Machining Centers, Machine-tool Structures, and Machining Economics

CHAPTER 25

- This chapter presents the characteristics, types, and advantages of machining centers, and the concept of reconfigurable machine tools.
- Emphasis is placed on the importance of understanding the performance of machine tools, and their modules and components, particularly with regard to stiffness, vibration, chatter, and damping characteristics. These are important considerations not only for quality and dimensional accuracy, but also because of their influence on tool life, productivity, and the economics of machining operations.
- Presented next are high-speed machining, hard machining, and ultraprecision machining operations, topics that are strongly tied to the economics of machining.
- The chapter ends with a simple method of cost analysis for determining the conditions under which machining parameters can be selected, so that machining cost per piece or machining time per piece can be minimized.

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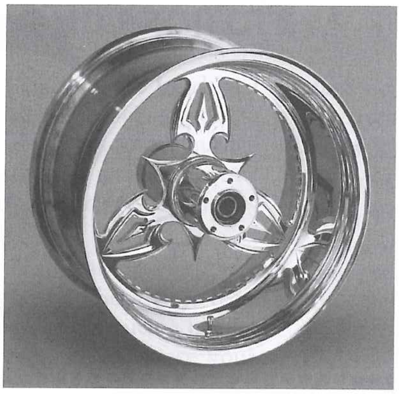
25.1 Introduction

The preceding four chapters have described machining operations and machine tools, but have not emphasized the widespread integration of advanced computer technology and the flexibility it allows in manufacturing operations. Computers have dramatically improved the capabilities of machine tools, whereby they now have the capability of rapidly and repeatedly producing very complex part geometries. The program controlling a machine tool can incorporate changes in cutting conditions, compensate for tool wear, automatically change tools, and machine a workpiece without refixturing or having to transfer it to another machine tool, as had been the practice for many years.

In addition to advanced computer technologies, vibration and chatter and their avoidance, high-speed machining, hard machining, and advanced analysis of machining economics are now highly developed and have revolutionized machining operations.

25.2 Machining Centers

In describing the individual machining processes and machine tools in the preceding chapters, it was noted that each machine, regardless of how highly it is automated, is designed to perform basically the same type of operation, such as turning, boring,



(a)

(b)

FIGURE 25.1 Examples of parts that can be machined on machining centers using various processes such as turning, facing, milling, drilling, boring, reaming, and threading; such parts ordinarily would require the use of a variety of machine tools to complete. (a) Forged motorcycle wheel, finish machined to tolerance and subsequently polished and coated. (b) Detailed view of an engine block, showing complex cavities, threaded holes, and planar surfaces. *Source:* (a) Courtesy of R.C. Components; (b) courtesy of Fotolia.

drilling, milling, broaching, planing, or shaping. It was also shown that most parts manufactured by the methods described throughout this book require further operations on their various surfaces before they are completed. Note, for example, that the parts shown in Fig. 25.1 have a variety of complex geometric features, and that all of the surfaces on these parts require a different type of machining operation to meet certain specific requirements concerning shapes, features, dimensional tolerances, and surface finish. Note also the following observations:

- Recall that some possibilities exist in *net-shape* or *near-net shape* production of these parts, depending on specific constraints on shapes, dimensional tolerances, detailed surface features, surface finish, and various mechanical and other properties to meet service requirements. Shaping processes that are candidates for such parts are precision casting, powder metallurgy, powder-injection molding, and precision forging. Even then, however, it is very likely that the parts will still require some additional finishing operations. For example, small-diameter deep holes, threaded holes, flat surfaces for sealing with gaskets, parts with very close dimensional tolerances, sharp corners and edges, and flat or curved surfaces, with different surface-finish requirements, will require further machining operations.
- If some machining is required, or if it is shown to be more economical to finish machining these parts to their final shapes, then it is obvious that none of the machine tools described in Chapters 23 and 24 could, *individually* and *completely*, produce the parts. Note also that traditionally, machining operations are performed by moving the workpiece from one machine tool to another, until all of the required machining operations are completed.

The Concept of Machining Centers. The traditional method of machining parts by using different types of machine tools has been, and continues to be, a viable manufacturing method. This method can be highly automated in order to increase productivity, and in fact it is the principle behind **transfer lines**, also called *dedicated* *manufacturing lines* (DML), as described in Section 37.2.4. Commonly used in *high-volume* or *mass production*, transfer lines consist of several specific (*dedicated*) machine tools, arranged in a logical sequence. The workpiece, such as an automotive engine block, is moved from one station to another, with a specific machining operation performed at each station, after which it is transferred to the next machine for further specific machining operations.

There are situations, however, where transfer lines are not feasible or economical, particularly when the types of products to be processed change rapidly, due to factors such as product demand or changes in product shape or style. It is very costly and time-consuming to rearrange these machine tools to respond to the needs for the next and different production cycle. An important concept that addresses flexibility in manufacturing, developed in the late 1950s, is that of **machining centers**.

A machining center (Fig. 25.2) is an advanced computer-controlled machine tool that is capable of performing a variety of machining operations, on different surfaces and different orientations of a workpiece, without having to remove it from its work-holding device or fixture. The workpiece generally is stationary and the cutting tools rotate, as they do in such operations as milling, drilling, honing, and tapping. Whereas, in transfer lines or in traditional shops and factories, the workpiece is brought *to the machine*; in machining centers it is the machining operation that is brought *to the workpiece*.

