment. Here the user selects the relevant details—from block-by-block machining up to a complete 3D depiction of the machining process with all the tools in the work area. Although effective collision monitoring has

been moved forward to the program-creation phase, this offers no guarantee of safety in the event of errors in the NC program!

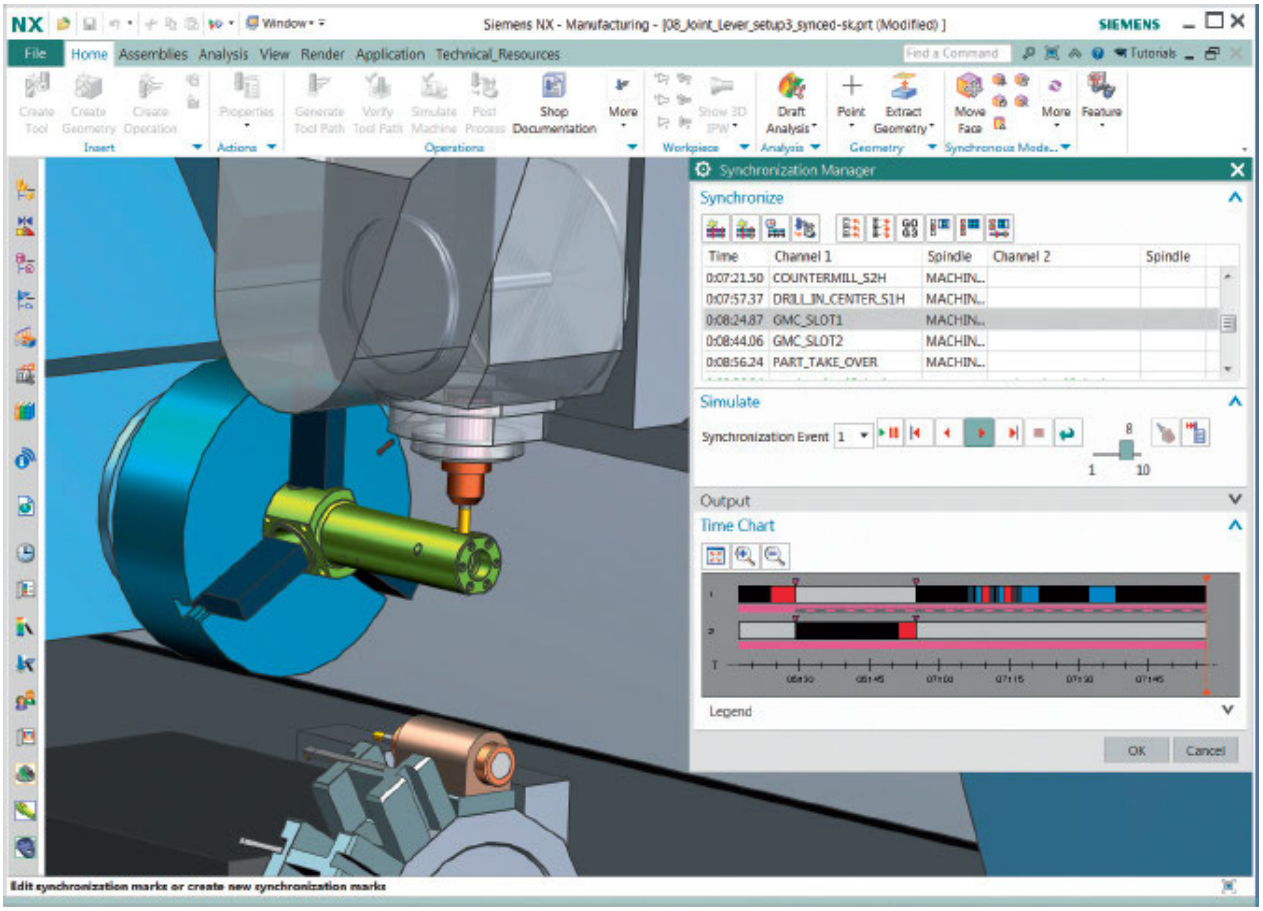

FIGURE 30.15 NC simulation must encompass all machine elements in order to deliver realistic results; the figure shows milling-turning simulation.

Another development stage is CNC-specific simulation. For this, CAM systems or special simulation programs access a special version of the original CNC software that has been supplemented with a module containing important parameters of common machine tools such as inertia, axis information, and spindle forces. The result of the simulation may eliminate or shorten the verification of programs on the machine. Calculations of the run time of NC programs on the machine are sufficiently accurate to meet the requirements for large-series production, within certain limitations and tolerances.

NC program simulations are also expected to deliver additional results. These include realistic, true-to-scale depictions of the machine, tools, and fixtures; dynamic processes during tool change; rotation/tilting of the workpiece with collision warning; and the types of finished boreholes, with or without thread, etc. (see Chapter

SUMMARY

The actual process chain of a modern manufacturing company from draft design to development, design engineering and verification, and production and shipping is effectively supported by a digital "backbone" that also encompasses customers, service providers, and suppliers. It must be possible for other companies to tap into this backbone using various software tools. The main requirement for manufacturing companies' software approach, at least as it pertains to CAD and CAM, should be openness. There has been much improvement in this area in recent years. Interfaces and standards, the open exchange of data, and cooperative agreements between system suppliers are the correct approach to providing greater utility for users.

The modularization and specialization of individual software systems within the process chain have eliminated many of the problems that previously existed and have led to great progress. For this reason, there are hardly any new CAD systems appearing on the market today with significant new design engineering functions. Instead, the greatest potential for improved efficiency in companies lies within their processes.

PLM is a very promising approach toward using modern software to integrate all areas of a company in lean, efficient processes. It links employees in marketing and sales, service, and installation with those in the development and production departments. A spectrum of digital information from a wide variety

of sources is available in a structured form whenever it is required. This is one reason why engineering "along the course of the sun," that is, international collaboration and production facilities located all over the world, has become an option for medium-sized companies.

These new work methods also place new requirements on employees. Openness and a sense of responsibility are just as important as the ability to work on a team, to understand other cultures, and to communicate clearly. Despite all these changes—or perhaps even because of them—product development and manufacturing will continue to present interesting career challenges in the future.

IMPORTANT POINTS TO REMEMBER

1. A distinction is made between 2D and 3D CAD systems depending on their methods of operation. 3D CAD systems are able to describe 3D bodies precisely and comprehensively. They also have 2D drafting functions.

2. Utility of 3D CAD systems can be derived not just during design engineering work but also in all subsequent steps of the process chain because more information is linked to the model.

3. CAE software can be used to check components at an early stage of the development, thus saving development time and the cost of errors in product development. Increasingly, design engineers are performing analyses of the results of their own work.

4. CAM should remain as tightly linked to product development as possible. A high degree of data consistency saves duplication of work, makes it easier to make last-minute changes, and makes manufacturing more flexible.

5. Every time an NC program is created, the last step should be a 3D simulation of the machining process on the computer screen. Simulated machining can provide absolute safety only if the conditions are realistic, that is, taking into account the machine, clamping fixture, tools, and all motions.

6. CAD, CAE, and CAM each describe subsections of the digital product definition. It is useful to view and organize them as a continuous process.

7. It is beneficial to integrate this process in a PDM system. Once the number of CAD workstations reaches five, it is no longer possible to adequately reflect product-development data using traditional PC directory structures.

8. PDM systems organize management, distribution, and use of all product information in modern database structures. They also specify established procedures for many processes in the company.

9. Parts drawings are still an important source of information. They play a key role in transferring information to the production shop and for product liability and warranty purposes. When working with 3D CAD systems, drawings are 2D derivates of the 3D model. Whether the information is correct and up-to-date depends on the 3D model.

10. Digital manufacturing encompasses all the preparatory measures for efficient, productive work in the shop. The choice of CAM and CAP system, as well as software for material flow and production system simulation, plays an important role when changing over from one product to another in large-series production.

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BASICS

The term *Industry 4.0* originated as a proclaimed future-oriented project of the high-tech strategy of the German federal government. It aims for the long-term preservation of the international competitiveness of domestic industry. Even though Industry 4.0 was pronounced by a particular country for the benefit of the domestic industry, the stated objectives apply to every industry and market in the global economy.

One goal of Industry 4.0 is to increase the flexibility of production so that, if required, a batch size of one can be economically produced and the customer receives an individually configured product. For this it is necessary to collect and refine raw data that result in huge quantities through the digitization of processes and products. This leads to new insights that enable rising quality requirements, shorter delivery times, shorter product lifecycles, and a growing product variety.

In the value-adding chain of Industry 4.0 manufacturing companies, business partners, suppliers, and potential customers will become a network that achieves the best possible flexible productivity. Individual components of Industry 4.0 technologies are already used in companies today, but there is a lack of area-wide standards.

A brief look back is indicated in order to grasp the core of this industrial revolution and its characteristic fundamental difference with the past. The signs of the historical three industrial revolutions were clearly visible early on by those affected. During the first industrial

revolution in the eighteenth century, the historical transition from muscle to machine power took place. The mechanical loom was introduced, and the stagecoach was replaced by the steam locomotive and steamboat, providing a huge productivity boost to the industry and beyond

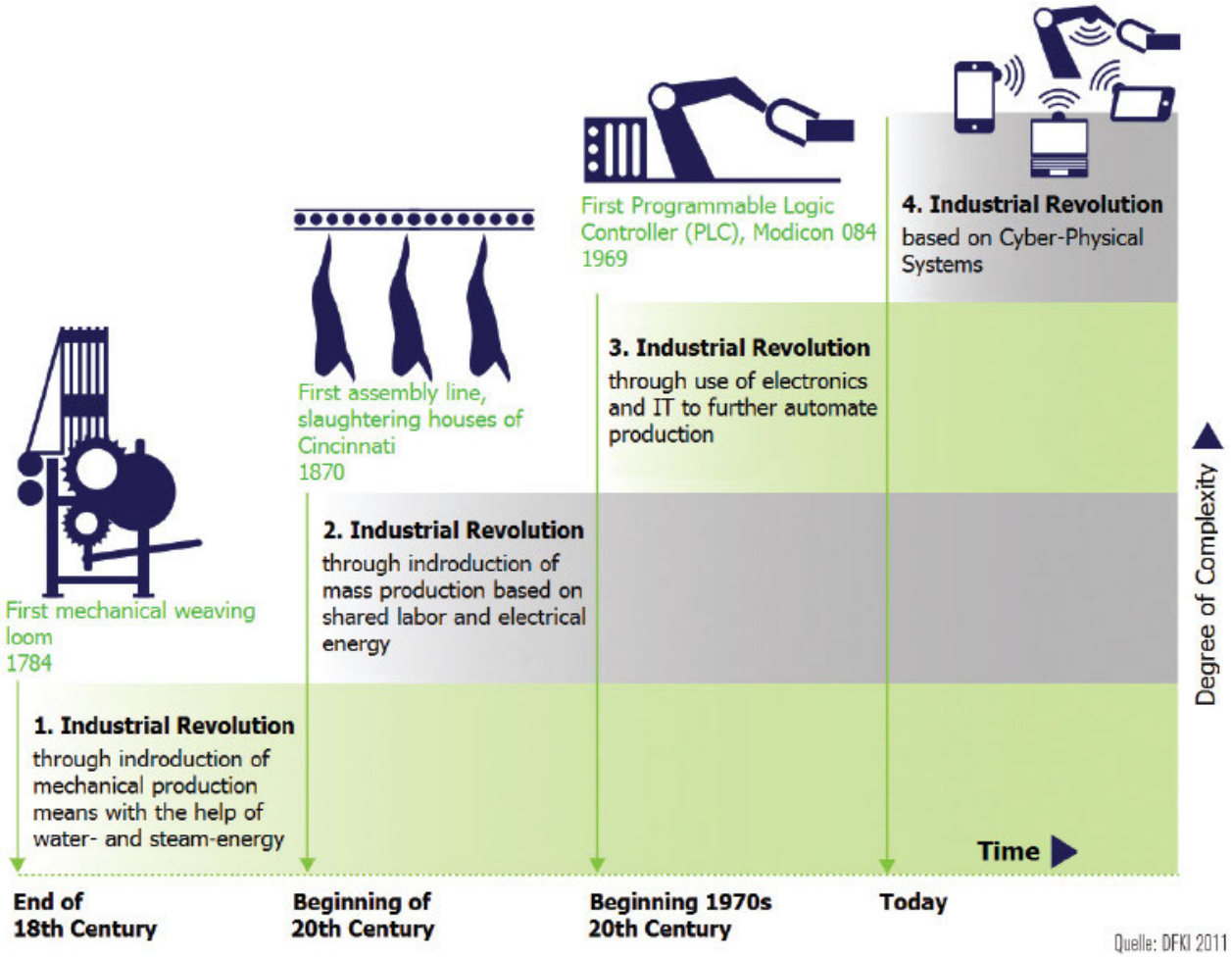


FIGURE 31.1 The industrial revolutions in a time line. Implementation guidelines of the German Department of Commerce.)

In the early twentieth century, mass production through the introduction of the assembly line and thus the division of labor led to the second industrial revolution. Conveyor belts for meat processing were used for the first time in the slaughterhouses of

Cincinnati. The principle was later adapted by the automotive industry. The last historical revolution took place in the 1970s. Automation found its way into the workplace and many other areas of life. Technological revolution, started by the invention of the microchip, fundamentally changed many aspects of our lives. NC machines, the predecessors of CNC machines, replaced machines that were controlled manually.

All three historical revolutions shared a fundamental change in the conditions of production, the effects of which had a tangible impact on society as a whole. The current situation of modern companies has become much more complex. Science and technology are becoming ever more important, while globalization is making international business ties commonplace. This requires a shift in production, an end-to-end networking that could be achieved through use of the internet as part of Industry 4.0.

CORE ELEMENTS OF INDUSTRY 4.0

The following are the best-known keywords of Industry 4.0.

Social Media

Social media is different from traditional media such as television or newspapers because of the nature of communication. It is done along a digital route, making communication immediate and interactive. The best-known examples of social media services are Facebook, Xing, and WhatsApp. The great advantage of social media is the simple way information is exchanged between users and devices. Social media was first used among individuals, but industry increasingly uses it in its corporate communication. Social media supports a global corporate presence with high accessibility, multimedia features, and best possible timeliness.

Interdisciplinarity

This term refers to the connection and combination of independent, scientific disciplines and their methods, approaches, or schools of thought. Various solution strategies are devised and applied for the best possible result. The results might be new ways of thinking and solutions to problems. Many synergies between individual disciplines can be used particularly at the onset of the current industrial revolution.

A salient example is the job description of the mechatronics technician This new occupation emerged a few years ago out of the respective occupational training programs of the machinist and the electrician, supplemented by control technology, control engineering, and information technology.

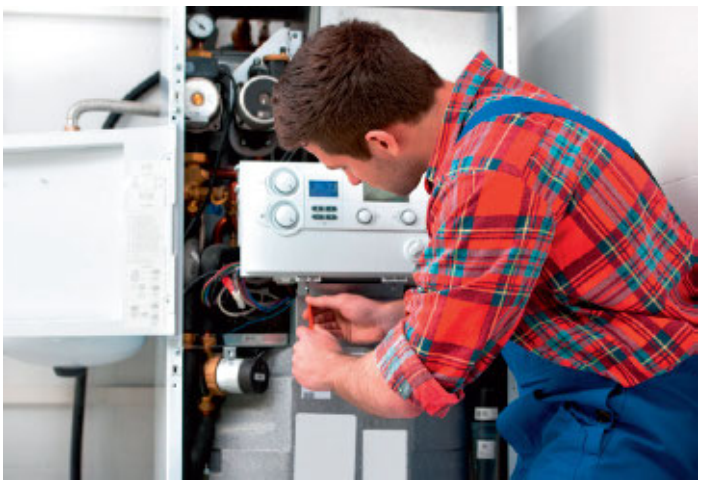


FIGURE 31.2 The mechatronics technician as an example of interdisciplinary vocational training.

Virtualization

Virtualization is a term borrowed from computer science. It means that a virtual realm is formed, detached from actually existing resources such as machines. In this way, existing resources can be structured and made transparent for the user. This principle can also be applied to production. In the CNC environment, virtualization already exists as the simulation of CNC processes. Virtualization can also be used as a real-time representation of actual factory processes.

Mobile Computing

Mobile computing is becoming increasingly relevant. It includes computer work on a portable device and mobile communication encompassing hardware and software. All portable computing devices can be used, such as smartphones, tablet PCs, and laptops. Simple and intuitive access to company data and applications from anywhere and at any time could become the standard for all companies. This

development is somewhat limited because of low transmission rates of the mobile internet, lack of security standards, and the low battery life of the devices.

Smart Objects

Smart objects can be packaging, objects, or workpieces that are equipped with a digital memory in the form a data-storage provision. In this way, the digital world is connected to the physical world. A requirement of this connection is the unique way to identify these objects. This can be done with the help of barcodes, radio-frequency identification (RFID), near-field communication (NFC), or iBeacon that are detected by scanners and computers.

RFID refers to a technology for transmitter-receiver systems for automatic and noncontact identification and localization of objects with radio waves. An RFID system consists of a transponder, which is located on or in the object and contains a distinctive code, and a reader for reading this identifier. In the manufacturing sector, RFID has been used for tool coding for many years

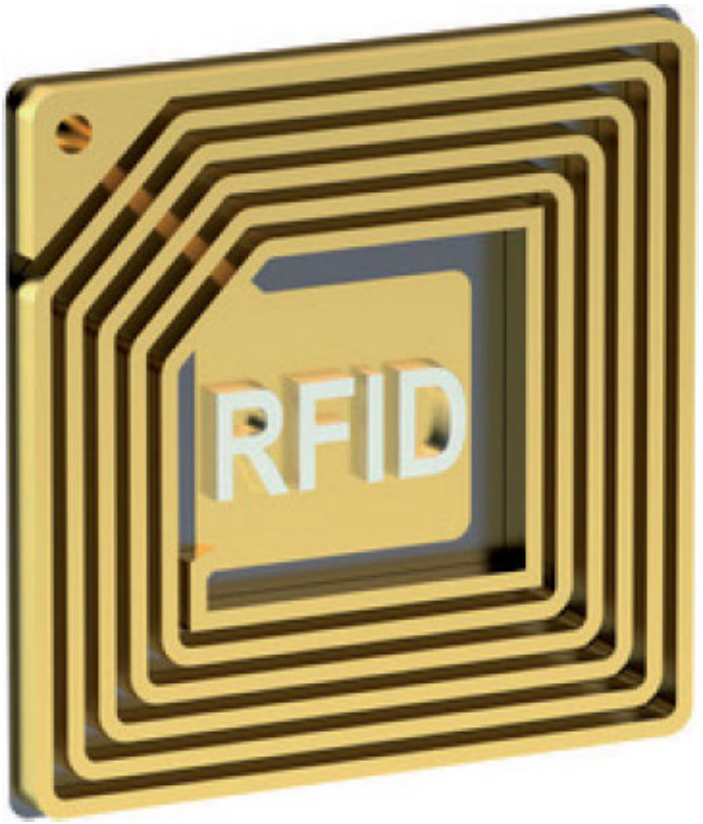


FIGURE 31.3 RFID Transponder

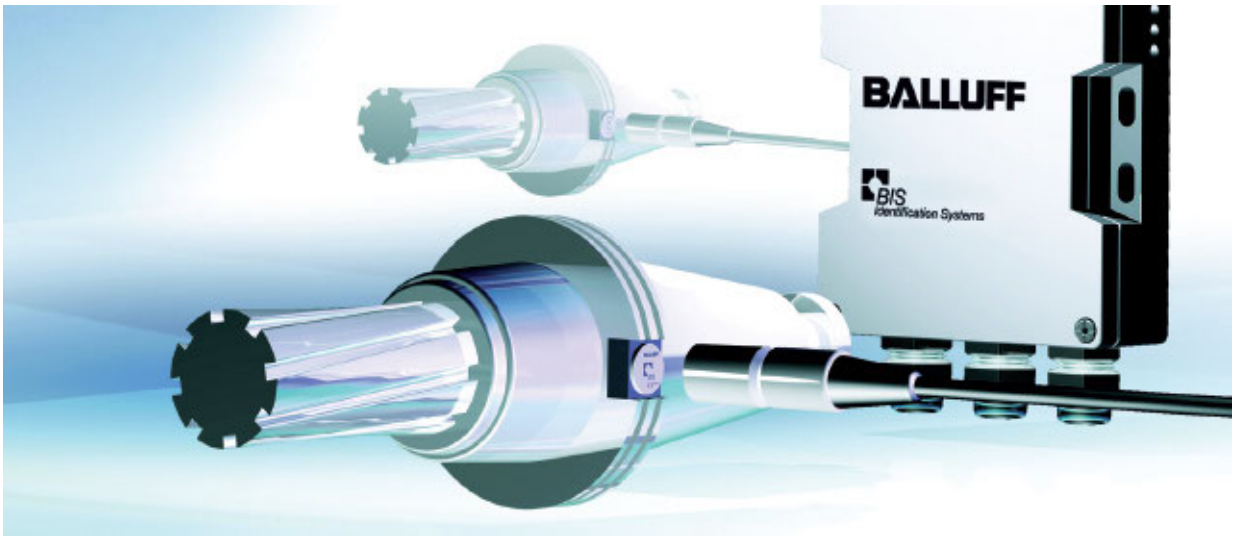


FIGURE 31.4 Tool coding with industrual RFID. Source: BALLUFF

NFC is an RFID technology–based international transmission standard for the contactless exchange of data via radio technology over short distances. Presently, with the help of smartphones and their NFC functionality, car doors of various models can be unlocked, and customized settings on car seats can be made

FIGURE 31.5 Near-field communication hardware.

iBeacon is a proprietary standard introduced by Apple, Inc., for indoor navigation based on Bluetooth technology. Beacons or small transmitters are placed in a room and send signals in fixed intervals. If a receiver, say, a smartphone app, comes within range of a transmitter, the transmitter can be localized, and actions are triggered.