The development of machining centers is related closely to advances in automation and computer control of machine tools, the details of which are described in Chapter 37. Recall that, as an example of the advances in modern lathes, Fig. 23.10 illustrates a numerically controlled lathe (**turning center**), with two turrets, each carrying several cutting tools.

Components of a Machining Center. The workpiece in a machining center is placed on a **pallet**, or *module*, that can be moved and swiveled (oriented) in various directions (Fig. 25.3). After a particular machining operation has been completed, another operation begins, which may require reindexing of the workpiece on its pallet. After all of the machining operations have been completed, the pallet automatically moves away with the finished part, and another pallet, carrying another workpiece or

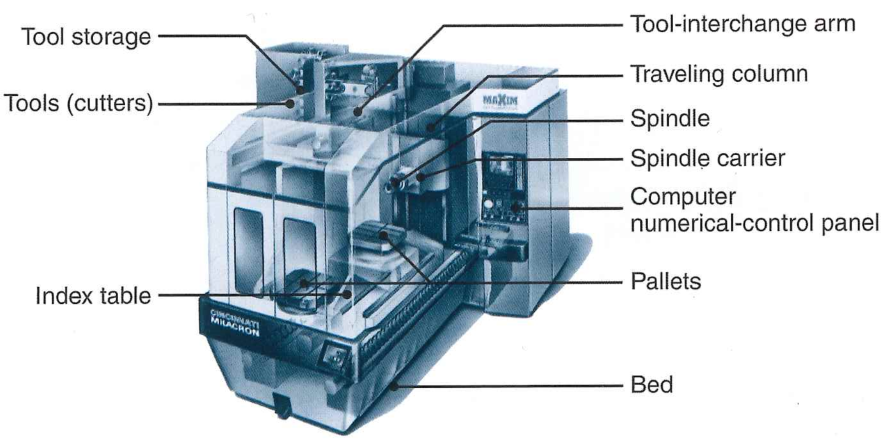


FIGURE 25.2 A horizontal-spindle machining center equipped with an automatic tool changer; tool magazines can store up to 200 cutting tools of various functions and sizes. *Source:* Courtesy of Cincinnati Milacron.

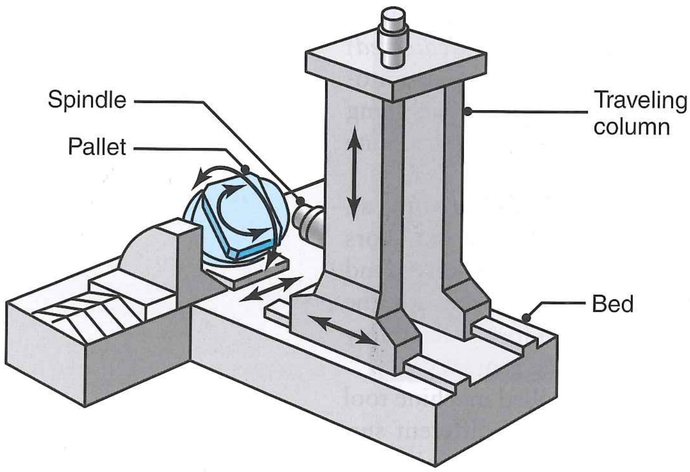


FIGURE 25.3 Schematic illustration of the principle of a five-axis machining center. Note that, in addition to possessing three linear movements (three axes), the pallet, which supports the workpiece, can be swiveled around two axes (hence a total of five axes), allowing the machining of complex shapes, such as those shown in Fig. 25.1. *Source:* Courtesy of Toyoda Machinery.

workpieces to be machined, is brought into position by an **automatic pallet changer** (Fig. 25.4). All movements are computer controlled, with pallet-changing cycle times on the order of only 10–30 s. Pallet stations are available with several pallets serving one machining center. The machines also can be equipped with various automatic features, such as part loading and unloading devices.

A machining center is equipped with a programmable **automatic tool changer** (ATC). Depending on the particular design, up to 100 cutting tools can be stored in a magazine, drum, or chain (*tool storage*). *Auxiliary* tool storage also is available on some special and large machining centers, raising the tool capacity to 200. The cutting tools are selected automatically for the shortest route to the machine spindle. The maximum dimensions that the cutting tools can reach around a workpiece in a machining center is known as the **work envelope**, a term that first was used in connection with industrial robots, as described in Section 37.6.

The **tool-exchange arm** shown in Fig. 25.5 is a common design; it swings around to pick up a particular tool and places it in the spindle; note that each tool has its own toolholder, which makes the transfer of cutting tools to the machine spindle highly efficient. Tools are identified by bar codes, QR codes, or coded tags attached directly to their toolholders. Tool-changing times are typically between 5 and 10 s, but may be up to 30 s for tools weighing up to 110 kg and less than one second for small tools.

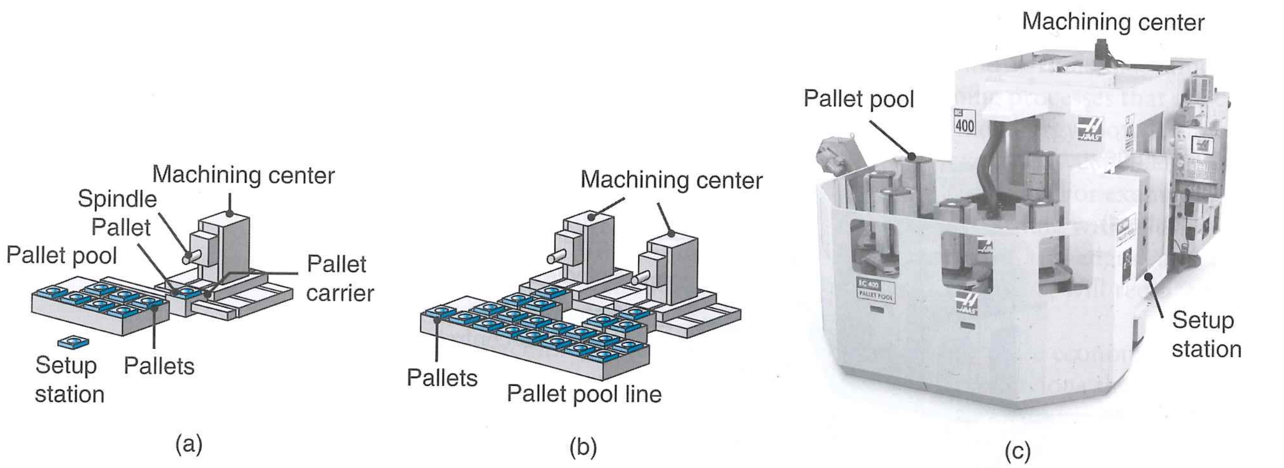


FIGURE 25.4 (a) Schematic illustration of the top view of a horizontal-spindle machining center showing the pallet pool, setup station for a pallet, pallet carrier, and an active pallet in operation (shown directly below the spindle of the machine). (b) Schematic illustration of two machining centers with a common pallet pool. (c) A pallet pool for a horizontal-spindle machining center; various other pallet arrangements are possible in such systems. *Source:* (a) and (b) Courtesy of Hitachi Seiki Co., Ltd.; (c) Courtesy of Haas Automation, Inc.

Machining centers may be equipped with a **tool-checking** and/or **part-checking station** that feeds information to the machine control system, so that it can compensate for any variations in tool settings or tool wear. **Touch probes** (Fig. 25.6) can be installed into a toolholder to determine workpiece-reference surfaces, for selection of tool settings and for online inspection of parts being machined.

Note in Fig. 25.6 that several surfaces can be contacted (see also *sensor technology*, Section 37.7), and that their relative positions are determined and stored in the database of the computer software. The data are then used to program tool paths (see, for example, Fig. 37.12) and to compensate for tool length, tool diameter, and for tool wear, in more advanced machine tools. Noncontact probes also can be used, and can measure dimensions, surface roughness, or temperature.

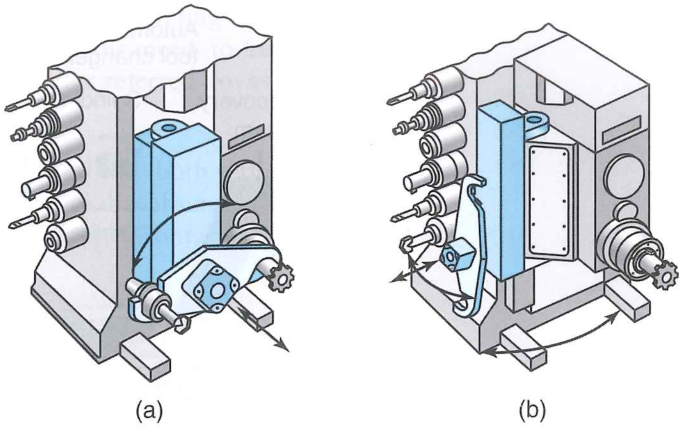


FIGURE 25.5 Swing-around tool changer on a horizontal-spindle machining center. (a) The tool-exchange arm is placing a toolholder with a cutting tool into the machine spindle; note the axial and rotational movement of the arm. (b) The arm is returning to its home position; note its rotation along a vertical axis after placing the tool and the two degrees of freedom in its home position.

25.2.1 Types of Machining Centers

There are various designs for machining centers. The two basic types are vertical spindle and horizontal spindle, although many machines are capable of operating along both axes.

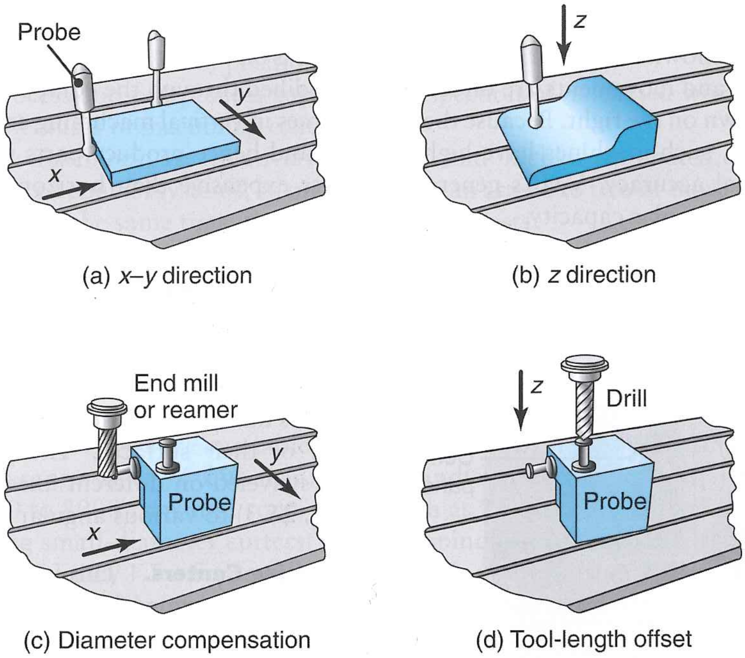


FIGURE 25.6 Touch probes used in machining centers for determining workpiece and tool positions and surfaces relative to the machine table or column. Touch probe determining (a) the $X-Y$ (horizontal) position of a workpiece; (b) the height of a horizontal surface; (c) the planar position of the surface of a cutter (e.g., for cutter–diameter compensation); and (d) the length of a tool for tool-length offset.