Internet of Things

The internet has changed from a medium for information exchange to an interactive connection of people and machines. The extension of the existing internet to the *Internet of Things* is the solution to connect objects of any kind in a digital network. This allows a

universal communication, both among objects and with their environment. Thus the physical world of things merges seamlessly with the virtual world of data. One possible future scenario in the IoT is that every consumer object has its own IP and is connected to the Internet. Once in use, each object will be connected to its service provider through the internet for the remainder of its life. The greatest challenge for the IoT is a unified communication standard among the systems.

Internet of Services

This refers to the part of the internet that offers web-based services and functions. Providers make these available on the internet and offer their use on request. Individual software modules or services can be integrated with each other via internet service technologies. Companies can create complex yet flexible solutions from the individual software components. This creates new business models that, in turn, act as a catalyst for the IoT and IoS.

Big Data

As a result of the technical development of the internet, it is becoming increasingly easier to collect, store, and analyze large amounts of data. *Big data* refers to this globally available and rapidly increasing data volume. The added value of big data for manufacturing is the fact that data can be used to automate, visualize, and analyze the processes.

Analysis and Optimization

The complexity and amount of data tend toward a maximum value. This is why it is becoming increasingly important to quantify and analyze them. Statistical methods can be used to extract information from the sea of data. Filtering out important information from a

large amount of data is also referred to as *data* Big data increasingly collects unstructured data, and only by means of heuristics and pattern recognition is new knowledge gained, for instance, for the optimization of processes.

Cyber-Physical Systems

Cyber-physical systems (CPSs) are systems in which computers communicate with and control actual devices. These are often referred to as *embedded systems* and open the door for completely new planning of production facilities. The internet or the intranet serves as the communication medium. The Fraunhofer Institute for Integrated Circuits (IIS) defines CPS in the strict sense as follows: "Cyber-Physical Systems are embedded systems that are spread out, interconnected, communicating in real-time using sensors to monitor processes in the real, physical world and act on them through actuators. They are also often characterized by high adaptability and the ability to handle complex data structures."

It could be in the future that an intelligent workpiece advances on its own and controls the fabrication process. This is a possible application scenario for CPS, and it remains to be seen whether this technology will prevail in the field of CNC machines. A more realistic CPS application in the context of CNC machines, for instance, is the intelligent chip container. By means of cameras and sensors, it monitors its fill level and organizes its service.

Assistance Systems

Constantly advancing technologies, machines, plants, processes, and procedures have increased the degree of difficulty in manufacturing in recent decades This reveals the crucial difference between complicated and complex: Complicated problems are predictable, manageable, and

can be automated if one has enough knowledge about them. They can be calculated and solved without human interference, solely with computing power. For example, two chess computers can compete with each other and come to a meaningful conclusion.

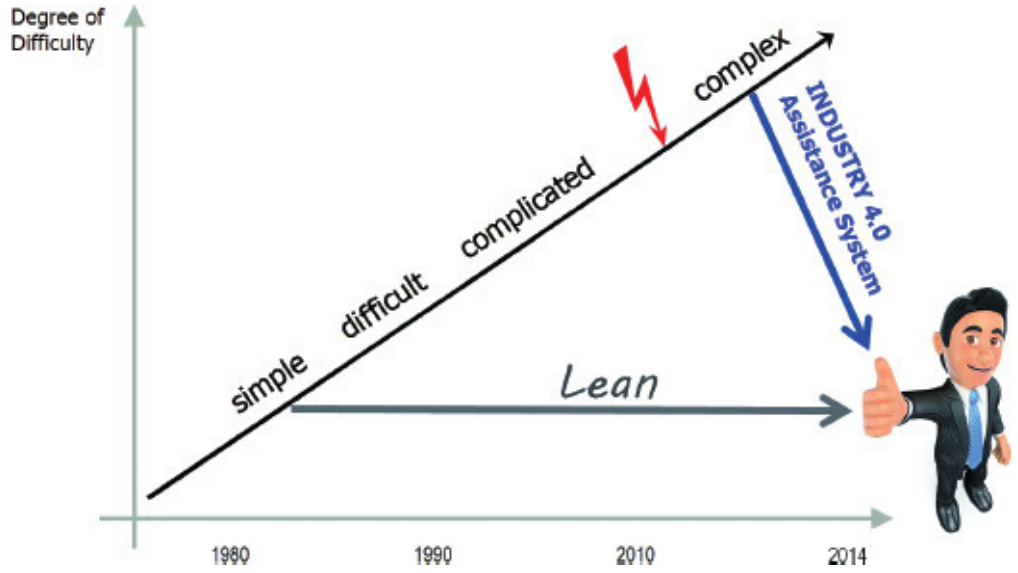


FIGURE 31.6 Increase in the degree of challenge and two methods for reduction.

Complex problems are not predictable, only observable. They can be influenced, but without foreseeing the consequences. Thus they cannot be calculated and are not manageable. Precise planning for a complex system is de facto pure illusion. For example in a soccer game one team is down 0 to 1. The losing team can send an additional forward on the field, but the consequences cannot be predicted.

LEAN and Industry 4.0 therefore use different approaches to meet this ever-growing challenge. LEAN uses methods and procedures for the efficient and simple design of work processes. This is to say that LEAN does not allow an increase of the challenge for humans.

However, as both the LEAN approach and the human reach their limits in modern high-performance processes, it is important to first implement all available LEAN methods successfully. Based on this, the building blocks of Industry 4.0 can be applied

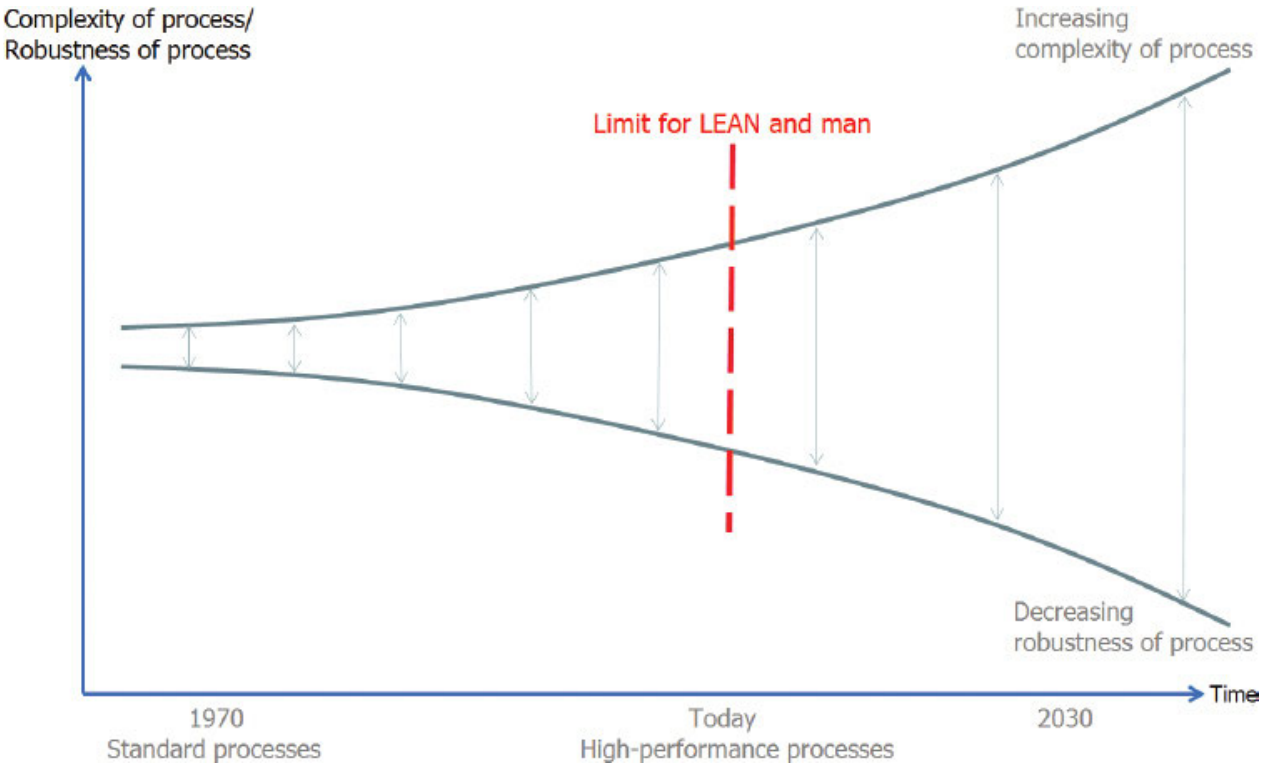


FIGURE 31.7 Limit for LEAN and human. JH.)

Industry 4.0 allows the increasing complexity and reduces the perceived complexity with assistance systems to a manageable degree. Assistance systems are able to produce the following positive effects:

the Example: The braking assistant in a car improves the braking distance and tracking while braking.

the competency development of the Example: The navigation system in a car allows the nonlocal driver to navigate in a foreign city.

the otherwise impossible Example: The modern fighter jet cannot be flown by the pilot without assistance systems.

A modern assistance system in the context of Industry 4.0 also works as a manufacturing execution system (MES). It acts as a link between the ERP system and the shop floor (vertical integration) and as a link between the individual units executing the production process on the shop floor (horizontal integration).

Smart Factory

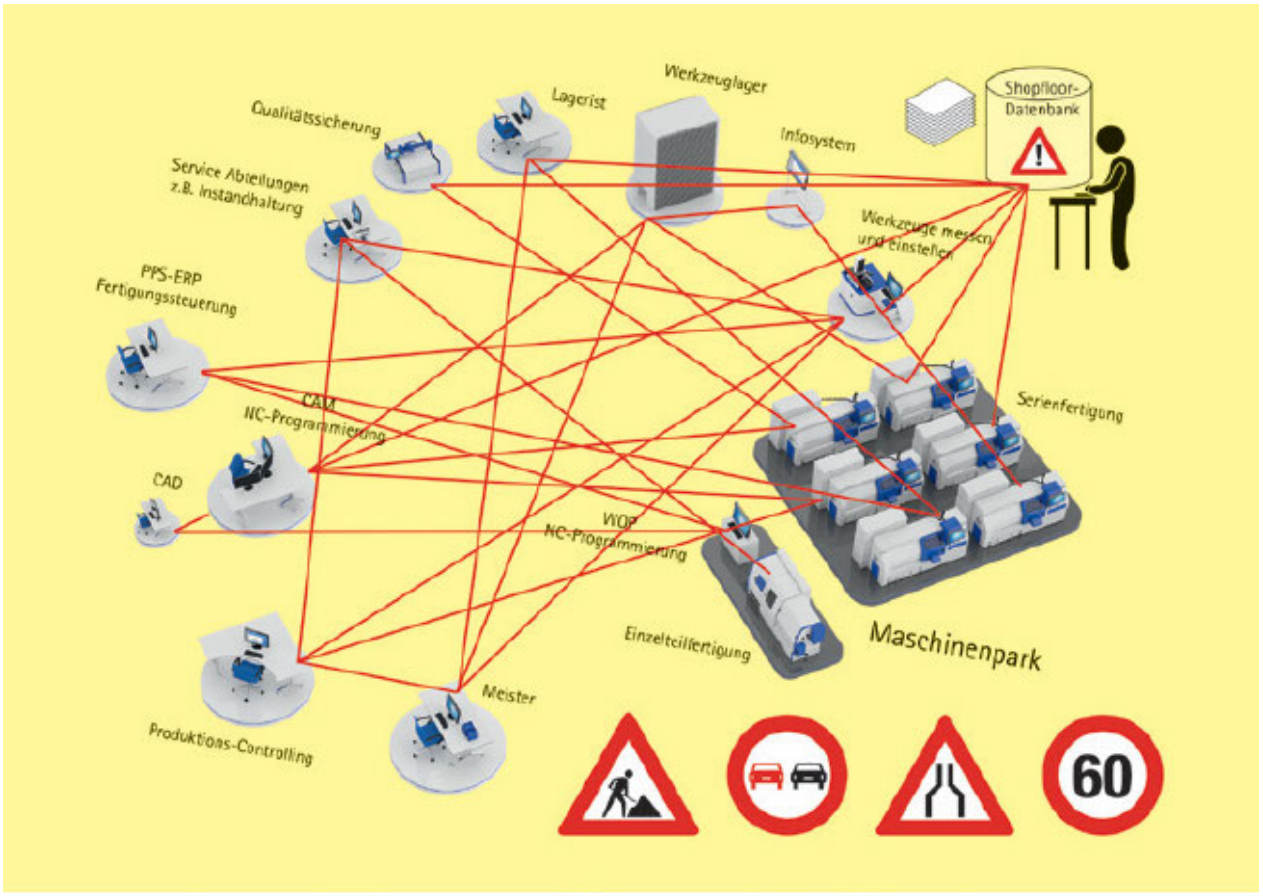
Smart factory refers to a new understanding of the use of the internet for production and the establishment of a resilient factory where people, machines, and components communicate with each other and only fabricate what is actually needed. The manufacturing process is decentralized, so it will be controlled by the products to be produced (CPS). The raw, semifinished products and finally the finished products are equipped with intelligence; they become a carrier of networked information and communicate with people, the environment, and equipment. The smart factory is more energy and resource efficient thanks to real-time control through the IoT.

INDUSTRY 4.0 IN PRODUCTION

CIM was developed in the 1980s as the first approach to networked production. At that time, island-type systems were used that were limited to distinct, very particular areas of fabrication. However, these systems could not branch out to other systems because of the lack of interfaces. Data had to be handled manually, and this was one of the main reasons for the failure of CIM.

The key difference between Industry 4.0 and CIM is the focus on the human. The human takes a salient position in the process, using completely new assistance systems that help to handle problems. The methods of Industry 4.0 make it possible to automate, visualize, and analyze, but eventually the human decides.

CIM used a 1-to-1 model of interfaces for communication that resulted in an unmanageable number of interfaces The smart data hub (= ValueFacturing) reduces the number and bandwidth of the required interfaces dramatically


Qualitätssicherung
Lagerist
Werkzeuglager
Shopfloor-Datenbank
Service Abteilungen z.B. Instandhaltung
Infosystem
Werkzeuge messen und einstellen
PPS-ERP Fertigungssteuerung
CAM NC-Programmierung
Serienfertigung
CAD
WOP NC-Programmierung
Einzelteilfertigung
Maschinenpark
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Produktions-Controlling
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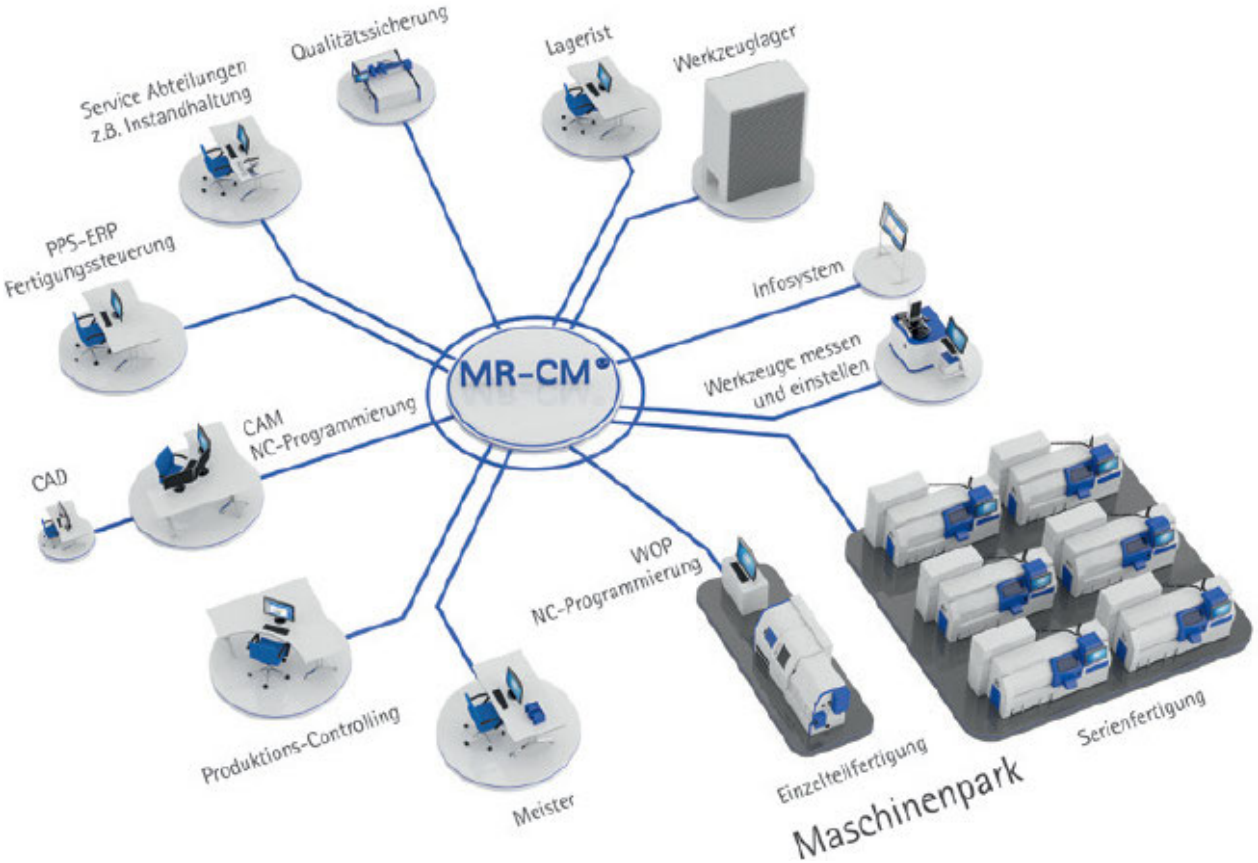
Service Abteilungen z.B. Instandhaltung
Qualitätssicherung
Lagerist
Werkzeuglager
PPS-ERP Fertigungssteuerung
Infosystem
Werkzeuge messen und einstellen
MR-CM®
CAM NC-Programmierung
CAD
WOP NC-Programmierung
Produktions-Controlling
Meister
Einzelteilfertigung
Serienfertigung
Maschinenpark

FIGURE 31.8 CIM versus ValueFacturing.