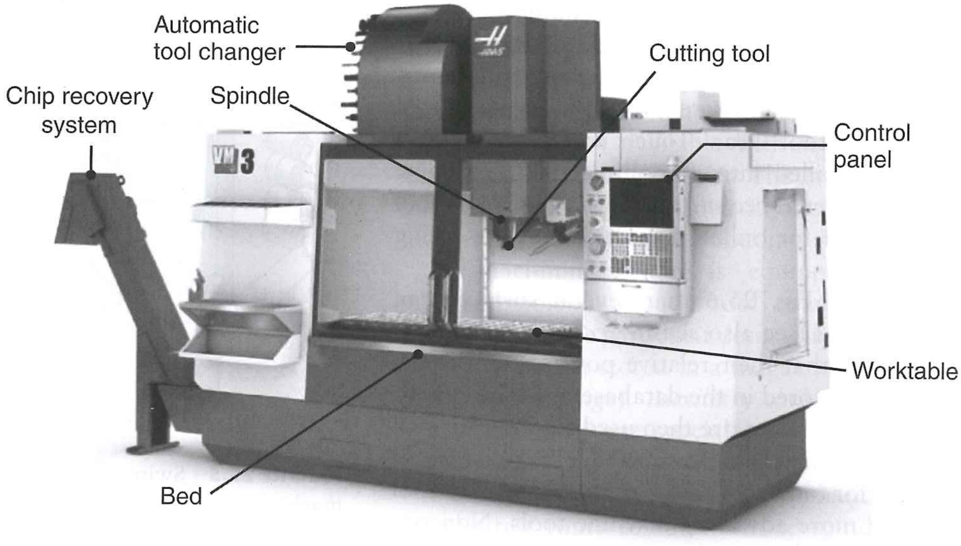


FIGURE 25.7 A vertical-spindle machining center; the tool changer is on the left of the machine, and has a 40 tool magazine. *Source:* Courtesy of Haas Automation, Inc.

Vertical-spindle Machining Centers. Also called *vertical machining centers* (VMC), these machines are capable of performing various machining operations on parts with deep cavities, as required in mold and die making (also called *die sinking*). A vertical-spindle machining center, which is similar to a vertical-spindle milling machine, is shown in Fig. 25.7. The tool magazine is on the left of the machine, and all operations and movements are directed and modified through the computer control panel, shown on the right. Because the thrust forces in vertical machining are directed downward, such machines have high stiffness and hence produce parts with good dimensional accuracy. VMCs generally are less expensive than horizontal-spindle machines of similar capacity.

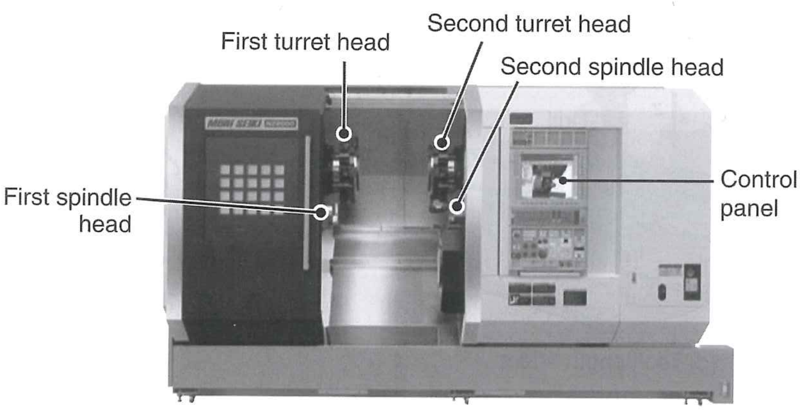


FIGURE 25.8 A computer numerical-controlled turning center. The two spindle heads and two turret heads make the machine very flexible in its machining capabilities; up to three turret heads are commercially available. *Source:* Courtesy of Mori Seiki Co., Ltd.

Horizontal-spindle Machining Centers. Also called *horizontal machining centers* (HMC), these machines are suitable for large as well as tall workpieces that require machining on a number of their surfaces. The pallet can be swiveled on different axes (e.g., see Fig. 25.3) to various angular positions.

Turning Centers. This is another category of horizontal-spindle machines, and basically are computer-controlled *lathes*, with several features. A multiturret turning center is shown in Fig. 25.8. It is constructed with two horizontal spindles and two turrets, equipped with a variety of cutting tools used to perform several operations on a rotating workpiece. The turrets can be powered to allow for drilling or milling operations within the CNC turning center, and without the need to refixture the workpiece. For this reason, such machines are often referred to as CNC **Mill-turn Centers.**

Universal Machining Centers. These machines are equipped with both vertical and horizontal spindles. They have a variety of features and are capable of simultaneously machining all of the surfaces of a workpiece, i.e., vertically, horizontally, and at a wide range of angles.

25.2.2 Characteristics and Capabilities of Machining Centers

The major characteristics of machining centers are summarized as:

- Machining centers are capable of handling a wide variety of part sizes and shapes efficiently, economically, repetitively, and with high dimensional accuracy and with tolerances on the order of ± 0.0025 mm.
- These machines are versatile and capable of quick changeover from one type of product to another.
- The time required for loading and unloading workpieces, changing tools, gaging of the part being machined, and troubleshooting is reduced. Because of the inherent flexibility of machining centers, the workpiece may not need to be refixtured during machining, referred to as the *one and done* approach. Productivity is improved, labor requirements (particularly skilled labor) are reduced, and production costs are minimized.
- These machines can be equipped with tool-condition monitoring devices for the detection of tool breakage and wear, as well as with probes for tool-wear compensation and tool positioning.
- In-process and postprocess gaging and inspection of machined workpieces are now features of machining centers.
- These machines are relatively compact and highly automated, and have advanced control systems, so one operator can attend to two or more machining centers at the same time, thus reducing labor costs.

Because of the high productivity of machining centers, large amounts of chips are produced and must be collected and disposed of properly (*chip management*, Section 23.3.7). Several system designs are available for *chip collection*, with one or more chain or spiral (screw) conveyors; they collect the chips along troughs in the machine and deliver them to a collecting point (see Fig. 25.7).

Machining centers are available in a wide variety of sizes and features. Typical capacities range up to 75 kW . Maximum spindle speeds are usually in the range from 4000 to 8000 rpm, and some are as high as 75,000 rpm for special applications, using small-diameter cutters. Modern spindles can accelerate to a speed of 20,000 rpm in only 1.5 s. Some pallets are capable of supporting workpieces weighing as much as 7000 kg although even higher capacities are available for special applications. The cost of machining centers ranges from about $50,000 to $1 million and higher.

25.2.3 Selection of Machining Centers

Machining centers generally require significant capital expenditure; to be cost effective, they may have to be operated for more than one shift per day. Consequently, there must be sufficient and continued demand for parts to justify their purchase. Because of their inherent versatility, however, machining centers can be used to produce a wide range of products, particularly for *mass customization* or *just-in-time manufacturing*, as described in Section 39.5.

The selection of the type and size of machining centers depends on several factors, especially the following:

- Type of products, their size, and shape complexity
- Type of machining operations to be performed and the type and number of cutting tools required
- Dimensional accuracy specified
- Production rate required

CASE STUDY 25.1 Machining Outer Bearing Races on a Turning Center

Outer bearing races (Fig. 25.9) are machined on a turning center. The starting material is a hot-rolled 52100 steel tube, with 91 mm OD and 75.5 mm ID. The cutting speed is 95 m/min for all operations. All tools are carbide, including the cutoff tool (used in the last operation shown), which is 3.18 mm instead of 4.76 mm for the high-speed steel cutoff tool that formerly was used

The amount of material saved by this change is significant, because the race width is small. The turning center was able to machine these races at high speeds and with repeatable tolerances of ±0. 025 mm (See also Example 23.2.)

Source: Based on data from McGill Manufacturing Company.

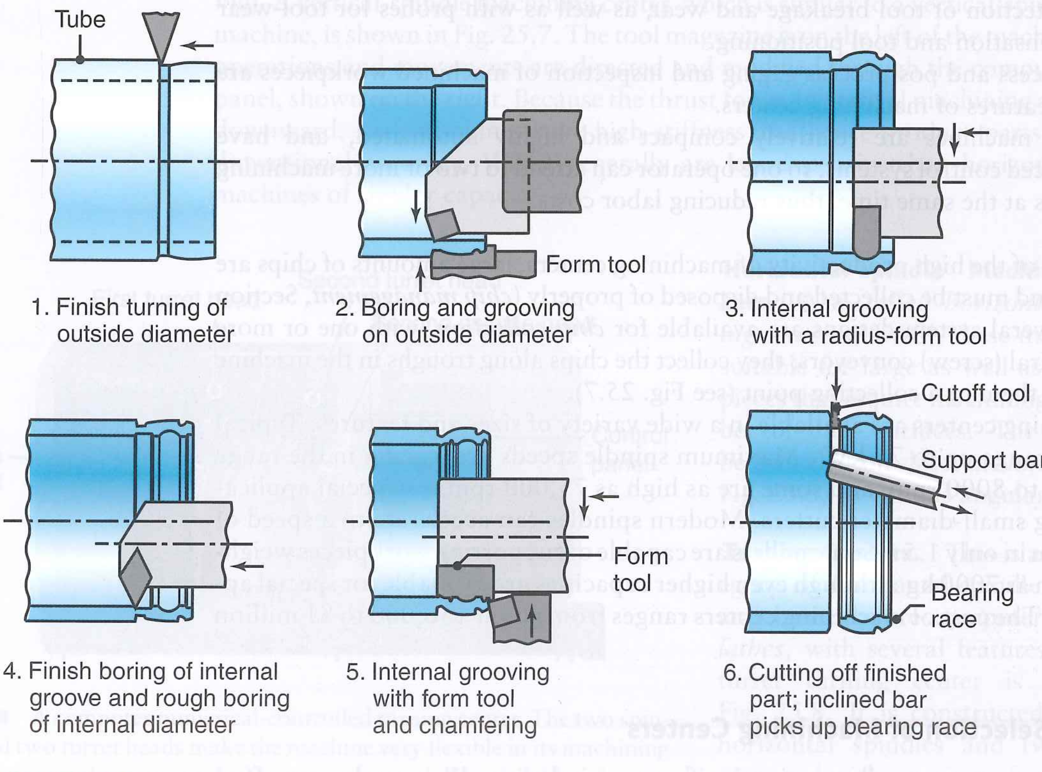


FIGURE 25.9 Steps in machining of outer bearing races.