MES AS A BUILDING BLOCK OF INDUSTRY 4.0

A hub aptly describes the core point of communication within an MES (Manufacturing Execution System): the MES acts as the interface of the company IT structure between the ERP system and the manufacturing level or shop floor. Thus the MES combines vertical and horizontal integration of a production installation, which in turn is a precondition for the smart factory

FIGURE 31.9 An MES connects the ERP system and the shop floor.

In the framework of vertical integration, the ERP system generates a fabrication order and transfers it to the MES. The MES will execute and conclude the order on the shop floor. It generates a holistic data flow as this process unfolds and reports back to the ERP after the job has been finished or partially finished. In this kind of networking, the ERP system has access to

all production data and can allocate orders based on up-to-date queries. It does not calculate existing capacities based on planned data that are prone to errors.

The horizontal plane of the production is realized by networking the machines of the shop floor. The hub as a central point of communication is connected to all machines and installations and enables their real-time communication. The complete horizontal and vertical linking of all actors in a fabrication process via the hub makes it possible to optimize production efficiency and transparency.

Although representation of the IT structure of production as a pyramid is still valid, it needs to be modified in the future. One reason for this is that Industry 4.0 changes this structure through extremely diverse and autonomous units

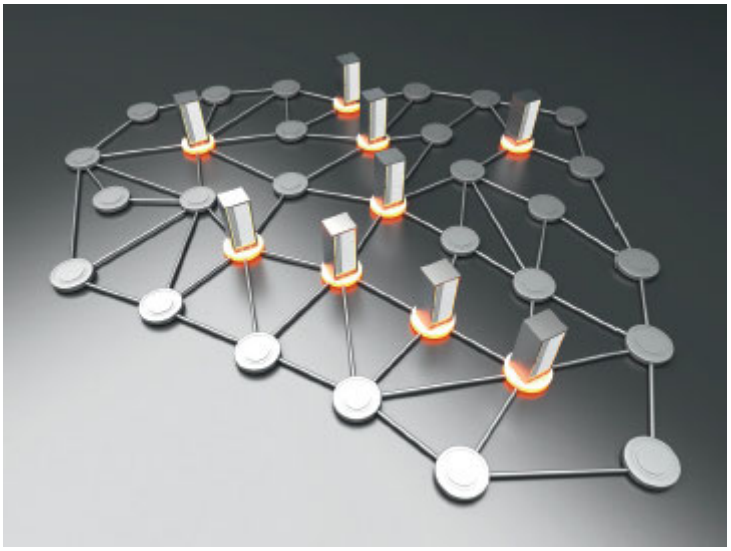

FIGURE 31.10 Industry 4.0 supports fractal operating fabrication units.

An MES can generate additional value for users if it is capable of performing data enrichment. Here the MES fetches data from various systems and on behalf of a requesting actor D. These data will generate new sets of relevant data for an efficient workflow through intelligent processing and linking

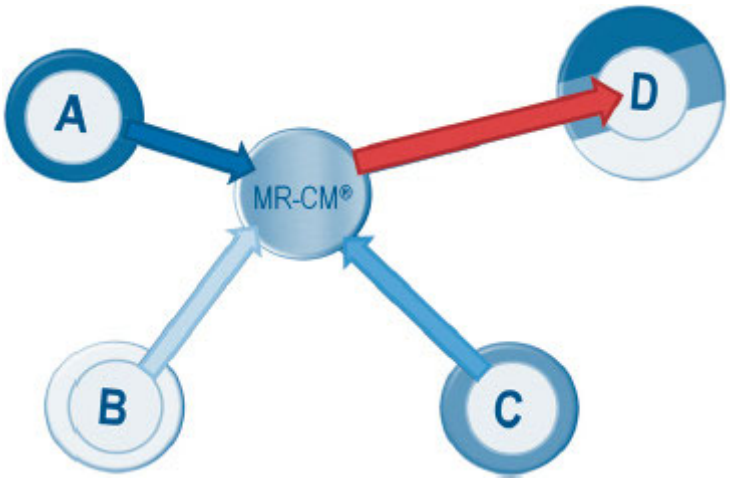

FIGURE 31.11 Schematic of data enrichment.

As an integrated system solution for complex machining tasks, an MES also allows an overview of the entire production installation and its processes. In addition, a continuous electronic workflow with tamper-proof production control is ensured with the automatic finding of the overall equipment effectiveness (OEE) code. The code expresses availability, performance, and quality rates. The overview ensures sustainable production efficiency because non-value-adding times of the machines are immediately detected and minimized. Thus an MES ensures the dissemination of pertinent knowledge among employees and machines at any given time and place. This is knowledge that in the past had

unsystematically accumulated among various individuals and databases.

The complexity of production increases steadily. A modern Industry 4.0–compatible MES therefore offers the user numerous assistance systems and data-enrichment tools in order to reduce the perceived complexity. Further advantages of an MES are evident, for example, in NC programming: tool lists are automatically and digitally provided and precise assembly graphics make further inquiries unnecessary. The NC documentation is standardized and recorded electronically, making hard copies superfluous. The well-known work folder with hard copies of NC program, tool list, clamping sketches, and so on will be replaced by a digital and thus paperless work folder. Furthermore, the MES records the life of all NC programs digitally and continuously.

This allows definite tracing of all changes in the NC program and the differentiation between the responsibilities of employees and machines involved Thanks to this comprehensive paperless documentation, an efficient and transparent design of the entire production process can be achieved.

When distributing orders among machines, decisions can be made based on up-to-date, universally provided data. Another step in the direction of Industry 4.0 in production is made with the establishment of suitable communication and interface standards. The exchange of information among machines and plants too often still takes place using proprietary data formats. This can result in transmission interruptions and data loss.

This problem is solved by an MES that is installed as a hub that centrally regulates communication as a multi-interpreter, performs automatic data enrichments, and makes information paths and data lines comprehensible. The scalability of the overall system can by realized with the use of open XML-based standards in the implementation of horizontal as well as vertical integration.

CHALLENGES AND RISKS OF INDUSTRY 4.0

Germany is one of the most competitive industrial locations and at the same time a leading factory supplier worldwide. With its strong engineering and plant engineering, its worldwide renowned IT competency, and know-how in embedded systems, technology, and automation technology, the country is in a remarkable position to expand its leadership in production technology. Unlike many others, the country will be able to unlock the potential of a new form of industrialization: Industry 4.0.

The road to Industry 4.0 requires companies to make enormous efforts in research and development. In order to be able to implement this dual strategy, there is a need for research on the horizontal and vertical integration of production systems and the consistency of engineering. In addition, a new social infrastructure of labor in Industry 4.0 systems must be taken into account, and CPS technologies must be developed.

In addition to research and development, industrial policy and industrial decisions must be made for the implementation of Industry 4.0. The working group Industry 4.0 stated the need for action in the following important areas:

■ *Standardization and software* Industry 4.0 means comprehensive networking and integration across the entire value chain. Today this cross-company communication is lacking a unified software architecture, so many forms of communication must be customized or need expensive adaptation and custom

programming. Projected extensions for cross-border or cross-company extensions are therefore rather restricted.

■ *Mastery of complex* Products and production systems are becoming increasingly complex. Adequate planning models are a basis for mastering the complexity, but today there are too few tools to create such models.

■ *Comprehensive broadband infra-structure for* A basic prerequisite for Industry 4.0 is highly reliable national and international communication networks of high quality. The global broadband internet infrastructure therefore must be massively expanded.

■ Operational security and protection from attack are critical success factors in intelligent production systems. On the one hand, production facilities and products should not jeopardize people and the environment; on the other hand, the installations and products also need protection from abuse and unauthorized access, particularly data and information protection. For this, integrated security architectures and definitive proof of identity must be realized.

■ *Education and* The job descriptions and competency profiles of workers will change considerably in Industry 4.0. Currently, there is a lack of qualification strategies.

■ *Legal* New production processes and networks in Industry 4.0 must conform to the law, and current laws must be adequately

adapted. The challenges include protection of corporate information, liability, personal data handling, and trade restrictions. Lawmakers and business leaders must take action such as issuing guidelines, model contracts, company agreements, and self-regulations such as audits and so on.

■ *Resource* High energy consumption proves to be a limiting factor because many objects are connected in terms of communication but have to operate independently of the energy supply. Sensors, actuators, and communication protocols have rarely been developed from the perspective of sensible use of resources.

resources. resources. resources. resources. resources. resources.

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REQUIREMENTS FOR INDUSTRY 4.0

The prerequisite for a smart factory is the continuous exchange of data between planning and production level. In practice, smart factory means that workpiece and machine communicate with each other. Industry 4.0 cannot be realized as a stand-alone solution consisting of local software modules and a minimum of interfaces. In these insular instances, PDA/MDA systems, DNC software, and modules for planning and maintenance run independently on the same network. But a prerequisite for the intelligent factory is the uncompromising merging of all IT modules. This encompasses the range of gathering process and quality data of the machine to the online connection to the customer. Industry 4.0 can become a viable reality for a medium-sizes precision parts manufacturer with a high degree of integration of the MES software modules PDA/MDA/PTK (personnel time keeping), CAQ, PPS, and the merging of process and quality data. Many facets of Industry 4.0 have already been implemented in industries because of the rapidly developing pace of IT.

In a smart factory, the following requirements must be met:

■ Workpiece and machine tool communicate with each other (web server and control center)

■ Merging of IT and production

■ Continuous information exchange between the planning and production levels

■ Unambiguous identification of workpieces and products

■ Knowledge of the current production location and the production status of the product

■ Constant evaluation of the value chain and semifinished parts

■ Genesis of the products

■ Knowledge of alternative manufacturing methods

■ Flexibility of production processes

■ Best possible production organization and IT infrastructure

■ Feedback from the production level

■ Exchange of information from the planning and shop-floor levels

■ Uncompromising integration of business processes encompassing every machine and device

■ Consistency in planning from calculation to the production machine

■ Real-time capture of production data in a heterogeneous production environment

■ Installation of a control loop between planning and production

BENEFITS OF INDUSTRY 4.0

Industry 4.0 offers the following benefits:

- Optimization of production through cyber-physical systems (actuator/sensor)
- Increase of productivity by up to 30%
- Worldwide access to information, seamless information chain from the machine to the smartphone
- Minimizing material consumption
- Minimizing energy consumption
- Tracking batches forward and backward
- Faster response times
- Key figures and status information in real time
- Accompanying calculation, constant comparison of command and actual value
- Comprehensive evaluations and visualization modules
- Vulnerability analysis

■ Worker exercised control mechanisms

■ Reduction of susceptibility to interference

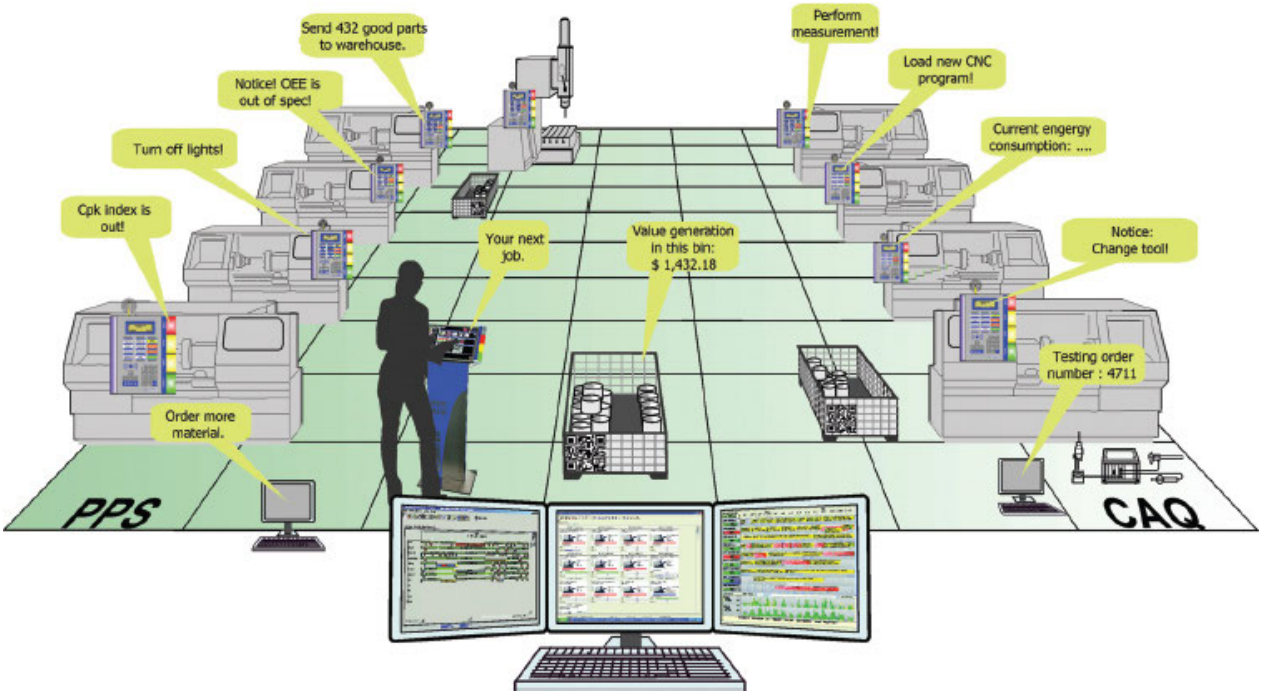

FIGURE 32.1 The comprehensible visualization of the entire production process, including all ancillary processes, such as personnel time recording, maintenance intervals, tool inventory, tool requirements, and so on, is a prerequisite for the success of networked production. GEWATEC.)

CYBER-PHYSICAL SYSTEMS (CPSS), THE INTERNET OF THE THINGS

CPSs are systems that consist of sensors for data acquisition and actuators for the execution of commands in the physical world. All sensors and actuators are logically linked with each other and controlled with software The physical world thus merges with the virtual world—cyberspace. It is also said that the physical world and the virtual world become the Internet of Things (IoT) through cyber-physical systems. On this basis, partially independent production systems can be realized with remote monitoring.

FIGURE 32.2 Industry 4.0 only works if the various processes of a production are interlinked. By linking quality management and production control, for example, a machine can be automatically

stopped if a feature of a workpiece is outside manufacturing tolerances. A message with the information about the stop of the machine can be sent by e-mail or text message to the machine operator or to the production manager GEWATEC.)

SIXTEEN CASE STUDIES ABOUT INDUSTRY 4.0

Work Order: Automatic Retrieval of Correct CNC Program

For medium-and small-batch production, machines often have to be retrofitted and set up for new parts. The process of retrofitting is explicitly specified by the production order. Conversion processes are logged onto the MDE terminal. The retrofitting process triggers a series of actions: the associated NC program with the valid version status is retrieved from the database and automatically loaded to the CNC machine by wireless connection. All CNC programs are given a version ID and are archived with the respective production order.

Automated Warehouse Updating at the End of the Shift

Automatic Material Request

A part counter in the MDA terminal registers and counts all workpieces produced. Possible cases of rejects are reported to the MDA. At the end of each shift, all good parts are automatically posted to an assigned storage location. In addition, the spent raw material is automatically deducted from the warehouse on the basis of the parts produced

FIGURE 32.3 MDE terminal IC901 captures all machine conditions; the operator can initiate a freely definable workflow. Typical examples of this are material requisition to raw parts warehouse, notification of order transfer, and ready message with automatic versioning of the NC program. The MDE terminal will continue to provide feedback such as the time of the tool change or maintenance measures. The integrated process light signals in traffic light colors (red, yellow, green) the most important quality and process indicators (OEE, CPK) for the process control of production. GEWATEC.)

When the supply of material on the machine is exhausted, the worker can send a material request to the warehouse operator by pressing a button. A workflow chart can be customized for measures that will start the resupply of material. Data entered in the material requisition form might include material ID, batch numbers, quantity, and warehouse location.

Request to Exchange Tools That No Longer Produce Good Parts

The time for a tool change is calculated for each individual tool based on the tool life and operating hours. During production, this calculation is constantly updated, and the system "knows" when a tool service life is up and must be exchanged. In this case, the process light on the terminal indicates to the worker the necessary tool change. The display provides the information about which tool needs to be changed, for instance, "Change insert of tool 4."

Automatic Job Change on a Machine

When the last operation of a production order has been completed, a new order is automatically activated and assigned to the machine by the planner with the help of interactive graphic software. With the change of a work order, the following processes are triggered automatically:

- Saving the current CNC program
- Retrieving the new NC program
- Generating a test order
- Setting the status of the machine to "Setup"

Delivery Schedules Online

Production, assembly, and logistics are closely linked. The customer enters delivery schedules and delivery requests as needed; these are then forwarded to the production planning department.

Container Management

At any given time, the systems knows the physical location and condition of the product. The container management links the finished lot sizes of a production order with the container. A log is kept with details of the container content.

Process Control by Process Traffic Light

The use of an industrial PC with corresponding software is sufficient to quickly capture the current status of production with a color-coded output. Red-yellow-green color-coding indicates the current status of the machine tool. The OEE indicator provides information about degree of utilization, efficiency, and quality rate of the respective machine. The CPK value informs about the statistical value of the process capability. The quality data acquisition (QDA), for example, indicates the time to perform another measurement cycle for quality monitoring. Manufacturing processes are monitored and controlled using statistical process control. The system also informs when tools need to be changed. The operator thus knows at any given time the condition of the machine and the process. Transparency in production creates the prerequisites for recognizing and correcting errors and weak points, as well as continuously optimizing production.

Accompanying Calculation in Real Time

During production all relevant parameters such as process time, tool use, and material consumption are continuously calculated and compared with the nominal specs. In case of deviations, appropriate measures are triggered, which are defined in a workflow. This could be an e-mail or text message sent automatically to the production manager.

FIGURE 32.4 Industry 4.0 only works if the various fabrication processes are interconnected. By linking quality management and production control, a machine can be halted if a feature of the workpiece is found to be out of tolerance. A "machine stopped" message can be send to the operator or the floor supervisor per email or text. Source: GEWATEC.

Intelligent Tool Issue

Tools are issued automatically to the operator based on the production order number For record keeping, the tools are automatically posted to the corresponding production order. Software manages tools, tool lists, setup sheets, and CNC programs. Part, work plan, operation, and finally the selection of the machine are used to access the CNC program and tool list. Freely configurable

input fields in tool tables enable the creation of machine-dependent tool lists and setup sheets.

FIGURE 32.5 Based on the Fabrication Order the operator is issued the toolset by the fully automated tool kiosk. This precludes the issuance of the wrong tool. Additionally, the tool usage can be fully planned and monitored. Source: GEWATEC

Correlation of Process and Quality Data

The test plan describes how the part is tested. The feature catalog manages all quality-relevant characteristics. The measured values are recorded in a quality log. The MDA system records process parameters such as pressure and temperature (process data collectors). If a value in a quality log falls out of the tolerance,

appropriate measures must be taken immediately, within seconds or minutes, depending on the process, in order to bring the process back into compliance. For example, the temperature for an injection process must be readjusted. The process parameters are automatically converted by a control unit according to the method described earlier and corrected via the standard interface EU-ROMAP 63 or OPC.

Automatic Tool Offset

Based on the measured values in the quality control chart, trends are determined over which intervention or tolerance limit violations can be predicted. Before a tolerance violation occurs, the tool offset of the relevant tool is adjusted accordingly and transmitted online to the machine control system.

Forced Stop, Machine Stop

A prime example for the linking of production processes is the interaction of quality management and production control. If CAQ detects a tolerance violation, the relevant machine is automatically stopped by the MDA terminal.

Check Request, Dynamic Test Control

A process light indicates to the worker to take a measurement. The test procedure is initiated by registration at the measuring station with the RFID chip, and the associated test order is automatically opened. The measurement can start immediately. The time interval for required measurements is specified in the test order. With dynamic test control, the control cycle can be relaxed or tightened depending on how well the process performs.

Energy Management, Turning Off Lights and Compressor

Machines 4, 5, 8, and 10 are standing still during the night shift due to lack of material and tool breakage. Because of this, the light in

this section of the facility is automatically switched off. When all machines are stopped, the compressor changes to “Standby” mode.

Software and sensors check the exact condition of all production machines (runs yes/no, output). Many machines operate until raw material has been spent; this can be late at night. Software-based energy management makes it possible to control compressors, lights, air conditioners, and other energy consumers according to the state of individual machines or machine groups, contributing to energy-efficient production. A freely definable event script allows the user to turn energy consumers on and off and send e-mail and text messages to selected recipients.

Maintenance, Preventive Maintenance, Range Control

Operational safety, reliability of complex equipment, and manufacturing resources and their availability can be kept on a consistently high level of productivity. For this it takes a preventive maintenance concept. A computer program keeps track of and calculates when a tool needs to be maintained, for instance, after a certain number of shots of an injection mold tool. When the set quantity of iterations has been reached, the process traffic lights at the MDA terminal indicate that the tool needs to be serviced or replaced.

A WORKDAY WITH INDUSTRY 4.0

The worker starts the night shift and takes over a dedicated machine. The computer informs about events, status of the machine, and work order. The work schedule indicates the next work order that must be started on the machine. Document control provides the input for preparation of the work order (tool list, etc.). Material is ordered via the BDE client. Tools are requested from the computer-controlled tool crib based on the production order.

After the current work order has been completed, the operator sends the NC program to the file server for storage, linked to the article number, word order, and so on. A new work order is issued. The system also automatically creates the corresponding inspection order. The terminal provides the new program for the next job, and the worker loads it into the CNC machine. Next, the worker sets up the machine and submits the “first piece” to the quality department for a compliance check. Switching the machine over to production mode and processing a few parts provides answers about the success of the setup.

An unforeseen problem occurs on the machine; a tool has failed. A new tool is requested corresponding to the work order and operation number. The worker fixes the problem and documents it via the terminal. The incident is automatically logged as a repair. After the tool change has been completed, the machine goes back into production mode. The worker recognizes

via the process lights that a measurement has to be taken. The statistical process control (SPC) measurement is carried out at the measuring station, with or without special measurement equipment. The process light switches to green, indicating execution of the measurement (QDE) and the result (CPK).

Next, the process lamp informs the operator of a pending maintenance activity. The PDM provides details, and the maintenance is carried out.

On the following day, the activities during the previous shift can be completely retraced by the production planning team/department manager/quality team. All pertinent data have been saved and can be reviewed.

Production planning realizes the disturbance of the work schedule due to the tool problem and the unplanned downtime of production. Thus the follow-up orders will experience a delay. The planner can determine the new completion date of the order and possibly inform the customer immediately and make a decision whether a rescheduling to fulfill the order is required.

Meanwhile, the producing machine continues to provide meaningful data about the progress of filling the current order (OEE info, Q-link View evaluations). The process light indicates that the drill on tool station 0606 must be changed. Based on the time in service, the system calculates the exact time for tool replacement.

A message is received in sales that the customer urgently needs parts, no matter how many. The sales department informs the machine operator by e-mail accordingly. The operator generates a ticket documenting the as yet produced parts and sends it to the sales department. The sales department generates the order for surface treatment, allowing the shipping department to load the parts on a truck and send them to the service provider. If a group of machines stands still during third shift, lights and compressor are automatically turned off.

The comptroller of the company requests information about the accounts receivable, production order 4711, and the costs in comparison with the offer.

SUMMARY

The objective of realizing an intelligent factory based on Industry 4.0 can also be achieved in medium-sized manufacturing companies. The requirement is the networking of machines, control units, test equipment, installation technology, and computer system, as well as installation of suitable sensors for the acquisition of process data and process monitoring. The online connection to customers, suppliers, and business partners is expanding the opportunities of digital production.

For smooth and trouble-free production, answers to many questions must be found and visualized on a daily basis. The first step toward Industry 4.0 is this visualization of manufacturing parameters such as remaining run time of a component, currently available tool supply, version of the NC program, and so on In this way, the production manager or machine operator can use the available information quickly and accurately and make the correct decisions. In the next step, sensors, actuators, and intelligent software allow also the automatic execution of decisions, such as a machine stop in response to tolerance violations. Thus step-by-step, reasonable and manageable Industry 4.0 applications can also be realized in the SME sector.

FIGURE 32.6 A clear visual representation of the entire production process including all ancilliary processes such as personnel time capture, maintenance schedule, tool needs and availability etc. is the basis for success of interconnected fabrication. Source: GEWATEC

IMPORTANT POINTS TO REMEMBER

1. Industry 4.0 is the next step of the past three industrial revolutions and is also called the *fourth industrial*

2. The term *Industry 4.0* originates from a high-tech strategy project of the federal government of Germany with the objective of increasing the competitiveness of German industry.

3. The basic idea of the fourth industrial revolution is the system-wide global networking of people, plants, and products.

4. In the future, products and production units should independently and locally self-organize and self-control.

5. Industry 4.0 is based on 12 pillars:

a. Interdisciplinarity

b. Social media

c. Virtualization

d. Big data

e. Smart data

f. Analysis and optimization

g. Mobile computing

h. Smart objects

i. Internet of Things

j. Internet of Services

k. Cyber-physical systems

l. Smart factory

6. Industry 4.0 is backed by the following industry associations: Bitkom (Federal Association for Information Technology, Telecommunications and New Media e.V.), VDMA (Association of German Mechanical and Plant Engineering e.V.), and ZVEI (Central Association of Electronics and Electronics Industry e.V.).

7. Industry 4.0 describes changes that culminate in a smart factory that connects all machines, products, and processes. It uses technologies that are also used in the IoT, such as wireless networks, intelligent objects, sensors, and actuators.

8. The current drawbacks for fast development include:

a. The energy supply of the autonomous objects

b. The limited life of the batteries

c. The lack of uniform interfaces, architectures, and platforms

d. Different transmission standards of wireless networks at close range

e. Unanswered questions about data and legal protection

f. Lack of data security on the internet

g. No consistent process design for new business models

models

Rapid advances in technology mean that the technical terminology is also constantly being adapted, expanded, and modified. The following terms and explanations refer primarily to the field of numerical control (NC) technology.

➔ see separate entry

2½D or 3D motion The positioning of machine slides in two (2½D) or more axes (3D) at the same time (contouring mode).

3D solid model Also called *volumetric* A three-dimensional (3D) geometric model to define the external shape and internal structure of a technical object by volumes.

Absolute measuring system Positionmeasuring system for NC axes in which all measured values are relative to a specified zero point. Each point of the measuring distance is identified by means of a unique measurement signal. The measuring systems used most often are linear and rotary encoders. Opposite: ➔ Incremental measuring system.

Access time In a computer, it is the time between the instant at which a control unit initiates a call for data or a request to store data and the instant at which delivery of the data is completed or the storage is started.

Accuracy, precision In NC machines, a distinction is made between static and dynamic accuracy. *Static* accuracy refers to absolute, repeatable positional accuracy. It is affected by systematic and random errors. *Dynamic* accuracy takes into account inaccuracies arising from the feed rate and acceleration. The accuracy that can be achieved on the workpiece is always lower than the machine accuracy because it is also influenced by other factors, such as the stiffness of the machine and clamping fixture, thermal affects, tool wear, tool weight, and the machining operation.

Actual position Also called *current* Instantaneous value of an NC axis.

Actual value Value of a controlled variable, for example, spindle speed, feed rate, or position of the NC axis, returned by a measuring system at a particular moment.

Actuator Actuating drives in a control system that transforms control signals into mechanical motion. Actuator types currently in use include electric motors, hydraulic and pneumatic cylinders, piezoelectric actuators, and ultrasonic motors. Linear technology

makes use of electromechanical lifting and positioning systems. Actuators can be controlled using openor closed-loop control.

Adaptive control (AC) Control system for automatically adapting the cutting conditions to optimize a specific variable, such as maximum stock removal rate or optimal tool utilization. These specifications can be achieved, for example, by altering the feed rate during milling. This requires special measuring sensors for spindle bending, motor output, torque, motor heating, and chattering. These sensors continuously report the current cutting and output data to the AC controller. These data are used to calculate the command variables for the feed rate and spindle speed, which are then output to the actuators.

Additional machine setup functions Setting up the machine or the workpiece is facilitated by additional measuring functions and displays of the CNC machine. ➔ Auxiliary functions.

Additive manufacturing processes An overall term for the process that was previously often referred to as *rapid rapid* and *rapid* quick, cost-effective production of models, specimens, prototypes, tools, and products. Fabrication is performed layer by layer based on internal CAD data models using amorphous materials (fluids, powders, etc.) or materials with a neutral form (strips, wires, paper, or film) applying chemical and/or physical processes. Examples of these processes include Stereolithography, ➔ Selective laser sintering, ➔ Fuseddeposition modeling, ➔ LOM (laminated object modeling) and 3D printing. They can be used economically to manufacture parts with a high level of geometric complexity.

Address Within an NC program, a letter that defines the assignment of the numerical values that follow. Example: X27.845 means the dimension 27.845 mm in the F125 means 125 mm/min feed. ➔ Alphanumeric notation.

Alphanumeric notation A code for NC programs using a combination of letters, digits, and special symbols. Example: N123 G01 X475,5 Y-235,445 F 250 T7 M02.

Alternate tool Also called *replacement* A tool of similar type in the tool magazine that can be used when the original tool is broken or has reached the end of its service life.

ASCII Abbreviation for American Standard Code for Information Interchange, a standardized code for data storage and transfer; also used for punched tape. Characters are depicted using seven bits for information; the eighth bit is a parity bit for even parity-checking number per character. With 7 bits, a maximum of = 128 characters can be coded.

Amplification factor Factor for amplification in closed-loop control or the lag (following error) of an NC axis depending on the feed rate k_v = following error [(m/s)/mm]. The greater the amplification factor, the stronger is the dynamic behavior of the control circuit.

Amplifier An electronic unit for increasing the power of an input signal to output signal. In NC systems, this is generally a servo amplifier that supplies the power for the servo drives.

Analog A physical variable is analogous to another physical variable if it changes in a certain way depending on the first variable. This relationship may be linear but does not have to be so. As a key feature, an analog signal can have any value between the limit values (theoretically infinite resolution). Examples: (a) Sundials, thermometers; (b) representation of a physical variable in the form of an electrical voltage, for example, speed as tachometer voltage, angle of rotation as potentiometer voltage, and temperature as the voltage of a thermocouple; (c) resolvers: these supply two output voltages that change proportionally to the sine and cosine of the mechanical angle of rotation of the resolver axis. Opposite: ➔ Digital.

Analog-to-digital converter Generally, an electronic device that converts an analog input signal into a digital output signal.

Artificial intelligence (AI) Branch of computer science research concerned with the development of computers that can replicate human intellectual performance. This term is difficult to define because no exact definition of intelligence exists. Examples: Pattern recognition, ability to learn, ability to carry on a conversation.

ASCII keyboard Alphanumeric keyboard for entering data in the form of letters, numerals, symbols, and auxiliary commands in ASCII format. Widely used keyboard with personal computers and CNC systems.

ASIC Abbreviation for *application-specific integrated* An electronic circuit implemented as an integrated circuit (IC) chip

manufactured according to customer specification and typically only supplied to the specific customer.

Assembly language, assembler Lowlevel symbolic programming language for a computer. (2) Translation program that converts programs written in an assembly language to machine instructions.

Asynchronous axes Auxiliary axes that can be programmed and controlled independent of the main axes of an NC machine, for example, for a loading robot.

Asynchronous mode Mode of operation or transmission that is not time dependent and functions independent of other processes.

Asynchronous motor Electric motor for three-phase direct-current (dc) in which, depending on the load, the rotor always runs slower than the rotating field generated in the stator via the windings. This is also called The rotor of the *squirrel-cage* or *short-circuit* consists of copper or cast-aluminum rods that are short circuited at both ends. This type of motor is the most widely used. Torque is created by the induction currents generated by the rotating field. In the case of *slip-ring* the rotor is designed with three windings connected via three slip rings and three brushes to enable high-inertia starts using external electrical resistors. Both motor types can be connected directly to the three-phase network. Depending on the stator winding, whether two, four, six, or eight poles, the rated speed at 50 Hz is 3,000, 1,500, 1,000, or 750 rpm minus the slip. In normal operation, asynchronous motors are not designed for and are not suitable for speed control. In order to allow speed control, a frequency converter has to be

connected upstream of each motor. In this combination, squirrel-cage motors are used primarily as speed-controlled main spindle drives. Speed is changed by changing the voltage and frequency. Modern asynchronous servomotors are specially designed to allow a wide range of speeds.

Automatic guided vehicle (AGV) Automated transport system: trackless, unmanned, ground transportation. Can be guided using various technologies: inductive, with wires embedded in the floor; optical, with markings on the floor; laser guided, with reflectors in the surrounding area; radio-frequency ID (RFID), with position sensors in the floor; and GPS, via satellite guidance.

Automatic mode NC operating mode in which a part program is automatically processed without interruption.

Automation Automatic sequence of a number of successive manufacturing processes in order to release humans from the need to perform repetitive mental or manual functions and to free them from dependence on the machine cycle. Unlike mechanization, in which the entire work process is repeated without changes, in automated systems, work is performed according to a program that is specified from the outside and that can be changed. The entire process is monitored, and deviations are corrected in a self-regulating manner, that is, automatically.

Auxiliary functions, miscellaneous functions Commands for controlling switching functions of an NC machine, such as spindle

ON/OFF, coolant ON/OFF, tool changing, workpiece changing, or end of program.

Axis The principal direction in which the motion of a tool relative to the workpiece takes place. In milling machines, these are the three linear axes and which lie perpendicular to each other. Additional parallel axes are designated and Additional rotational axes (rotary and swivel axes) are designated and ➔ DIN 66217, ISO 841. When defining the positive axis direction etc.), it is assumed that the tool is moving and the workpiece is stationary. If the workpiece moves, such as on coordinate tables and rotary tables, then the axis is marked with an prime ‘, *Y* ‘, or *C* ‘). This makes it possible to carry out the NC programming independently of the structural design of the machine.

Axis calibration Also called *axis error* A CNC function to compensate for systematic position-measuring errors in the NC axis, thus achieving greater accuracy. This can be done, for example, by measuring the NC axis precisely with a laser interferometer and saving the dimensional deviations of the path-measuring system as compensation values. In subsequent operation of the machine, these values are added to the measured values depending on the position and direction (positive or negative).

Axis change Switching the and in the NC program in order to process NC programs on machines with different axis arrangements and angular heads placed in front.

Axis lag Also called *following* Dynamic distance of an NC axis between the calculated position and the actual position during axis motion. The lag value depends on the control-loop amplification factor) of the drive and the feed rate.

Backlash Also called A relative movement delay between mechanical parts resulting from looseness.

Backlash compensation CNC function of indirect travel measurement of an axis by means of a ball-screw and rotary encoder. An electronic compensation is performed between the drive mechanism and the measurement unit. At a reversal of direction, the travel measurement only starts when the compensation value, stored in the CNC system, has been passed. Can be adjusted and corrected for each axis separately.

Ball screw Also known as *recirculating ball* Thread spindle with low friction between the spindle and recirculating ball nut, used for force transfer in NC machine slides. Additional advantages are high pitch accuracy, minimized backlash between spindle and nut, and a high efficiency of approximately 98%.

Barcode This code consists of a band of bars of various widths that represent alphanumeric characters. There are a number of different encoding systems. These are hard to decipher visually, which is why Arabic numerals are generally also printed. Barcodes are used for labeling and automatic identification of tools and workpieces. Instead of barcodes, increasing use is being made of data matrix codes, which require less space (2 × 2 cm) and can contain up to 200 characters. The general trend is toward the

replacement of optically readable encoding systems by RFID systems.

Baseband The unmodulated frequency range of a signal, for example, in a LAN. Only one transmission channel is available, which is used by the connected stations one after the other. Opposite: ➔ Broadband.

Baud Data communication term that defines the transmission speed. One baud equals the transmission of one symbol per second. It is often confused with *data transmission* defined as bits per second.

Behind-tape-reader (BTR) input Data input for an NC downstream of a tape reader to input data to controllers that do not have a DNC interface. No data output is possible.

Binary-coded decimal code A method of encoding decimal numbers using several binary numbers. Each digit is represented by its own binary number. Example: 0001 0010 0011 0100 1000 1001 = 123.489. The BCD code makes it easy to represent any numerical value because the number of digits is unlimited, and conversion is very simple.

Big data Refers to data volumes that are too large, too complex, too fast paced, or too weakly structured to evaluate them with manual and conventional methods of data processing.

Binary Two mutually exclusive states, for example, yes/no, correct/incorrect, on/off, 1/0. These are very easy to depict digitally, for example, with hole versus no hole in a punched tape.

Binary code Code that uses only two different elements to represent data, that is, 0 and 1. Especially suitable to represent data that are transmitted in digital form or processed in a computer. Thus *n* binary signals can be used to define 2 *n* states. Example with punched tape: seven tracks (eighth track is used for a check bit) can be used to express = 128 signs. ➔ Binary numeral system; ➔ BCD code.

Binary digit (bit) The smallest representation unit in a binary number: 0 or 1. Transmission rates are given in bits per second.

Binary numeral system Base-2 number system; that is, all numbers are represented as powers of 2. For example, the decimal number 51 in binary equals 110011; that is, 1 × + 1 × + 0 × + 0 × + 1 × + 1 × = 32 + 16 + 0 + 0 + 2 + 1 = 51.

Bit Abbreviation for binary digit. The smallest representation unit in a binary number: 0 or 1. Transmission rates are given in bits per second.

Block In an NC program, a group of words containing all instructions for one operation. A complete block consists of the following "words": *N* (number); *G* (prep function); *Z* (coordinates); *F* (feed); *S* (speed); *T* (tool number); and *M* (miscellaneous functions) and ends with the "end of black" or "line feed

character." One block generally comprises one line in the NC program printout.

Block cycle time Indication of how quickly an NC system prepares and presents sequential NC blocks for processing. This can be used to calculate the following: (1) the maximum feed rate for polygonal lines (linear interpolation) produced by very short displacement intervals or (2) the minimum permitted displacement intervals per block for a specified feed rate.

Block delete An NC function for selectively deleting blocks designated for deletion in an NC program. Such blocks are generally indicated by a slash in front of the block address (/N478).

Block number Ordinal number for numbering the blocks of an NC program, programmed under the primarily used to inform the operator about the status of the machining.

Block or sequence search NC function for reading an NC program over to a specific point, with all machine functions being disabled. In order to start the program at the required block number, it is also necessary for the tool, speed, feed, and compensation values to be activated.

Bridge Electronic device that joins two data networks of similar type. ➔ LAN.

Broadband transmission Denotes a data network that has a number of frequency bands for simultaneous selective data transmission between numbers of stations. The best example is cable television.

Business line (bus) A group of conducting wires used for a group of electronic devices that are connected in parallel in order to exchange binary signals. A bus is a bidirectional data link between parts of an electronic system. A distinction is made between address bus, data bus, and control bus.

Byte A group of eight binary numbers stored and processed as a unit. Historically, 1 byte is a group of 8 bits for encoding a single text or digit character. It is therefore the smallest addressable element in many computer architectures, which are also stored and processed as a unit. With 1 byte (8 bits), the addresses (letters), numbers (0–9) and all auxiliary characters are displayed in an NC program. Example: a letter, a digit, or a symbol on punched tape.

CA Abbreviation for "computer aided," with the following additions: **A** for "assembly"; **D** for "design"; **E** for "engineering"; **M** for "manufacturing"; **P** for "planning" or "production planning" or "programming"; **Q** for "quality assurance"; **T** for "testing."

CAD/CAM The integration of computer-aided design and drafting (CAD), computer-aided planning (CAP), and computer-aided manufacturing (CAM) techniques through standard communication interfaces to ensure access to a common CAD database by all

departments of a company involved in design, engineering, and manufacturing processes of a product.

CAN bus Abbreviation for controllerarea network developed by BOSCH for applications in the automotive industry. Together with Interbus and Profi-Bus, CAN bus is one of the three most important field buses, also called *sensor/actuator* Suitable for transmitting small quantities of data in a rapid sequence between the controller and the sensors/actuators via a short communications path.