25.2.4 Reconfigurable Machines and Systems

The need for the flexibility of manufacturing processes has led to the more recent concept of *reconfigurable machines*, consisting of various modules. The term reconfigurable stems from the fact that, by using advanced computer hardware and reconfigurable controllers, and utilizing advances in information management technologies, the machine components can be arranged and rearranged quickly into a number of configurations to meet specific production demands.

Figure 25.10 shows an example of how the basic machine-tool structure of a three-axis machining center can be reconfigured to become a *modular* machining center. With such flexibility, the machine can perform different machining operations while accommodating various workpiece sizes and part geometries. Another example is given in Fig. 25.11, where a five-axis (three linear and two rotational movements) machine can be reconfigured by assembling different modules.

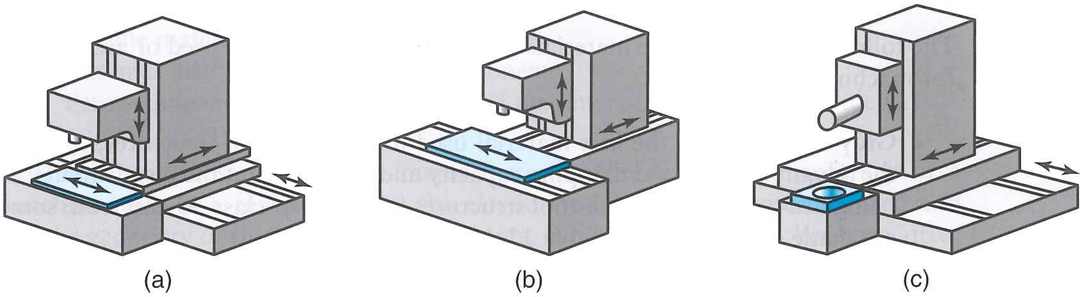


FIGURE 25.10 Schematic illustration of a reconfigurable modular machining center capable of accommodating workpieces of different shapes and sizes, and requiring different machining operations on their various surfaces. *Source:* After Y. Koren.

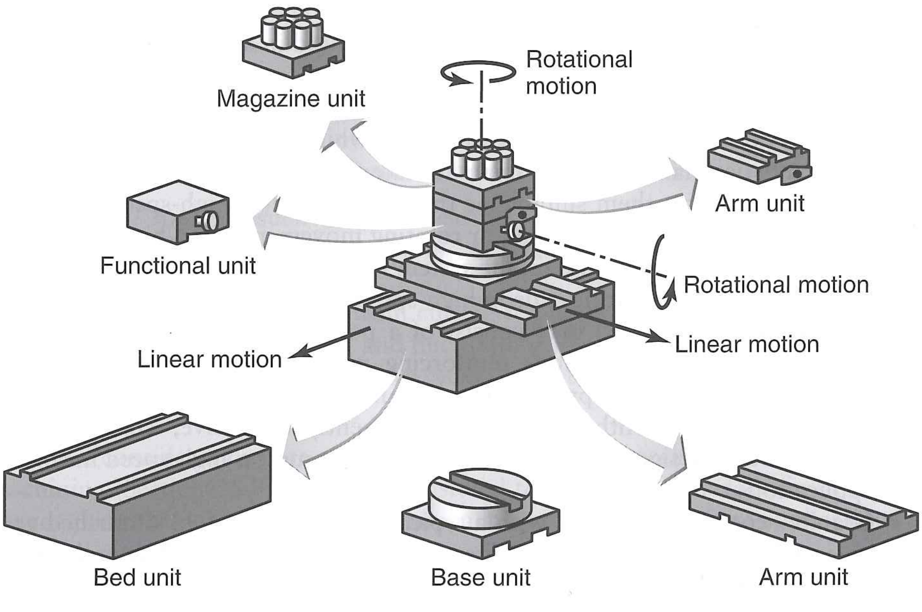


FIGURE 25.11 Schematic illustration of the assembly of different components of a reconfigurable machining center. *Source:* After Y. Koren.

Reconfigurable machines have the promise of (a) improving the productivity and efficiency of manufacturing operations, (b) reducing lead time for production, and (c) providing a cost-effective and rapid response to market demands (see also Chapter 39). These capabilities are significant, especially in view of the frequent introduction of new products into a highly competitive global marketplace, fluctuations in product demand and product mix, and unpredictable modifications in product design.

25.3 Machine-tool Structures

This section describes the materials and design aspects of machine-tool structures that are important in producing parts, with acceptable geometric features and dimensional and surface finish characteristics.

25.3.1 Materials

The following is a list of the materials that commonly have been used or are suitable for machine-tool structures.