CANopen, DeviceNet CANopen and DeviceNet are CAN-based layer 7 communication protocols that are used primarily in automation technology. CANopen is mostly used in Europe. It was initiated by small and medium-sized German companies and developed in the framework of an ESPRIT project led by BOSCH. It has been managed by CiA since 1995, and now it has been standardized in the form of European Standard EN 50325-4. DeviceNet, by contrast, is more common in America.

Cardrack Mechanical holder for a number of electronic modules for controllers. The modules are generally of plug-in design.

Cartesian coordinates Perpendicular coordinate system with axis designations and *Z* for determining the position of a point in a plane or in space.

Cathode-ray tube (CRT) Simply called *screen* or *computer screen* in normal usage. In today's CNC machines and NC programming

systems, mostly flat screens are used to display data and graphics.

Cell, manufacturing cell ➔ Flexible manufacturing cell.

Central processing unit (CPU) The part of a computer in which programs are interpreted and executed. The CPU contains the main memory, the arithmetic logic unit, the control unit, and the input-output interfaces.

Channel Communication channel, a path for the transmission of signals, data, control information, etc.

Channel structure Capability of a CNC system to subdivide all NC axes if necessary into synchronous, that is, mutually interpolating, main axes and asynchronous, that is, auxiliary or secondary, axes that function in a time-independent manner from the main axes.

Circular interpolation Calculation within an NC system of the points on a circle between the programmed start and end points. Circular interpolation is generally only possible in the planes and *XZ* and not diagonally in space.

CISC Abbreviation for "complex instruction set computer."

CLDATA Abbreviation for "cutter line DATA," that is, the preliminary results for the tool path calculated by the computer program in computer-aided programming systems. These data are

only converted to the block format of the specific NC machine by the postprocessor.

Closed-loop control, servo loop Definition according to DIN 19226: "In the closed loop, the variable to be controlled acts on the result of the comparison with the predetermined value in the sense of a feedback back to itself." In other words, an electronic comparator continuously compares the feedback signal with the command variable and generates a correction signal until the difference has been adjusted or minimized to the smallest possible extent. CNC machines have a number of closed-loop systems, such as for the spindle speed, feed rate, and axis positions.

CMM Abbreviation for "coordinate measuring machine."Manual or CNC-controlled automated coordinate-measuring machine, used for manufacturing quality control or tool data measuring. The measuring system comprises the probes and software for programming, evaluating, and processing the measured data.

CNC Abbreviation for "computerized numerical control," used in CNC systems containing one or more microprocessors. The identifying characteristics are monitor, keyboard, and the ability read in and read out programs automatically, as well as store and correct them. Because all current NC systems have at least one microprocessor, the terms *NC* and *CNC* now can be regarded as synonyms.

CNC core The central processing unit in a CNC machine. A core is part of a CPU that receives instructions and performs

calculations or actions based on those instructions. CNC machines can have a single core or multiple cores. A processor with two cores is called a *dual-core*

CNC machine tool Machine tool equipped with a soft-wired NC system that incorporates one or more microprocessors to perform the control functions.

Code Rules that have been agreed on for converting data from one representation to another, for example, the assignment of specific hole combinations in a punched tape to specific numerals, symbols, or letters or combinations of vertical lines in a barcode. In NC systems, data encoding is used to store data on data carriers and to read data in and out automatically. In communication science, code, in the broadest sense, is a language. There are various codes: ASCII (American Standard Code for Information Interchange) is used in computers to express letters, numbers, and signs in the form of bits. It has been expanded as Unicode to represent almost all sign systems in the world. Machine code or binary code is used in computer technology and contains instructions and data for the processor. Line code is used for data transmission. Geek code is used in E-mails and Usenet. Source code is used for algorithms in programming.

Code checking Control function of an NC or programming system to detect incorrect symbols during data transmission. This is done by means of a parity check of all bytes in the ISO code and checking the meaning versus the information permitted in the programming rules. Information with the wrong values cannot be detected by code checking. ➔ Error-detecting code.

Code converter This electronic device converts digital input signals in one code into another code, for example, binary code into BCD code.

Command position Programmed dimensional data for an NC axis (machine slide).

Comparator A functional unit that, for example, compares the nominal value for an axis with the actual position value and in the event of a deviation generates a correction signal for the closed-loop control to minimize this difference.

Compatibility Two systems (hardware or software) are compatible if they can work with each other without additional equipment or modifications or if they can be exchanged for each other.

Compiler A computer program that translates a program written in a higherlevel programming language into the machine language or operation code of a specific computer.

Computer Program-controlled electronic computing machine used to solve mathematically defined tasks. A distinction is made between analog and digital computers. CNC technology uses digital computers exclusively.

Computer-aidedmanufacturing(CAM) The use of a computer to assist in the preparation for and control of production engineering

and monitoring. CAM is a generic term grouping together all technical and managerial shop-floor activities.

Computer-aided planning (CAP) A computer system to assist in the generation of manufacturing-oriented data. This includes essentially the generation of process plans, part programs for NC machines, and programs for robots.

Computer-aided programming (CAP) (1) Computer-aided planning: a system that uses a computer to assist in the generation of manufacturing-oriented data. This includes essentially the generation of process plans, part programs for NC machines, and programs for robots. (2) The generation of NC programs using a computer-based NC programming system. These systems provide interactive programs with graphical support for the programmer. The output is a CLDATA file (cutter location data) that has to be translated by a postprocessor for use with any suitable NC machine.

Computer-aided quality control (CAQ) A system that uses a computer to assist in quality assurance operations.

Computer-Aided Three-Dimensional Interactive Applications Programming language for 3D surfaces and volumes developed by the French company Dassault and marketed by IBM.

Computerized numerical control (CNC) Used in CNC systems containing one or more microprocessors. The identifying characteristics are the display or monitor, keyboard, and ability

read in and read out programs automatically, as well as store and correct them. Because all current NC systems have at least one microprocessor, the terms *NC* and *CNC* now can be regarded as synonyms.

Concurrent engineering (CE) Simultaneous development of a number of assemblies for a product in different locations, preferably using a uniform CAD system.

Continuous path control, contouring control NC system in which the relative motion of the tool and workpiece is controlled continuously along a programmed path. This is achieved through the coordinated simultaneous motion of two or more machine axes. In addition, continuous path control includes so-called interpolators, which for CNC systems come in the form of software. When the start and end points of a defined-path element (straight line, circle, parabola, etc.) are entered, the interpolator calculates the exact path and velocity of each axis between these two points.

Contour segment programming Programming function for inputting a number of contiguous geometric contour segments that are not dimensioned individually but which, when taken together, produce a clear pattern. The system automatically calculates the individual points of intersection, transition radii, and tangential transitions and generates the appropriate NC program.

Controller, machine control unit Electrical or electronic device for controlling the programmed functions of a machine. In NC

technology, all the control functions are divided between the NC system and the PLC.

Converter Electronic device that changes signals, codes, or numerical data from one form to another. In connection with NC, code converters, digital-to-analog converters, serial to-parallel converters.

Coordinate measuring machine (CMM) Manual or CNC-controlled automated coordinate-measuring machine, used for manufacturing quality control or tool data measuring. The measuring system comprises the probes and the software for programming, evaluating, and processing the measured data.

Coordinates Numerical values used to define a point in space. NC technology is generally based on Cartesian coordinate systems and polar coordinates.

Coordinate system Mathematical system in which the position of a point in a plane or in space can be determined using numbers. Possible types are Cartesian, cylindrical, joint, polar, and spherical coordinates.

Coordinate transformation Mathematical term for the conversion of space coordinates into the axis coordinates of an NC machine with swivel or rotary axes or into the axis coordinates of a robot with a nonlinear kinematic system. This makes programming of such systems easier because programming can be performed in space coordinates.

Corner deceleration In order to prevent overloading of a milling tool when milling inside corners, a special reduces the feed automatically to previously programmed values and sets it back to 100% behind the corner.

Corner rounding Automatic insertion of transition radii at erratic transitions in order to achieve rounded transitions.

CPU Abbreviation for "central processing unit," the part of a computer in which programs are interpreted and executed. The CPU contains the main memory, the arithmetic logic unit, the control unit, and the input-output interfaces.

CRT ➔ Cathode-ray tube.

CSMA/CD (Carrier-Sense Multiple Accesswith Collision Detection) Access procedure for transmission media (buses). A station that wants to transmit senses the transmission medium to check whether the network is free of other traffic.

Cutter compensation ➔ Cutter radius compensation, tool nose radius compensation.

Cutter radius compensation A control function to compensate for the difference between programmed and actual cutter diameters. For each cutter diameter, the NC system calculates the correct equidistant center point path from the workpiece contour, as well as the points of intersection and transition radii at corners. The NC system uses the functions G41 = cutter left and G42 = cutter right of the contour to calculate the compensation value. For lathes, this function is known as *tool tip radius*

Cycle A fixed sequence of a number of individual steps that are stored in an NC system and can be called up using a programmed or Cycles are supplemented with specific parameter values, such as drawback level, drilling depth, and number of cutting passes. They ease programming and reduce the length of

programs considerably. NC programs with cycles are much easier to modify than those without. Examples: cycles for tapping, deep drilling, rough machining, tool changing, pallet changing, and measurement operations.

Cycle time Minimum time required by an NC system to prepare sequential program blocks and make them available for execution. If the time needed to execute a block is shorter than the cycle time, then the machine stops briefly until the next block is released for execution. To prevent this, the feed rate has to be reduced.

D/A converter Digital-to-analog converter, an electronic unit that converts a digital input signal into an analog output signal.

Data Numerical values intended primarily for automated processing. ➔ Information.

Database Data stored in a computer that have been gathered from various sources, can be sorted according to various criteria, and can be accessed by multiple users.

Data carrier, data-storage medium Portable data memory that can be used to save and transport data so that they can be read out and used again later. Today almost exclusively electronic memory cards, such as CD-ROMs, DVDs, USB sticks, and memory cards.

Data interface Connection point between a CNC system and external systems for automatic transfer of data and control

information. Examples: DNC interface, drive interface, computer interface. ➔ Interface.

Data memory Sorting of data in an electronic medium from which it can be used later.

Data processing Performing calculations or other logical operations according to certain rules in order to obtain new information, in order to put it into a specific form, or in order to use it to control devices, for example, NC machines.

Datum point, zero point (1) The origin of a coordinate system or (2) the starting point (zero point) of a measurement system.

Decade Group of 10 units or the interval between two numerals with a ratio of 1:10.

Decimal-point programming Programming and input of displacements using the decimal point instead of leading or trailing zeroes. Examples: 417 instead of 417000 with trailing zeroes; .75 instead of 750 with trailing zeroes; .001 instead of 000001 with leading zeroes.

Decimal system Base-10 decadic number system. This uses the numerals 0 to 9, where the positional values of adjacent numerals are integer powers of 10.

Dedicated computer A computer that is used exclusively for a specific task, such as a DNC computer for the data transmission

for a limited group of CNC machines or for the material transportation logistics or a CAD computer as a workstation for the mechanical design of machine parts.

Degree of automation Ratio of automated work processes to the total number of work processes. As the degree of automation increases, the costs also increase progressively, thus also increasing the production costs. At the same time, there is greater output, increasing productivity and decreasing production costs.

Deviation For NC machines, the departure of the actual path from the programmed command path. Also called *dynamic path* This has an effect on the contour accuracy of the workpiece. To keep the deviation as small as possible, the appropriate countermeasures that the controller provides should be applied.

Diagnosis Special functions of computers or CNC systems that make it possible to find and locate error sources using the screen. For CNC systems, for example, this includes the software functions logic analyzer, PLC monitor, multichannel storage oscilloscopes, logbooks, graphical display of measured values, etc.

Dialog mode Data-input method where the user is “guided” by means of screen masks. This makes it easier to input data and helps to prevent input errors.

Digital measuring system Path- or position-measuring system that uses discrete individual steps to measure either the path that has been traveled (incremental) or the specific position (absolute).

Digital, numeric Information representation working with discrete numerical values or signals.

Digital readout, numerical display Values displayed directly as decimal numbers. In NC systems, for example, the axis positions are shown in millimeters or inches, the feed rate in millimeters per minute, and the speed in revolutions per minute.

Digital-to-analog converter Usually an electronic unit that converts digital input signals into analog output signals.

Digitizing Capturing a physical model or a mathematically undefined curve from a drawing in the form of individual sequential coordinates. The digitizer systems for 3D surfaces use a spindle-mounted probe or a laser system.

Dimensional data In an NC program, these are all the nominal value specifications for the NC axes under the addresses and

Direct measurement A linear positionmeasuring system in an NC machine is called *direct* if the system is immediately coupled to the machine slide without conversion into a rotational motion for position measurement via a rotary encoder. This means that the measuring accuracy is not compromised by any inaccuracy in the spindle, measuring rack, or rotary transducer.

DNC Abbreviation for “direct numerical control” or “distributed numerical control,” a system in which one or more computers are

used to save and manage all NC programs and to transmit them to the connected NC machines via cable or network connections (LAN) when they are called up. To do this, the CNC requires a DNC or LAN interface (e.g., Ethernet) for bidirectional data exchange.

DRAM Abbreviation for "dynamic random-access memory." Dynamic read/write memory in which stored information has to be refreshed periodically in order for it not to be lost.

Drilling cycles (G80–G89) Work processes for drilling, reaming, countersinking, tapping, etc. that recur frequently and are stored as subprograms. They are called up with G81–G89 and supplemented with parameter values (reference plane, drilling depth). Subsequently, the appropriate machining is performed at each *Y* position. ➔ Cycle.

Dual system ➔ Binary, BCD.

Duplex mode Simultaneous data transmission in two directions.

Dwell, dwell time Waiting time after a block end, for example, to cut the tool free. Can be programmed in seconds or spindle revolutions.

EIA code Eight-track punched-tape code for NC machines, standardized by the U.S. Electronic Industries Alliance. EIA-358B corresponds to the ISO code, where the number of holes is even for each character.

EIA-232C, RS-232C Standardized interface for serial data transmission in NC systems, used primarily as a DNC interface. Because its transmission speed is generally inadequate, it is replaced with faster interfaces EIA-422, -423, and -449 or LAN interfaces such as Ethernet.

Electronic handwheel Electronic substitute for the absent mechanical handwheels on NC machines. Can be built into the NC control panel or be a hand-held control device. It consists of a handwheel connected to an electronic pulse generator and can be used by the operator to adjust each axis manually in the operating mode "SET-UP." The adjustment motion can be changed from 1 to 1,000 increments per step.

Encoder ➔ Feedback device.

Encoding In general, changing information while observing certain defined rules. In NC systems, converting the control data into automatically readable coded symbols and saving them on data carriers or any other memory devices.

End-of-block character A defined character at the end of a block ($, LF, or *) that separates the individual machining information from each other.

End of program (EOP) Programmable miscellaneous function (M00, M02, M30) for stopping an NC machine once machining is completed. It generates the commands for "Spindle off," "Coolant

off," "Tool back into magazine," and "Move all axes to starting position."

Energy efficiency In terms of machine tools and peripheral devices, reduction of energy use for drives, hydraulic and pneumatic tools, chip disposal during processing, and transport and storage of parts. Current CNC systems include special programs for recording, analyzing, and reducing energy consumption for each individual machine.

Engraving cycles Programming directly at the machine of any text or numbers that need to be cut on the workpiece surface, such as the date, time, quantity, or serial number. The cutting is done using laser beams or special milling cutters.

EPROM, EEPROM, FEPROM Electronic memory chip whose contents can be erased and programmed by means of ultraviolet (UV) light or electrical pulses (FEPROM).

ERP The enterprise resource planning (ERP) system controls and supports all business processes of a company (materials management, production, accounting, etc.). This includes the provision of raw materials, consumables, and tools.

Error-detecting code (1) Simple method for data validation by checking each character for an even number of bits per character (ISO code). ➔ Parity check. (2) Higher-level data check by comparing the total digits of each block with the value programmed under an additional e-address on the end of each

block in the NC program (only possible with computer-assisted NC programming).

Ethernet Ethernet is a family of network technologies used primarily in localarea networks (LANs) but also for connecting large networks (WANs). There are a number of standards for Ethernet, for which the Institute of Electrical and Electronics Engineers (IEEE) is responsible. Since the establishment of a working group for the standard of a local network, the name *Ethernet* has become synonymous with all the specifications proposed and standardized under Working Group 802.3.

Executive program System software for a CNC system containing the range of functions of the CNC machine and the special functions for a specific type of machine. ➔ Open-ended control.

Expert system A knowledge-based computer program that uses previous experience and available knowledge for problem solving within a limited technical field and also applies the necessary rules, methodology, and procedures.

External memory Data memory (memory expansion) outside the CPU of a computer, generally designed as a mass storage device (hard disk, memory card, flash memory).

Feature A term often used in technical descriptions that has the meaning of a characteristic or property.

Feed, feed rate The distance a tool travels per minute or per revolution = mm/min, mm/revolution). In NC programs, programmed under the address *F* and defined using a specific (G94 = mm/min or G95 = mm/revolution).

Feedback Transmission of a signal from a later stage to an earlier stage within a closed-loop system, for example, the actual speed or actual position. Using the feedback signal, a controller performs adjustments automatically when there is a deviation from the command value.

Feedback device A device, such as a sensor, that measures physical variables and converts the measured values into output signals that can be evaluated electrically. Various feedback devices are used in NC technology, for example, to measure axis positions, velocities, speeds, torques, currents, and temperatures.

Feed-rate override Manual means of engagement to temporarily change the programmed feed rate of an NC machine to adapt it to the machining circumstances.

Field bus Globally standardized (IEC 61158) industrial communication systems that link a large number of field devices, such as measuring probes, actuators, and drives with a control device. Field-bus systems were developed to replace analog signal transmission and the costly parallel wiring of binary signals. Instead, digital transmission technology is used. A number of field-bus systems with various characteristics are available: BitBus, Profi-Bus, InterBus, ControlNet, CAN, and increasingly industrial Ethernet.

File Defined memory area in a computer or CNC system where certain data are stored for subsequent reuse, such as tool data, materials data, cutting data, or undercut data.

Firmware Software permanently saved by the manufacturer of an electronic device on a programmable chip, generally flash memory, EPROM, or EEPROM. The manufacturer's intention in doing this is to prevent tampering by third parties.

Fixed-zero dimension Also called *absolute* Dimensions relative to the coordinate zero point. Opposite: ➔ Incremental dimension, relative dimension.

Fixture, clamping fixture, chuck Mechanical clamping equipment that is used to hold workpieces of the same type in a precisely defined position on a machine table in order to machine them with high repeatable accuracy.

Flexible manufacturing cell (FMC) Highly automated autonomous production unit consisting of an NC machine with tooland workpiece-changing equipment, additional monitoring equipment, and a DNC connection.

Flexible manufacturing island A clearly delineated shop area with a number of machines and devices necessary to be able to perform all the required operations on a limited selection of workpieces. The people who work there carry out planning, decision making, and monitoring of the operations themselves.

Flexible manufacturing system (FMS) Grouping of a number of machining centers and/or flexible manufacturing centers to enable fully automated complete machining of groups of related parts in any desired lot size and desired sequence and without any manual intervention because the elements are linked by means of a common automated workpiece transport and workpiece changing system. Generally, the entire system is linked to a host computer.

Following error ➔ Axis lag.

Frame Commonly used term for a calculation rule, such as coordinate translation or rotation.

Free-form surface Complex surface, generally with multiple curves, that cannot be defined mathematically using simple basic geometric forms such as straight lines, circles, and conic sections. Examples: asphere, hyperbola.

Frequency controller Processorcontrolled speed and position controller with amplifier for speed control of synchronous motors for servo and main spindle drives. It requires an which reports back the angular position of the permanently excited rotor to the control unit and thus controls the continuation of the rotating field. The simplified speed control of asynchronous motors often only requires a speed sensor instead of a position encoder. Energy generated by breaking can be fed back into the network.

Fused depositing modeling (FDM) A rapid prototyping process for layer-by-layer creation of precision plastic parts.

Fuzzy logic Logic using "degrees of truth," for example, to optimize or correct programmed machining processes within certain limits by a relatively simple control system. Application examples: wire-cut electrical-discharge machining and die-sinking electrical-discharge machining.