- **Gray cast iron** was the first material used in machine-tool structures, and has the advantages of good damping capacity and low cost, but the disadvantage of being heavy. Most machine-tool structures are made of class 40 cast iron; some are made of class 50 (see Table 12.4).
- **Welded steel** structures (see Chapters 30 and 31) are lighter than cast-iron structures. Wrought steels, typically used in these structures, (a) are available in a wide range of section sizes and shapes, such as channels, angles, and tubes, (b) have good mechanical properties, (c) possess good manufacturing characteristics, such as formability, machinability, and weldability, and (d) have low cost. Structures made of steels can have high stiffness-to-weight ratios, by using cross-sections such as tubes and channels; in contrast, however, their damping capacity is very low.
- **Ceramic** components (Chapters 8 and 18) are used in advanced machine tools for their strength, stiffness, corrosion resistance, surface finish, and thermal stability. Ceramic components were first introduced in the 1980s. Spindles and bearings now can be made of silicon nitride, which has better friction and wear characteristics than traditional metallic materials. Furthermore, the low density of ceramics makes them suitable as the components of high-speed machinery that undergo rapid reciprocating or rotating movements, in which low inertial forces are desirable to maintain the system's stability, reduce inertial forces, and thus reduce the noncutting time in high-speed machining operations.
- **Composites** (Chapter 9) may consist of a polymer matrix, metal matrix, or ceramic matrix, with various reinforcing materials. The compositions can be tailored to provide appropriate mechanical properties in selected axes of the machine tool. Although they are presently expensive, composites are likely to become significant materials for high-accuracy, high-speed machining applications.
- **Granite–epoxy composites**, with a typical composition of 93% crushed granite and 7% epoxy binder, were first used in precision centerless and internal grinders in the early 1980s (see Section 26.4). These composite materials have several favorable properties: (a) good castability, thus allowing for design versatility in machine tools, (b) high stiffness-to-weight ratio, (c) thermal stability, (d) resistance to environmental degradation, and (e) good damping capacity.

- **Polymer concrete** is a mixture of crushed concrete and plastic (typically polymethylmethacrylate), and easily can be cast into desired shapes for machine bases and various components. Although it has low stiffness (about one-third that of class 40 cast iron) and poor thermal conductivity, polymer concrete has good damping capacity and also can be used for sandwich construction with cast irons, thus combining the advantages of each type of material. Plain concrete can be poured into cast-iron machine-tool structures, to increase their mass and improve their damping capacity. Filling the cavities of machine bases with loose sand also has been demonstrated to be an effective means of improving damping capacity.

25.3.2 Machine-tool Design Considerations

Important considerations in machine tools generally involve the following factors:

- Design, materials, and construction
- Spindle materials and type of construction
- Thermal distortion of machine components
- Error compensation and the control of moving components along slideways

Stiffness. Stiffness, which is a major factor in the dimensional accuracy of a machine tool, is a function of (a) the elastic modulus of the materials used and (b) the geometry of the structural components, including the spindle, bearings, drive train, and slideways. Machine stiffness can be enhanced by design improvements, such as using diagonally arranged interior ribs.

Damping. Damping is a critical factor in reducing or eliminating vibration and chatter in machining operations. Principally, it involves (a) the types of materials used and (b) the type and number of joints (such as welded versus bolted) in the machine-tool structure. Cast irons and polymer-matrix composites have much better damping capacity than metals or ceramics; also, the greater the number of joints in a machine structure, the more damping there is.

Thermal Distortion. An important factor in machine tools is the thermal distortion of their components, which contributes significantly to their lack of precision.

There are two sources of heat in machine tools:

1. *Internal sources*, such as from bearings, ballscrews, machine ways, spindle motors, pumps, and servomotors, as well as from the cutting zone during machining (Section 21.4).
2. *External sources*, such as from cutting fluids, nearby furnaces, heaters, other nearby machines, sunlight, and fluctuations in ambient temperature from such sources as air-conditioning units, vents, or even someone opening or closing a door or a window.

These considerations are significant, particularly in **precision** and **ultraprecision machining** (Section 25.7), where dimensional tolerances and surface finish are now approaching the nanometer range. The machine tool used for these applications are equipped with the following features:

- Various thermal and geometric real-time error-compensating features, including (a) the modeling of heating and cooling and (b) electronic compensation for accurate ballscrew positions

- Gas or fluid hydrostatic spindle bearings, allowing tools to more easily achieve precise motions without encountering high friction or stick-slip phenomenon (Section 33.4)
- New designs for traction or friction drives, for smoother linear motion
- Extremely fine feed and position controls, using microactuators
- Fluid-circulation channels in the machine-tool base, for maintaining thermal stability

The structural components of the machine tool can be made of materials with high dimensional stability and low coefficient of thermal expansion, such as Super-Invar (Section 3.6), granite, ceramics, and composites. *Retrofitting* also is a viable option for enhancing the performance of older machines.

Assembly Techniques for Machine-tool Components. Traditionally, machine-tool components have been assembled using threaded fasteners and by welding (Part VI). Advanced assembly techniques now include integral casting and resin bonding. Steel guideways, with their higher stiffness, can be cast integrally over a cast-iron bed, using a hybrid casting technology. *Resin bonding* is being used to assemble machine tools, replacing mechanical fastening. Adhesives, described in Section 32.4, have favorable characteristics for machine-tool construction, as they do not require special preparation and are suitable for assembling both nonmetallic and metallic machine components.

Guideways. The preparation of guideways in machine tools traditionally has required significant effort. The plain cast-iron ways in machines, which is the most common material, require much care to achieve the required precision and service life. The movements of various components in a machine tool, along its various axes, usually have utilized high-precision *ballscrews*, *rotating-screw drives*, and *rotary motors*. This system of mechanical and electrical components has several unavoidable design characteristics, such as speed limitations, length restrictions, inertia effects, gear backlash and other errors, wear of the components, and low efficiency. Modern controls can compensate for these characteristics to achieve higher precision as discussed above.