Also called *preparatory* Consist of the word address *G* and a two-digit coded number. These commands for NC machines specify, for example, how the programmed end point should be approached: in a straight line, via a clockwise or counterclockwise circular path, or in combination with a particular cycle (G80–G89).

Gantry-type machine Machine tool with a movable gantry. Used mainly in the aerospace industry to machine multiple surfaces and long parts simultaneously using multiple spindles. Advantage: requires less floor space than table milling machines.

Gateway Electronic device, generally a computer, used to connect dissimilar networks with different protocols by providing protocol translation.

Geometric data Complete information concerning the geometry and dimensions of a workpiece as they appear on the workpiece drawing.

Graphic assistance Using the screen of a CNC machine or a programming system for multiple graphical depictions, such as input graphics for programming that show the workpiece contour, simulation graphics for testing the program sequence with dynamic depiction of the tool paths, auxiliary graphics to inform the operator quickly about problems that arise, diagnostic graphics for troubleshooting, etc.

Graphical programming Hardware and software that help the programmer to produce, modify, or simulate the part program, for example, graphic terminals, editors, simulators, etc.

Group technology Group of geometrically and technologically similar workpieces that can be processed using the same machines and tools without any significant changeovers.

Handling unit Another term for a robot used for loading/unloading of a machine, for tool changing, or for assembling components.

Handshake In data transmission, a process that serves to coordinate the transmission and prevent transmission errors. The individual data blocks are transmitted only if the recipient has acknowledged error-free reception of the previous block.

Hard disk Encapsulated magnetic system for data storage with a significant storage capacity.

Hardware All devices and components comprising a computer or controller system. Opposite: ➔ software.

Hard-wired NC An NC system in which all functions and commands are processed in fixed-wire circuits and components. Control functions can be altered only by changing the wiring and possibly exchanging or adding modules. Opposite: Soft-wired NC = CNC.

Helical interpolation, helix interpolation In addition to circular interpolation in a single plane linear interpolation is performed in a third axis perpendicular to the It is used to create internal and external threads with form cutters and to mill lubrication grooves (thread milling).

Hertz, kilohertz, megahertz, gigahertz (abbreviated Hz, KHz, MHz, GHz) SI unit for frequency, that is, number of cycles per second. 1 KHz = Hz; 1 MHz = 1 GHz = Hz.

Hexadecimal Base-16 number system, that is, with 16 numerals. Mainly used by computers; 0 to 9 are used for the first 10 digits, and the first six uppercase letters of the Latin alphabet (A to F) are used for the remaining six digits.

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Hexapod Also called a *Stewart* Kinematic structure of a machine or a robot with the characteristic that linear and rotational motions of a platform can be executed using six struts (axes) with adjustable lengths (i.e., jacks). This provides six degrees of freedom. Each position corresponds to a defined combination of the six axes. Via simultaneous control of all six struts, it is possible to generate any desired spatial motion sequence in the platform and the spindles and tools mounted on it. The work space is not cubic but rather hemispherical. ➔ Parallel-kinematic machines.

High tech Abbreviation for "high technology." The state of the art achieved based on the latest results of research and development; cutting-edge technology. It will be outmoded by further developments in the near future, at which point it will become the normal/ordinary state of the art. Examples: microprocessors, bus systems, CDs, data memory.

HMI Abbreviation for "human-machine interface" (HMI) or "man-machine interface" (MMI). Interface that expresses that a human is interacting with a machine via a display.

Host computer A central computer in a computer network that provides services to terminals or satellite computers. In a flexible manufacturing system, the host performs process-control functions for data distribution, transportation control, tool management, materials management, and error monitoring and collects feedback messages to generate management reports.

HSC machine Abbreviation for "highspeed cutting machine," that is, milling machines with extremely high speeds (up to 100,000 rpm) and feed rates (up to 60 m/min). This places particularly demanding requirements on the machine and NC system, such as high stiffness, low mass, short block cycle time, zero lag, lookahead, etc.

Hub Telecommunication devices used to connect a number of computers in a star configuration; also used to describe multiport repeaters. These are used to connect network nodes or additional hubs to each other, for example, via Ethernet.

IGES Abbreviation for "Initial Graphics Exchange Specification," a non-manufacturer-specific standardized data format for transferring geometric data between different CAD systems. It is also used to transfer data from CAD systems to CAM systems. ➔ STEP, VDA-FS.

Increment Growth of a variable in individual steps of the same size.

Incremental dimensioning All dimensions are relative to the previous position.

Incremental jog A manual control function that allows the operator to move an NC axis in defined increments, for example 1 µm, 10 µm, 0.1 mm, 1 mm, etc.

Incremental measuring system A measuring system in which each displacement is measured by adding up displacement increments (e.g., 0.001 mm) in an electronic counter or in the CNC system. The counter value thus is a measure of the actual position.

Incremental programming NC programming in which the coordinate values are specified as an increment relative to the previous position (G91).

Indirect measurement Position-sensing method in which a rotational measuring system (e.g., rotary encoder, pulse generator) is driven by the lead screw or measuring rack and pinion. The inaccuracies of the transmission elements have a negative effect on the measuring accuracy. Modern CNC machines can compensate for systematic measuring errors. Opposite: ➔ Direct measurement.

Industrial robot (IR) A mechanical device that is freely programmable in several axes (degrees of freedom) and is equipped with grippers or tools and can perform handling and/or manufacturing tasks (e.g., workpiece or tool changing, welding, laser machining, painting, and assembly). They can be categorized according to (a) their kinematics, that is, Cartesian, cylindrical, spherical, or joint-coordinate robots; (b) their programming, with the teach-in/playback method or with external data input; (c) their control, with pick-and-place or NC continuous path control; (d) their type of drive, that is, hydraulic, pneumatic, or electric; (e) their use as universal, special-purpose, or movable robots (gantry or Cartesian gantry robots); and (f) their load capacity and carrying capacity.

Information Data in a clearly organized, easy-to understand summary, primarily intended as information for humans. ➔ Data.

Interface (1) Electrical interface: in an NC system, a special hardware and/or software link between the NC and the machine controller for data transfer and control signals. Examples: IGES, VDAFS, SERCOS, V.24, RS 232, etc. (2) Human-machine interface or man-machine interface: also called *HMI* or consisting of a control panel with displays and input elements.

International Standards Organization (ISO) code Standardized 8-bit code with 7 information bits and 1 parity bit in track 8. It is the standard code used for NC systems.

Internet Global computer network by which users can communicate with each other and exchange data. Various

protocols are available for this (TCP/IP). For CNC machines, the internet is also used for remote diagnosis and correction of errors and intervention to correct CNC executive programs.

Interpolation Calculation of intermediate points between specified start and end points to produce a smooth curve. If the connecting segments are straight lines, then it is called *linear* if they are arcs or parabolas, then it is called *circular* or *parabolic* Modern systems also offer the option of spline interpolation.

Interrupt The temporary or lasting interruption of a running program at a point that is not intended as an end of program.

Intranet Private networks that exist within a company or other entity and use internet protocols. Their main purpose is to make internal data and information available to employees while preventing access to these data by outsiders. If access to the external internet is required, this can be implemented via gateway computers.

Just-in-time production A manufacturing strategy aimed at reducing stocks and work-in-process by scheduling the delivery of the right amount of parts at the required time.

kB Abbreviation for "kilobyte." Used to define the memory capacity of a computer or CNC system. It is written with a lowercase k and specified using the binary numeral system: 1 kB = 1 × bytes = 1,024 bytes; 8 kB = 8 × bytes = 8,192 bytes.

Kernel Elementary component of an operating system, with the following functions: interface to application programs (i.e., starting, stopping, input-output, memory access); controlling access to the processor, devices, and memory; allotting resources, such as allotting processor time to the application programs; monitoring access rights to files and devices in multiuser systems; etc.

Kinematics Generally, a branch of classical mechanics. In machines and robots, the kinematic configuration describes the structure with regard to motions, that is, the motions they can perform in Cartesian, cylindrical, spherical, or joint coordinates.

LAN Abbreviation for "local-area network," that is, a data network that is limited with regard to its scope and range and that is not subject to any regulation by communications authorities. It is used to connect a number of computers and peripheral devices within a limited area and enables direct communication between the devices. Data transmission mostly takes place via broadband technology, that is, using frequencymodulated carrier frequencies via copper cables, fiber-optics, radio waves, or lasers.

Laser cusing This rapid prototyping laser process can be used to build up highdensity components layer-by-layer by melting single-component metallic powders.

Lead-error compensation CNC function for programmable correction of measured lead errors in a ball screw or a measuring rack and pinion.

LED Abbreviation for "light-emitting diode," that is, illuminating diode or luminescent diode. Semiconductor that emits colored light that is used, for example, to replace incandescent lamps while using less energy.

Linear interpolation Calculation within the CNC system of all points on a straight line between the programmed start and end points. A distinction is made here between simple 2D interpolation, interpolation with plane switching (2½D), and interpolation in space (3D).

Linear motors Electric drives for linear motion of machine axes without additional mechanical gearing. With linear directdrive technology, it is possible to avoid elasticity, backlash, and friction effects, as well as oscillations in the drive mechanic. Linear motors enable maximum dynamics and high precision.

Logistics A PLC or decentralized host computer that coordinates the workpiece flow and tool transportation of a flexible production line. This computer, for instance, controls the pallet transportation system or gantry robot loading and unloading station at the CNC machines. In automated manufacturing systems the procurement, coordination, maintenance, and transportation of materials, parts, tools, and fixtures in a production plant. ➔ Dedicated computer.

LOM Abbreviation for "laminatedobject manufacturing," an additive CAD/CAM-based rapid manufacturing process. The workpiece geometry is generated by gluing together successive layers of paper and then cutting them to shape by an NC-controlled laser. The result is a wood-like 3D model. ➔ RPD.

Look ahead function Automated function of CNC systems to look ahead to a tool path a number of blocks in advance in order to reduce the feed rate at critical contour transitions, such as corners and radii, in accordance with the machine kinematics. This makes it possible to maintain contour accuracy on the workpiece. It is also possible to detect and avoid impending contour violations, for example, if the tool diameter is greater than the workpiece contour during tool entry.

Also called *on/off command* or *switching* Abbreviation for miscellaneous or auxiliary functions. Programmable commands that control the switching functions of a machine tool, for example, switching the coolant (M08/M09) or spindle (M03/M05) on and off or activating the tool-changing process (M06).

Abbreviation for “miscellaneous functions” or “auxiliary functions.” Switching functions of the machine, programmed in the NC program behind the

Machine-control interface Electrical or electronic control for adapting a CNC system to a machine tool. It has the following functions: decoding, saving, and amplifying the coded signal output by the CNC system and forwarding that output to the actuators, linking the signals with limit-switch feedback signals from the machine, and locking out commands to prevent impermissible on/off commands. Most often a function of the PLC. ➔ PLC.

Machine data acquisition (MDA) Automatic acquisition and storage of essential machine data during the machining phase, supplemented with additional manually entered information. Allows greater transparency of the production equipment and facilitates quick analysis of technical and organizational weak points. Examples of the data acquired include the machine operating time, downtime, and outage time and the reasons for them; error messages and their causes; manual interventions in the automatic process; correction-value inputs; etc. MDA is a subcomponent of a comprehensive manufacturing data-collection (MDC) system. ➔ Manufacturing data-collection (MDC) system.

Machine tool Machines that use different tools to perform cutting or noncutting machining of workpieces made of metal, wood, plastic, or other materials. Examples: turning, milling, drilling, electrical-discharge, and grinding machines and nibbling, shearing, punching, pressing, and rolling machines. Newer types of machine tools include water-jet cutting machines and laser-beam machines for welding, cutting, stock removal, or forming. Machine tools are operated either manually or automatically, with the latter being significantly faster and more precise. In the case of *NC machine* a freely programmable sequence of machining operations can be executed, thus allowing different workpieces to be machined automatically in any desired order. A distinction is made between *single-purpose* or *production machines tools* for one or more operations and *universal machine tools* for a variety of different operations and subsequent processing steps. In series production, a number of machining units or machine tools are often grouped together and linked to each other in such a way that different machining operations take place one after the other (automatic rotary indexing or transfer units, assembly lines, and flexible

manufacturing systems). Robots, painting machines, measuring machines, welding equipment, and many other types of production equipment are *not* considered to be machine tools.

Machine zero point Defined zero position of an NC axis, generally the coordinate zero point that can be reproduced precisely by the position-measuring system.

Machining center There is no standardized definition of a machining center. These are CNC machines with a high degree of automation for fully automated complete machining of components. Machining centers, also called *manufacturing* are CNC machine tools equipped for automated operation. Automation functions can be expanded by providing additional peripheral devices, such as a tool magazine with workpiece changer or pallet changer. In modern machining centers, the tool-changing times and chip-to-chip times are sometimes under 3 seconds, resulting in significantly shorter cycle times. Machining centers are categorized according to the orientation of their main spindle (horizontal and vertical machining centers). Another distinction involves the number of NC axes, mainly three to five. Machining centers can have one or two additional NC axes for rotating and swiveling tables; some machines even allow the execution of sophisticated turning operations on rotating tables (turning/milling centers, hybrid machines). The costeffectiveness of this type of machine has led to similar upgrading and redesign of other kinds of machines, such as turning centers, grinding centers, sheet-metal working centers, and combined laser/water-jet machines. The goal is a fully automated NC machining of different parts without manual intervention.

Machining cycles Processing routines for standard geometries, circular pocket milling, thread undercuts, engraving cycles, deep-hole drilling, and so on in a plane or also on the end face or lateral surface of turned workpieces or on swiveled workpieces.

Machining time Also called *cutting time* or *production* For machine tools, the sum of all machining times during which the feed is active.

Macro A group of prestored instructions (control data) that can be called up as a unit and that reduce the programming effort required for repetitive tasks. ➔ Subprogram.

Mainframe computer A computer with high computational power, a large byte width, and very fast simultaneous processing. Generally, the central computer of an enterprise, with a number of terminals or separate computers connected to it from various departments.

Manual data input control A CNC machine with an integrated programming system that enables programming of complete machining processes directly at the machine. ➔ Dialog mode.

Manual programming The preparation of NC programs for a specific machinecontroller combination without the use of a computer-based programming system.

Manufacturing Automation Protocol (MAP) Bus-based broadband network using the token-passing principle with seven defined hierarchical levels. Standardized protocol developed by General Motors for interconnection of individual independent manufacturing islands and computers in order to enable a seamless flow of information. The objective was for all data and information relating to proposal preparation, order management, work scheduling, materials management, production control, quality assurance, and accounting to be exchangeable via standardized non-manufacturer-specific interfaces and communication protocols.

Manufacturing execution system (MES) Also referred to as a *production control* It serves as a guide and control of production in real time. Such systems include the functions BDE, MDE, and PPS. An MES must offer for each product the following features: a production-planning system, a production schedule (before the start of the process), management of the means of production, current allocation of all resources, local production control centers in both production and predictive planning of maintenance work, management of production resources, recording and evaluation of production data, and a connection to materials management, design, order processing, and so on.

MB Abbreviation for "megabyte" (1 million bytes), but actually 1,048,576 bytes = ➔ Byte.

Mb Abbreviation for "megabit" (1 million bits), but actually 1,048,576 bits = ➔ Bit.

MDA ➔ Machine data acquisition.

MDC Abbreviation for "manufacturing data collection," such as production quantities, rejects, interventions, times, employees, etc. MDC allows greater transparency in the operating sequence and quicker analysis of weak points. ➔ PDA/MDA.

Measuring gear High-precision gear that is used between an indirect positionmeasuring encoder and the mechanical measure material (rack and pinion or ball screw and nut).

Measuring system ➔ Feedback device, path-measuring system.

Mechatronics An interdisciplinary field of engineering based on mechanical engineering, electrical engineering, and computer science. The emphasis is on supplementing and expanding mechanical systems with sensors and microprocessors in order to implement semi-intelligent products and systems.

Memory Electronic functional unit that can receive, save, and then output data. In NC technology, various memory elements are used, including RAM, ROM, EPROM, and FEPROM. Menu selection of options offered to the user on the screen to perform a necessary task.

Memory card Portable, pluggable electronic data memory in the format of a check card about 3 to 4 mm thick that can be equipped with RAM, EPROM, or EEPROM. Different designs are still current, such as SD, mini-SD, and micro-SD (e.g., in mobile phones).

Menu List of options in a computer program from which a user can make an appropriate choice.

Method of measuring A measuring method is the practical application and evaluation of a measuring principle. Measuring requires a measuring standard and a reading or evaluation device. One differentiates between direct and indirect measuring methods. Direct measuring provides an immediate comparison with a reference value of the same measured variable, such as a length comparison with scale or mass comparison with weights. The indirect measurement method determines the unknown value based on a feedback of others physical quantities, such as length of a traveled distance via the number of revolutions of a ball screw.

Method, process A planned, deliberate goal-oriented process to achieve a specific goal.

Metrology Generally, the theory, science, and application of measurement.

Microcomputer Functional unit consisting of a microprocessor, program memory, main memory, and an input-output unit. Minimum configuration for functional computer hardware.

Microprocessor A large-scale integration (LSI) module containing the central element (CPU) of a computer. It essentially comprises the arithmetic unit, various working registers, and the sequential

control. A microprocessor is still not functional in this configuration, however. ➔ Microcomputer.

Micro system technology (MST) Also called *microelectromechanical systems* Production of extremely small precision components weighing approximately 1 mg with a correspondingly small volume.

Minicomputer A medium-performance computer occupying an intermediate position between a mainframe and a microcomputer.

MIPS Abbreviation for "million instructions per second," a unit of measurement for the processing speed of a computer.

Mirror-image operation By changing the direction of an NC axis (swapping of + and –), it is possible to manufacture two mirror-imaged workpieces using the same NC program. Examples: milling leftand right-hand doors and drilling housings and lids.

Modal function Commands of an NC program that remain in effect until they are deleted or overwritten by another command. Examples: G90/G91, G80–G89, or and *T* words. In contrast, nonmodal functions only take effect in the block where they are programmed, such as G04 or M06.

Modem Electronic device for modulation and demodulation of data in data-transmission systems. It converts data from one form to another, for example, characters from 8-track code into bit-serial pulses for transmission via telephone lines.

Modular design Assembling principle for complex, extensive electronic controllers from a number of simple modules.

Modularity, module Modularity can vary somewhat based on context. In industrial design, modularity refers to an engineering technique that builds larger systems by combining smaller subsystems, components, and modules.

Monitor Screen for textual or graphical display of data, operations, processes, dynamic simulations, and results from electronic devices and computers.

Motor spindles A main spindle with an integrated, coaxially arranged motor. The advantages are high control dynamics; a stiff, compact design; extremely high power density; and lower overall mass and frictional force. The direct acquisition of the measured data for the spindle position and speed allows high production accuracy when operated as a

Multitasking machine Originally a term from computer technology. It describes the general ability of a system to execute several tasks almost simultaneously. Multitasking CNC machines, through combinations of various processing technologies such as drilling, milling, turning, and grinding, make the complete processing of highly complex workpieces possible.

NC Abbreviation for “numerical control.” ➔ Numerical control.

NC axis NC machine axis whose positions and motions are programmed by entering the dimensional values directly and are controlled using an NC system. To do this, each NC axis requires a path-measuring system and a drive with closed-loop control.

NC or CNC machine Machine tool equipped with a numerical control system. ➔ Numerical control.

NC program Set of instructions for machining a workpiece on an NC machine. It contains all the necessary data and control commands in the correct sequence and is processed by the NC machine step by step.

NC programming Also called *part* Creating control programs for the machining of workpieces on NC machines. A distinction is made here between manual NC programming, computer-aided NC programming (CAD/CAM), and shopfloor programming (SFP).

Network protocol Also called *transmission* A precise convention for data exchange between computers and processes that are linked via a network. It consists of a set of rules and formats (syntax) that defines the data traffic (semantics) between the communicating computers.

Nonproductive time In machine tools, it expresses the sum of all times that the machine is not in production, for example, when it is in rapid traverse, times for tool changing, workpiece changing, measurement operations, etc.

Numerical control (NC) A control system that "understands numbers"; that is, all commands are input in numerical form. In the case of machine tools, this means in particular the numerical values that control the relative motion between the tool and the workpiece (dimensional or geometric data). In addition, there are the numerical values for speed, feed rate, tool number, and various miscellaneous functions (switching information). The control information can be entered via a keyboard, data-storage device, or a direct cable connection (DNC). Modern CNCs are based without exception on microprocessor technology. ➔ CNC.

NURBS Abbreviation for "nonuniform rational B splines," a method for mathematical modeling of ruled and free-form surfaces such as cylinders, spheres, or tori by means of points and parameters. NURBS allow more efficient processing of such curves and surfaces than is possible with point models. As opposed to other splines, these have the advantage of being able to represent cleanly all kinds of geometries, even sharp corners and edges. Newer CAD/CAM systems can process the NURBS output by the CAD system directly in the CNC system. Advantages: reduced amount of data, higher accuracy and speed, even motion of the machine, and longer service life of the machine and tool.

Off-line Not connected to the computer, that is, an operating mode of a computer system in which the peripheral devices operate separately and independently of the central computer. This is done by saving the data generated by the computer temporarily and only processing them later. Opposite: ➔ Online.

Offset compensation Electronic compensation for clamping tolerances in the workpiece or tools in order to eliminate the need for mechanical alignment or adjustment. ➔ Zero offset.

Offset path Path with constant distance from the programmed workpiece contour. Example: cutter-radius compensation that is calculated automatically by the NC system.

On/Off control Simple control circuit in which the feedback signal (actual value) is used only for switching a process on and off when a specified set point is reached. Also called a *two-position* Examples: refrigerator temperature, filling-level control, and hot-water tanks.

Online Connected to the computer. An operating mode of a computer system in which the peripheral devices are controlled directly by the central computer. This is done by connecting them to the computer via a data cable and executing the data generated by the computer immediately.

Open-ended control A CNC system containing an industrial PC and using a PC operating system such as DOS, Window, OS/2, or UNIX. *Open* signifies that the user has the ability to intervene in the operating system. Thus the user is in a position to introduce customer-specific modifications and machine-specific functions. Yet it is not possible to execute older NC part programs.

Open-loop control A control system in which proper execution of a control command is not monitored and regulated by means of

a feedback signal. ➔ On/Off control. Opposite: ➔ Closed-loop control.

Operating system (OS) Software for automatic control and monitoring of program processes in a computer, for example, UNIX, Windows, or Linux.

OS ➔ Operating system.

OSACA Abbreviation for "Open System Architecture for Controls within Automation Systems" project sponsored by the European Union (EU) for the development of an open architecture for machine tool controllers. It is carried out by three research institutes, three machine tool manufacturers, and five controller developers.

Override A manual function for NC machines that enables the operator to modify the programmed feed rate or spindle speed temporarily to adapt it to the machining circumstances.

Overall equipment effectiveness (OEE) Figure for calculating the overall effectiveness of an installation. Is used to determine, monitor, and improve productivity and net effectiveness of production means, such as machines, production cells, and assembly lines.

Pallet A transportable workpiece clamping table that makes it possible to clamp/unclamp workpieces outside the machine and that can be exchanged into the machine automatically for

machining. This reduces machine downtime and enables automated transport of the clamped workpieces by an automatic transport system to multiple machines. ➔ Flexible manufacturing system.

Parallel axes (1) Two mechanically coupled NC axes, for example, *Y* 2 of gantry-type machines, that have to be activated simultaneously to avoid skewing. (2) Two NC axes acting in the same direction, such as the machine column and the spindle of a boring machine or tables and spindles with the same axis directions. (3) Two mutually independent NC axes, for example, main spindles and of two different headstocks of a vertical milling machine that can work simultaneously on two identical workpieces.

Parallel data transmission In parallel data transmission, a number of bits are transmitted simultaneously (in parallel), that is, on a number of parallel lines or via a number of logical channels at the same time. The number of data lines is not defined, but a multiple of 8 is generally used, thus allowing the transmission of full bytes (e.g., 16 lines mean 16 bits = 2 bytes). Often additional lines are used to transmit a checksum (parity bit) or a clock signal. Opposite: ➔ Serial data transmission.

Parallel input mode Programming a new workpiece by means of manual input control of a CNC machine while still processing another workpiece.

Parallel kinematic machine (PKM) Collective term for machines that generate all motions via kinematic struts. Examples: tripods, hexapods.

Parallel programming, parallel input mode Programming a new workpiece using manual data input controls while a different workpiece is still being machined.

Parametric programming NC programming by inputting the parameter values instead of numeric values in single words describing the process. For rings of holes, this could be, for example, the diameter, the number of holes, the start angle and angular step, and the desired drilling cycle. With just these few input values, the system calculates the individual positions and machining sequences.

Parity check A method for checking binary data for single-bit errors by adding an additional parity bit on track 8 to make the sum of bits per character always odd. The parity check detects incorrect characters during data transmission. Example: an uneven number of bits for a character in an ISO code.

Part program zero Generally identical with the program zero point defined by the programmer in each coordinate to which all the dimensions of the NC program refer. The reference to the machine zero point is taken into account via the zero offset.

PC card Credit-card-sized writeable and erasable data memory card for insertion in a notebook or laptop computer (PCs). Storage capacities up to 16 GB, today mainly flash ROM, for CNCs used as transportable program memory.

PDA ➔ Production data acquisition.

Performance This term has various meanings depending on the specific field. In a technical context, it means the sum of all features.

Peripheral units Collective term for additional devices connected to a computer. Examples: printers, DVD players/recorders, plotters, and monitors.

Photoelectric line tracer A non-NC controller with a photoelectric read head that traces the lines of a special template in 1:1 scale. Primarily used with older flame-cutting machines but declining in popularity because of the large 1:1 templates.

Playback Programming method mostly used with robots in which the robot is guided manually, and the NC system saves the entire motion sequence simultaneously (teaching). The stored motion sequence can be automatically repeated at a different (higher) velocity.

PLC ➔ Programmable logic controller.

Plotter Also called a computer-controlled drawing machine that provides a graphical representation on paper.

Pocket milling, pocketing NC function for removing metal from an enclosed surface up to a certain depth using a single instruction instead of programming each single step.

Point-to-point control NC system that moves to all programmed positions over an uncontrolled path without engagement of a tool. The machining starts after positioning is complete. Used for drilling, punching, and spot welding.

Polar axis Term for swivel axes, jointed axes, and rotary tables of NC machines.

Polar coordinates Mathematical system for determining the position of a point in a plane using the length of its radius vector and the angle of this vector relative to the datum line.

Polynomial interpolation Interpolation method in which the NC axes follow the function: $f = + p + +$ (pol., max. third degree). This can be used, for example, to generate straight lines, parabolas, and power functions.

Position display Visual display of the absolute position of a machine slide returned by the path-measuring system, measured from the axis zero point or the program zero point.

Position-feedback control, closed-loop control Closed-loop control system that continually compares the command values with the actual values and, in the case of deviations, outputs a correction signal until the difference between the two values has been corrected and the desired position has been reached.

Position-measuring system Measuring devices with signals that can be evaluated electrically to measure the axis motions and positions of an NC machine. A number of different types of measuring systems and measuring processes are available for this purpose: linear scales and rotary encoders, absolute and relative systems, analog and digital systems, and pseudoabsolute systems.

Postprocessor (PP) Software program required for computer-aided programming; converts the standard data for the tool motions (CLDATA) calculated by the computer into a machine-specific NC program. A special postprocessor is required for each machine-CNC combination.

Potential capability Process capability is understood to mean how well a process or its result (output) matches the requirement (customer request). With the help of the process capability index, one can unequivocally describe the performance of a process, easily compare multiple processes with the same output, and depict process improvements. The *Cpk* value is the most important parameter for describing the capability of processes. It contains information about both the spread and relative position with respect to the tolerance limit A single *Cpk* value always refers to a single measure. *Cpk* values indicate whether a statistical process control (SPC) is applicable or not.

Preset NC function for defining a specific position of machine coordinates without axis motion. No axis motion is triggered; merely a new position value is set for the current axis position.

Principle Basic tenet or rule.

Probe, switching probe A device that is used for obtaining an automatically measurement cycle on workpieces or tools during or after the machining process. A switching probe delivers only a highly precise switching signal but no data.

Probing cycles Subprograms stored in an NC system for automatic measurement of boreholes, pockets, or notches using a sensing probe for immediate calculation of positions, accuracies, tolerances, centers of circles, actual dimensions, and inclinations.

Procedure The process and/or way in which operations for obtaining, manufacturing or disposing of products is performed.

Processor (1) Special electronic hardware in a computer that performs certain functions such as data processing, arithmetic or logic functions, etc. (2) Computer software for converting a part program that has been written in a problem-oriented language and processed by the computer into a general NC system independent form (CLDATA). This is converted into an NC program by the postprocessor.

Product data management (PDM) A concept for storing and managing productdefining data and documents and to make these data available in downstream phases of the product lifecycle. It is based on an integrated product model. PDM largely arose from problems in the management of CAD drawings that resulted from dramatic increases in the quantities of product data associated

with the introduction of CAD systems. The ISO 10303 series of standards (STEP) has assumed a dominating position for data exchange between participating systems and for describing product models. CAD systems can be considered as the origin of PDM. The purpose of PDM is to increase the quality of product development and to reduce the time and expense of product development. By achieving a fully integrated flow of information, it should be possible to pass these benefits on to downstream points that are tied in with the product lifecycle. PDM systems are generally specific to a particular industry and company.

Product lifecycle management (PLM) Designates an IT solution system in which all data that are generated during creation, warehousing, and marketing of a product are stored, administered, and called up in a uniform manner. This means that all departments and systems access a common database: planning (PPC/ERP), design (CAD), production (CAM, CAQ), controlling, and sales and service. Because of its complexity, PLM should not be understood as a product that can be purchased but rather as a strategy that has to be implemented on a company-specific basis by means of suitable technical and organizational measures.

Production data acquisition ➔ PDA

Production planning and control (PPC) Integrated use of IT in production for organizational planning, control, and deadline monitoring for production processes from preparation of proposals to shipping. The main functions are forward planning of machine utilization, production deadlines, checking stocks of materials, and assembly times.

Programmable logic controller (PLC) In their simplest configurations, these electronic controllers replace earlier relay controls for interlocks and linking of switching commands and functions (bit processing). In their higher configuration, a system with a computer-like structure to perform specific functions such as logic control, timing, counting, arithmetic operations, and data manipulation. High-performance PLC systems are special word-processing computers with a number of inputs and outputs for continuous monitoring and control of the process with data feedback. ➔ PLC.

PDM ➔ Product data management.

PLM ➔ Product lifecycle management.

PROFIBUS DP (decentralized peripherals) A data bus used mainly in manufacturing technology to connect sensors and actuators with a centralized control unit. Additional areas of application are connecting distributed intelligence, that is, the mutual networking of multiple controllers (similar to PROFIBUS FMS). Data rates of up to 12 Mb/s are possible using twisted-pair cables and/or fiber-optic cables.

Program ➔ NC program.

Program edit Correcting NC programs by inserting, deleting, or modifying digits, words, or blocks. Rules and definitions for arranging data on a data carrier, for example, to design an NC program consisting of addresses, characters, words, and blocks with a variable block length.

Program format Rules and stipulations for the arrangement of data on a data carrier, for example, for the construction of an NC program consisting of addresses, characters, words, and blocks with variable block length.

Program interrupt Programmed STOP command (M00) that interrupts the machining process and allows the operator to perform checks, make measurements, change tools, or reclamp the workpiece. Machining is resumed with a START command.

Program word Basic unit of an NC block, consisting of an address and a numeric value. ➔ NC programming.

Programmable read-only memory (PROM) An electronic memory that can be programmed only once, after which its data are retained permanently.

Programming language Artificial language for symbolic description of computer instructions using mnemonic code. In the context of NC programming, this means a problem-oriented language that can be used to create a source program. This is the input into the computer, compiled by the language processor and then processed into a generally valid NC program (CLDATA). After that, it is converted by the postprocessor for the particular NC machine. Examples for problem-oriented languages include APT, EXAPT, and RADU.

Programming system Equipment for programming NC machines, consisting of a PC equipped with programming software and the corresponding peripheral devices.

Protocol Rules for the exchange of data between computers and/or other electronic devices.

Pseudoabsolute measuring (1) The use of two cyclic absolute encoders (resolvers) in connection with a special measuring gear and an electronic evaluation system. The fact that the angular positions of the two encoders differ by approximately one degree per rotation creates a phase shift that the electronics can use to calculate the absolute position. It is possible to measure a limited distance absolutely depending on the resolution, for example, approximately 5 to 8 m at 0.001-mm resolution (23 bits = 838,860,800 increments). (2) Pulse scale that is provided with distance-coded reference marks and special evaluation electronics at intervals of 20 mm. The absolute displacement is available once two reference marks have been moved over. (3) Rotary pulse generator with a backup battery for the encoder and counterelectronics so as to detect every motion of the machine even when switched off. The absolute axis positions are available immediately after switch-on.

Pulse generator, digitizer A rotary measurement device that generates a defined number of pulses per rotation with very high angular accuracy. In NC machines, digitizers are used as incremental encoders for measuring displacements or the spindle position of lathes. ➔ Feedback device.

Qlink view The main product of QlikTech, a former Swedish software company headquartered in Radnor, Pennsylvania. QlikView belongs to the category business intelligence software. QlikView is an analysis and reporting system. Associative in-memory search technology analyzes data and provides users with insights into their business data.

Quadrant (1) One quarter of a circle or the area of a quarter of a circle. (2) One of the four parts of a plane divided by two perpendicular coordinates.

Quality assurance Generic term denoting quality engineering, quality control, and quality audit.

Quality management Contains all organizational measures that serve to improve and secure process quality, services, and thus products of any kind. Quality management is a core task of management and, above all, concerns the internal organization of all areas of responsibility that design, plan, manufacture, test, and maintain a product.

Radiofrequency identification (RFID) This is a method for reading and writing data in data memory (in this case, a transponder) without physical or visual contact. This transponder can be attached to objects to allow them to be identified quickly and automatically based on the data saved there. The term *RFID* is used as a blanket term to describe the entire technical infrastructure. An RFID system contains the following: a transponder, also called an *RFID RFID RFID* or *radio* a send/receive unit, also called a and the integration, with servers,

services, and other systems, such as cash registers and merchandise management systems. Data transmission between the transponder and reader/receiver unit takes place by means of electromagnetic waves. At low frequencies, this occurs inductively via a near field and at higher frequencies via an electromagnetic far field. The distance over which an RFID transponder can be read can vary between a few centimeters and more than a kilometer depending on its design (passive/active), the frequency band being used, the transmission power, and environmental influences.

Random-access memory (RAM) Electronic memory (read/write memory) in which each storage location can be addressed, written to, or read out directly. A distinction is made between DRAM = dynamic RAM with very short read times and SRAM = static RAM.

Random tool access A method for identifying tools in the tool magazine. Tools are placed in any free magazine pocket when the magazine is loaded. The tool location within the magazine is variable and changes with every tool change. The CNC system performs the logical management of the tools and pocket numbers. Advantages: use of uncoded tools and programming of tool numbers in the NC program. The programmed tool is searched for via the shortest distance.

Rapid product development (RPD) Collective term for generative manufacturing of prototypes. ➔ Rapid prototyping.

Rapid prototyping (RP) One of the computer-assisted additive manufacturing processes, a relatively new technology. It is used for the computer-based construction of physical models, using special hardware and processes. It starts with a complete, closed set of CAD data (volume model) that will be "parsed" into individual layers using special software. Examples: stereolithography, laser sintering/melting, layer (laminate) process, and 3D printing.

Rapid tooling Fabricating tools that are used as permanent molds for plastic injection molding or metal die casting using rapid prototyping (RP) technologies, such as laser sintering/melting,

forming of RPD models through precise casting, etc. ➔ Rapid prototyping (RP).

Rationalization Technical and organizational measures for increasing efficiency, such as increased productivity or decreased resource requirements or costs. Rationalization saves means of production (raw materials, capital, and labor) as well as time. In a production environment, rationalization is generally associated with automated processes and personnel reductions.

Reactive current Attends to the necessary magnetization and demagnetization of an alternating-current (ac) motor and does not contribute to the shaft power of the motor. Reactive current is measured by × sin

Read-only memory (ROM) Electronic memory whose contents can only be read and cannot be changed.

Real-time processing, online processing Computer operating mode in which calculated data are immediately processed. The numerical control of machine tools is a typical example.

Reference point Defined position of an NC axis that has a particular relationship to the axis zero point. The machine, after it has been turned on, will move to it in order to zero the machine coordinate system unambiguously. With the advent of absolute encoders, there is no need to move to the reference point.

Repeatability, repetitive accuracy Accuracy achieved by repositioning the machine carriage several times in the same position under the same conditions. The deviations are determined by random errors and not by systematic errors.

Reproducibility Basically identical to repeatibility, yet measured over a longer period.

Reset Command to set a device or control system to a predefined initial state. Not to be confused with homing the NC axes.

Resolution Also called *measurement* (1) The smallest increment that can be detected by a measuring system in order to distinguish between two discrete positions. In NC machines, generally this is 0.001 mm. (2) Distance between pixels on a screen.

Resolver Measuring system based on an electromagnetic principle. It dissolves the angular position of a rotor into sine and cosine components. It provides absolute measurement within one revolution of the rotor.

Restricted area Also called *software limit* Programmable NC function that temporarily prevents a tool from moving out of a programmed area or entering a specific area. The programmable limit switches prevent collisions between the tool and workpiece based on incorrect dimensional data input. ➔ Software limit switch.

Retrofitting Conversion of a CNC machine from an obsolete to a newer, more powerful control, most of the time with the modernization of drives and the measuring systems, as well as exchange of the control electronics with a PLC. Cost-effective only for large, expensive machines that are in good condition.

RFID ➔ Radio-frequency identification.

RISC Abbreviation for "reduced instruction set computer." By dispensing with complex, rarely needed instruction sets, the computer becomes easier to use, cheaper, and faster. Complex commands are broken down into several simple ones and executed one after the other. Opposite: ➔ CISC.

Robot A program-controlled device that can perform complex motion sequences and is equipped with grippers or tools. Used primarily for handling tools or workpieces or for assembly. Examples: coating, welding, deburring, polishing, and tool changing.

ROM ➔ Read-only memory.

Rotary encoder, shaft encode, rotary position transducer A measurement device that converts angular positions into digitally encoded data. This is done using an encoded disk that is subdivided into a certain number of discrete positions. These are scanned by photocells; each track of the coded disk is assigned to its own measuring position values are output as binary code. The Gray code is the most suitable.

Rotary milling Economical alternative for turning operations on large workpieces using rotating tools (milling cutters). A distinction is made between rotary milling parallel to the axis and orthogonal rotary milling. Not to be confused with turning machines that also can be used for milling or milling machines that also can be used for turning (turning/milling centers).

Rotary position transducer Term for rotating encoder for position measuring of NC axes.

Rotary table Rotating clamping and worktable to allow machining of cubic workpieces from several sides. *B* '-axis in machining centers, that is, rotation about the ➔ Tilting or swiveling table.

Safety clearance Minimum distance of the from the workpiece for automatic tool changing without any risk of collision.

Safety functions Additional safety functions are used, for example, to fulfill the requirements for safety integrity level (SIL) 2 of IEC 61508 and performance level (PL) EN ISO 13849 for adjustment and test operation when a safety gate is open. This makes it possible to implement the primary requirements for functional safety in a simple, cost-effective manner: monitoring of velocity and standstill, reliable delimitation of workspaces and protected spaces, and safety-related signals and their internal logical links.

Scaling This CNC function can be used to produce workpieces with different scales using the same NC program. This is done by

specifying a scaling factor for each axis, thus modifying the programmed dimensions accordingly.

Scanner In NC technology, a device for digitizing the coordinate values of a workpiece and saving them to a data carrier. In principle, a measuring machine that uses a measuring probe to scan the workpiece line by line and store the measurement data.

SCARA robot Abbreviation for "selective compliance assembly robot arm" or "selective compliant articulated robot arm."

Sculptured surface ➔ Free-form surface.

Selective laser sintering (SLS) Rapid prototyping process for heavy-duty prototypes based on CAD data with layer-bylayer melting of powdered materials using a focused laser beam. With special molding sand, it is possible to create molds and cores for metal casting.

Selective mask sintering (SMS) A digital additive fabrication technique for 3D parts that are produced by melting a thin layer of plastic powder, one layer on top of the previous layer, by exposure to infrared light through a digital printed mask.

Semiclosed loop Although this term is not defined in measurement and control technology, it is used for position measurement and control of a longitudinal axis by means of a rotary encoder on the servo motor of the recirculating ball-drive spindle *position* Position errors resulting from pitch problems and

backlash are not captured. The rotary encoder only measures the angular position of the feed spindle and calculates the position from it. Opposite: ➔ Closed-loop operation.

Semiconductor components Electronic switching elements with special characteristics to trigger, generate, rectify, switch, and control electric currents. Examples: photoconductive cells, diodes, transistors, microprocessors, RAM, ROM, etc.

Sensing probe, touch probe, measuring probe Precision gauge with high switching accuracy and reproducibility of the switching point. These devices are mounted like a tool on the main spindle of an NC machine and are used to measure the tool length or workpiece position or for monitoring the machining accuracy. The CNC system has to have special software programs in order to save the measured position values and to use them to calculate compensation values, centers of circles, or tolerances, for example. ➔ Probing cycles.

Sensors Electrical feedback devices for nonelectrical variables such as length, angle, pressure, torque, force, and temperature. When the measured variable changes, the sensor's output signal has to react as quickly as possible.

SERCOS Abbreviation for "Serial Real-Time Communication System." Comprehensive specification for digital interfaces between CNC systems and drives. Its purpose is to combine CNC systems and drives from various manufacturers and to synchronize them with greater precision than with analog control circuits.

Serial data transmission Transmission of information one bit at a time via a single data channel. Opposite: ➔ Parallel data transmission.

Server A computer in a LAN that uses special software to control the connection to other connected devices (computers, drives, printers, etc.). ➔ LAN.

Servo control A closed-loop control circuit whose controlled variable is a mechanical motion. In NC machines, this can be the position feedback control of the NC axes. ➔ Closed-loop control.

Servo cycle time Time in microseconds for how often the actual position of an NC axis is scanned electronically and fed back to the closed-loop position control. This is an important factor for the dynamic accuracy of an NC machine.

Shop-floor programming (SFP) Easyto-use programming procedure suitable for use by a machine operator on the shop floor by interactive menus and graphically based input functions. A defining characteristic of SFP is the strict separation of geometry and technology inputs; that is, inputting the workpiece geometry does not specify the subsequent machining process. The workpiece contours are programmed and not the tool paths.

Silicon-controlled rectifier (SCR) Also called a a semiconductor component with three junctions that can be triggered from its

blocking state into its conducting state and vice versa. SCRs are used in power electronics for speed and frequency controllers.

Simulation Computer-generated reproduction of a complicated technical process in an as realistic a manner as possible, which is then presented on a screen. Can be used to check the subsequent process with regard to costs and time requirements. Simulation programs are used at various levels of product design, process planning, and manufacturing. Examples: graphical-dynamic simulation of NC machining or robot motions for the purpose of error detection. Simulation of a planned FMS in order to study bottlenecks, capacities, possible expansions, setup variants, and processing times before the system is installed.

Single-block mode Also called *blockby-block* Operating mode of an NC system in which the operator must initiate the execution of each block.

Softkeys Freely assignable function keys, also called *multifunctional* Generally, five to eight mechanical or electronic touch keys with varying functions arranged around the screen of a CNC system. A number of various functions are assigned to these keys in sequence via software for operation of the CNC system. Softkeys replace many hardware keys with discrete individual functions.

Software In general, a program that is necessary for operation of a computer or a computer-based system. The software of a CNC machine comprises the system program for the microprocessors that execute the NC functions plus monitoring, diagnosis, and

adaptive and machine-specific programs. Should not be confused with the user's NC programs.

Software limit switch Programmable axis limitation for NC machines intended to prevent undesirable exceeding of the limits. Used as a replacement for mechanical axis limit switches or for temporary limitation of the workspace in order to protect the machine and workpiece from damage caused by incorrect dimensional data input.

Source program NC program written in a problem-oriented programming language.

Speed (1) Speed as in millimetres per minute, e.g., feed rate of an NC axis, or (2) speed as in revolutions per minute, e.g., spindle rpms.

Speed control Speed control of synchronous motors is performed by changing the feed voltage and frequency using a frequency converter. The speed-control range extends from standstill (with standstill torque) up to the maximum permitted speed. This is motor dependent and can be from 2,000 to 9,000 rpms. The advantages of the speed-controlled synchronous motor are such that it is the preferred axis drive for CNC machine tools. Contemporary synchronous servo motors are special designs that allow a large control range and dynamic speed response.

Spindle orientation Programmable NC function for main spindles with position feedback for stopping the spindle in a defined or

programmable angular position. Necessary when withdrawing a boring tool with a one-sided cutting edge out of a cavity or for tool changing in the case of tool holders with gripping and fixing positions.

Spline function A mathematical function for approximation of curves. This produces smooth curves that connect the specified interpolation points with a smooth, constant progression. A distinction is made between and C splines. ➔ NURBS.

Spline interpolation Concatenation of thirdor higher-degree polynomials that exhibit a transient behavior with minimal bending. Used to calculate free-form curves based on a small number of interpolation points.

Static RAM (SRAM) Electronic readwrite memory whose contents are retained without periodic refreshing.

Statistical process control (SPC) Also called *process* a procedure for optimizing production and service processes based on statistical methods.

STEP Abbreviation for "Standard for the Exchange of Product Model Data," international standard to allow the free exchange and processing of CAD data (ISO 10303).

Stepping or stepper motor An electric motor in which the rotor moves in small, discrete angular steps (e.g., 400 steps per revolution). The displacement angle of the rotor corresponds to

the number of pulses generated by the control device, and the rotational speed corresponds to the pulse frequency. There is no feedback and therefore no closed-loop control. Only relatively low speeds and torques can be realized. Hydraulic amplifiers are connected downstream to achieve greater torques.

Stereolithography (SL) CAD/CAM process for creating prototypes without a casting mold and without tools. The basis material is a bath of liquid plastic that is subjected to a numerically controlled laser or ultraviolet beam, which cures the plastic layer by layer. ➔ RPD.

Straight-cut control NC system that can only move the tool parallel to the axes *Z* in sequence) at the feed rate.

Subprogram, subroutine, macro Frequently-used program sections stored in memory that can be called up by the main program. After that, the program sequence jumps back to the main program.

Surface-mounted devices (SMD) Special method for mounting microelectronic components on circuit boards.

Synchronous motor Electric motor for three-phase current in which, regardless of the load, the rotor always runs synchronously with the rotating field generated in the stator. The stator winding is identical to that of an asynchronous motor. The rotor is equipped with permanent magnets or separately excited magnets, with one or more pairs of poles depending on the design. Synchronous

motors cannot be run up directly by switching on the three-phase current; to reach their rated speed, they also require a startup device, generally in the form of a squirrel cage.

Speed control Speed control of synchronous motors is performed by changing the feed voltage and frequency using a frequency converter. The speed-control range extends from standstill (with standstill torque) up to the maximum permitted speed. This is motor dependent and can be from 2,000 to 9,000 rpm. The advantages of the speed-controlled synchronous motor are such that it is the preferred axis drive for CNC machine tools. Contemporary synchronous servo motors are special designs that allow a large control range and dynamic speed response.

Syntax (1) In grammar, study of sentence structure and the placement and functions of individual words and phrases, main and subordinate clauses, etc. (2) In NC technology, defined rules for structuring instructions in characters, words, and blocks.

System An integral combination of things, processes, and components; may have been created by humans. Examples: the periodic table of the chemical elements, planetary systems, systems of measurement, cybernetic systems, programming systems, and manufacturing systems.

Systematics Division according to objective, logical relationships.

Teach-in mode, teach mode Programming by moving the NC axis to various positions in a sequence. Used primarily for robots by

moving the robot arm step by step to the desired positions in setup mode. The CNC stores these values when a "Save" button is pressed. After that, the individual positions are moved to automatically by "Playback" mode.

Technical and Office Protocol (TOP) Communication concept (LAN) developed by Boeing for administrative networks.

Technological data As a supplement to the geometric data, all the information in an NC program for selecting the technological functions such as the speed, feed rate, coolant, and tools.

Terminal Devices for data input and display, generally consisting of an ASCII keyboard and screen.

Thread milling ➔ Helical interpolation, helix interpolation.

Thyristor ➔ Silicon-controlled rectifier (SCR).

Tilting or swiveling table Clamping table or worktable at machine tools that can be tilted or swiveled to machine diagonal surfaces and holes and sculptured surfaces on cubic workpieces. The *A* '-axis in machining centers means tilting around the ➔ Rotary table.

Time sharing Computer operating mode in which multiple users can use the computer simultaneously for various tasks. This results in cost-effective utilization of the computer without noticeable wait times for the individual users.

Token Ring More precisely, TokenAccess Protocol for Local Networks (LANs). Controls access of the individual participants to the bus. The token, a specific bit pattern that grants transmission rights, can only be transmitted from one participant to another. This ensures that only one participant is transmitting at any given time and that the data are transmitted without collisions.

Tool changer Mechanical device on NC machines for automatically changing tools from the magazine into the working spindle and vice versa. The changing process is performed by single or double grippers or directly from the tool magazine to the spindle.

Tool compensation Correction values stored in the NC system to compensate for deviations in the tool length, different tool radii, the tool position, or tool wear.

Tool data The data describe a tool, such as diameter, length, and service life. In some cases supplemented with cutting parameters, weight, shape, type, and other data concerning the tool.

Tool function A programmable function that identifies a tool number in an NC-program by the The M06 command is then used to insert the tool into the work spindle.

Tool-length compensation Value stored in the CNC system to compensate for the actual tool length compared with the programmed tool length, for example, for drills, countersinks, or taps.

Tool management (1) Within machines, an NC function for management of the tools located in the magazine according to their tool numbers, location numbers, service life, compensation values, breakage, and wear and tear. (2) Outside machines, a central tool computer that carries out all the management tasks that take place outside the NC system, such as tool numbers, tool data, compensation and adjustment values, availability, remaining service life, etc. Data exchange between the computer and the NC system is either via DNC or special readwrite-capable data memory chips in the tool holder. Seamless management and permanent updating of tool data are very important for the cost-effectiveness of a tool machine.

Tool monitoring, tool-life monitoring CNC function for monitoring the theoretical service lives (periods of use) for each individual tool in the magazine of an NC machine. The NC system does this by adding the individual usage times for the tools and comparing them with the specified theoretical service life. At the end of it service life, a tool is locked out, and an alternate tool may be called up.

Tool path The path calculated by an NC system on which the tool center point moves relative to the workpiece in order to create the programmed contour.

Tool presetting Precise measurement and adjustment of tools to defined values regarding length, for drills and end mills, and diameter, for boring tools. Special presetting devices are available for this purpose. These are equipped with dial gauges,

microscopes, profile projectors, and computers for measuring or setting the values exactly. These tool data are stored for subsequent transfer to an NC machine.

Tool tip compensation Equidistant path compensation value for lathes to compensate for various tool nose radii of cutting tools. It requires consideration of the cutting-edge center point (right/left, in front of/behind center, axis parallel). It is different from cutter radius compensation.

TOP Abbreviation for "Technical and Office Protocol," a communication concept (LAN) developed by Boeing for administrative networks.

Topology, structure In computer networks, topology designates the structure of the interconnections between a number of devices in order to ensure the mutual exchange of data. A distinction is made between star, ring, bus, tree, meshed network, and cell topology. The topology of a network has a decisive effect on its reliability. When individual links fail, functional capability is retained only when alternative paths exist between the nodes. In this case, there are one or more replacement paths (or detours) in addition to the normal path.

Torque motor Torque motors are gearless direct drives with very high torque (>8,000 Nm) and relatively low speed. They are used for quick, precise movement and positioning tasks. Thanks to their compact construction and limited number of components, they require very little space. They are suitable for use with rotary tables, swivel and rotary axes, spindle machines, dynamic tool

magazines, and spindles in milling machines. Torque motors can be manufactured with internal or external rotors. With external rotors, they have greater torque with the same external dimensions.

Touchscreen Screen with touch sensors to activate menu options by touching them with the finger.

Transfer line Grouping of a number of machine tools in a manufacturing line, where all parts pass through the individual stations in a specific sequence and are processed using subsequent supplemental programs. The machining processes can be changed only within certain limits. This means that transfer lines are ideal for series production without major product variations. Transfer lines have lost their relevance in terms of numbers in automobile production because of the required flexibility and great variety of products. They are substituted by flexible manufacturing systems.

Transmission Control Protocol/Internet Protocol (TCP/IP) A network protocol that, because of its great importance for the internet, is also simply called the *Internet Protocol*

Turning center NC turning machine with automatic tooland workpiece-changing and additional equipment providing expanded machining options, such as eccentric drilling and milling, reclamping of parts, milling of surfaces, and possibly even grinding, measuring, and hardening.

Turn milling Economical alternative when turning large workpieces using rotating tools. A distinction is made between axis-parallel and orthogonal rotary milling. Not to be confused with lathes that also can mill or milling machines that also can turn (turning and milling centers).

Ultrasonic technology A new technology for the cost-effective machining of ceramics, glass, carbides, silicon, and similar materials. This is done by superimposing a mechanical oscillation of approximately 20,000 Hz on the milling tool in the direction of the using a special ultrasound spindle at speeds of 3,000 to 40,000 rpm. The vibrating diamond tool knocks very small powdery particles off the workpiece, thus creating a surface with extremely high quality.

Undershoot Undesirable rounding of corners and other erratic transitions on a workpiece made by the a cutting tool, caused by the axis lag (following error) of the NC axes. This can be avoided by programming "exact stop" (G60, G61), a high-kV factor, or "corner braking." ➔ Corner rounding.

UNIX Computer operating system developed by AT&T Bell Laboratories for multiple users.

Upward compatibility The capability of a newer CNC machine to execute NC programs written for an older NC/CNC machine.

USB stick Portable semiconductor memory, generally flash ROM. Unlike the main memory of a PC, these memory chips retain their

contents even when no operating voltage is present. USB is the ideal connection technology for this because it is now in widespread use, brings the required power supply along with it, and specifically supports plugging in and unplugging during operation.

V.24 interface Data interface recommended and standardized by CCITT that largely corresponds to the EIA-232-C interface. It is used in NC systems for automated data input-output.

Variable-block format NC program format in which the length of each block can vary depending on the number of addresses and numeric values.

VDAFS Abbreviation for "Verband der Automobilindustrie – Flächen-Schnittstelle," a surface-translation format from the German Association of the Automotive Industry (VDA). Became a DIN standard (DIN 66301) in 1986. A purely geometric translation format especially for exchanging three-dimensional (free-form) curve and surface data, for example, between CAD systems. It is characterized by having only a few basic elements, a simple data format, and simple syntax.

Vector feed rate Feed rate that results when a tool moves along the workpiece contour. The axes involved change their velocities in such a way that the resulting vector feed rate of the tool corresponds to the programmed value and remains constant.

Virtual product Realistic computer-based representation of a product as a solid body on the screen, with all the required

functions. Realistic assessments can be made without creating a physical model.

VLSI (very large-scale integration) Designates the scale of integration of electronic semiconductor modules. VLSI processors have between 100,000 and 1 million transistors, for example.

Volatile memory A data-storage device that loses its stored information when power is turned off. Example: RAM.

Wide-area network (WAN) A data connection between computers over long distances using public facilities such as telephone lines or ISDN.

Wizard A software tool used, for example, in CAD and PDM systems to automate processes and significantly reduce processing times.

Work area limit Programmable limitation of the permitted workspace of an NC machine by entering the upper and lower limit values for each axis. The machine switches off immediately if a command position outside these limits is entered. ➔ Software limit switch.

Workpiece changer The programmable, automatically executed loading/uploading process in an NC machine with the aid of a pallet changer or a robot.

Workstation A terminal for communication with a computer, generally equipped with its own CPU.

Addresses for the three main linear NC axes, which are generally perpendicular to each other. *X* is the horizontal longitudinal axis, *Y* is a transverse motion, and *Z* is the motion in the direction of the spindle axis.

Zero lag Also called *feed-forward* This NC function corrects the expected deviation, that is, the NC axes move directly to the desired contour without any following error. ➔ Deviation; ➔ Following error.

Zero offset An NC function for shifting the program zero point as desired, manually or by means of a program. For this purpose, CNC systems have separate memory areas for a number of zero offsets that can be called up by the NC programs.

Zooming, zoom function Continuously adjustable enlargement or reduction of a graphical depiction on a screen to allow better identification of the details.

details.

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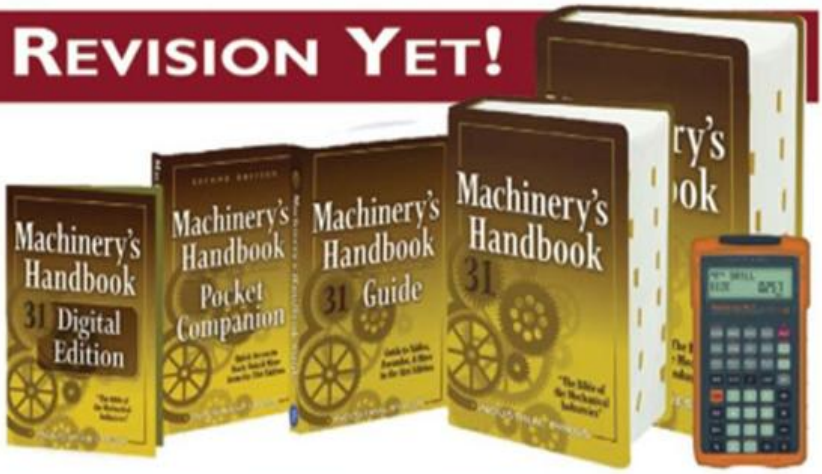

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Digital manufacturing is everywhere. Technology advances in production engineering have reduced the "artisan skill" traditionally required in manufacturing processes and replaced it with high-precision, computer-controlled machinery. This reduces human errors and variability in output, but it does not reduce the knowledge required of the professional engineer or shop floor worker. In fact, the reverse is true. They still need to understand the fundamentals, and must acquire other important skills.

Anyone who works in machining or additive manufacturing technology must have a solid technical knowledge of CNC technology. It is important to know how the individual components work and how they affect the overall system, the quality of the products produced and the profitability of production. Professionals should be familiar with today's machine tools and the numerous functions of CNC, electrical servo drives, tool systems, NC programming through to digital information processing and automation.

The CNC Handbook was a critically acclaimed bestseller in Germany for 30 editions, and is now available in English for the first time. This groundbreaking work introduces readers to the CNC world, and teaches practical details about how different components are applied in practice. Next, the authors explain the functions and connections of all integrated components, and clearly describe CNC and drives, tooling, flexible manufacturing systems (FMS), NC-programming, DNC, digital manufacturing, Industry 4.0 and computer integrated manufacturing (CIM). The book then covers industrial robots, additive manufacturing, energy-efficient manufacturing, simulation systems, and state-of-the-art of machine integrated measuring systems. This authoritative, heavily illustrated book is the perfect resource for the avid CNCer, but also for those who plan and program, set up, operate machinery, or are responsible for operation, maintenance and repair.

FEATURES

- Packed with more than 800 figures, 4-color pictures, and product shots.
- Authors use their more than 150 combined years of industrial and academic experience to impart CNC knowledge.

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Hans B. Kief has more than 35 years of experience in the field of NC/CNC machine tools and manufacturing automation with the firm of Robert Bosch GmbH.
Helmut Roshiwal founded Roschiwal+Partner Engineering GmbH, and is now active on its board of advisors.
Karsten Schwarz is the head of Siemens Technology and Application Center in Erlangen, and responsible for Siemens CNC training activities worldwide.

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