Linear Motor Drives. A *linear motor* is like a typical rotary electric motor that has been rolled out (opened) flat. This is the same principle used in some high-speed ground transportation systems in which the cars are levitated by magnetic forces (Maglev). The sliding surfaces in these drives are separated by an air gap and, as a result, have very low friction and energy loss.

Linear motor drives in machine tools have important advantages:

- Simplicity and minimal maintenance, since there is one moving part and no mechanical linkages
- Smooth operation, better positioning accuracy, and repeatability, at as low as submicron ranges
- A wide range of linear speeds, from 1 μm/s to 5 m/s
- Acceleration rates of about 1–2 g (10–20 m/s^2), and as high as 4–10 g for smaller units
- The moving components do not undergo any wear, because there is no physical contact between the sliding surfaces of the machine

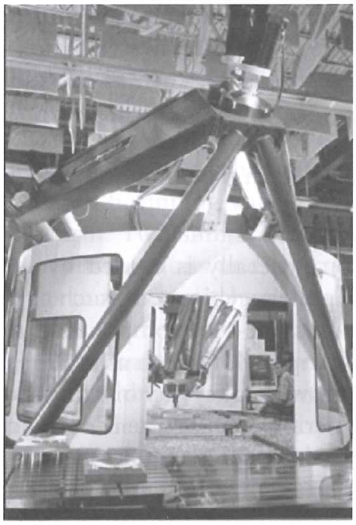
Machine Foundations. Foundation materials, their mass, and the manner in which they are installed in a plant are important considerations, as they help reduce vibration and do not adversely affect the performance of nearby machinery in the plant. For example, in the installation of a special grinder for high-precision grinding of 2.75-m diameter marine-propulsion gears, the concrete foundation was 6.7 m deep. Its large mass, combined with the machine base, reduced the amplitude of vibrations. Even better results can be obtained when a machine is installed on an *independent* concrete slab, that is isolated from the rest of the plant floor with shock-isolation devices.

25.3.3 Hexapod Machines

Developments in the design and materials used for machine-tool structures and their various components are taking place continually, with the purposes of (a) imparting machining flexibility to machine tools, (b) increasing their machining envelope (the space within which machining can be done), and (c) making them lighter. A truly innovative machine-tool structure is a self-contained octahedral (eight-sided) machine frame.

Referred to as **hexapods** (Fig. 25.12) or *parallel kinematic linked machines*, these machines have a design that is based on a mechanism called the *Stewart platform* (after D. Stewart), developed in 1966 and first used to position aircraft cockpit simulators. The main advantage of this system is that the links in the hexapod are loaded axially, thus the bending forces and lateral deflections are minimal, resulting in a very stiff structure.

The workpiece is mounted on a stationary table. Three pairs of *telescoping tubes* (called *struts* or *legs*), each with its own motor and equipped with ballscrews, are used to maneuver a rotating cutting-tool holder. While various features and curved surfaces are being machined, the controller automatically shortens some tubes and extends others, so that the cutter can follow a specified path around the workpiece. Six sets of coordinates are involved in these machines (hence the term *hexapod*, meaning "six legged"): three linear sets and three rotational sets. Every motion of the cutter,



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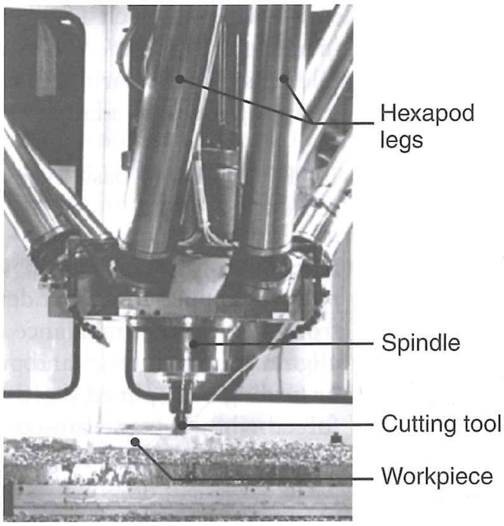

(b)

FIGURE 25.12 (a) A hexapod machine tool, showing its major components. (b) A detailed view of the cutting tool in a hexapod machining center. *Source:* Courtesy of National Institute of Standards and Technology.

even a simple linear motion, is translated into six coordinated leg lengths, moving in real time. The motions of the legs are rapid; consequently, high accelerations and decelerations, with resulting high inertial forces, are involved.

These machines (a) have high stiffness, (b) are not as massive as machining centers, (c) have about one-third fewer parts than machining centers, (d) have a large machining envelope (hence greater access to the work zone), (e) are capable of maintaining the cutting tool perpendicular to the surface being machined (thus improving the machining operation), and (f) have high flexibility (with six degrees of freedom) in the production of parts with various geometries and sizes, without the need to refixture the work in progress. Unlike most machine tools, these are basically portable; in fact, *hexapod attachments* are now available so that a conventional machining center can easily be converted into a hexapod machine.

A limited number of hexapod machines have been built. In view of their potential as efficient machine tools, their performance is being evaluated continually regarding stiffness, thermal distortion, friction within the struts, dimensional accuracy, speed of operation, repeatability, and reliability.

25.4 Vibration and Chatter in Machining Operations

In describing machining processes and machine tools, it was noted on several occasions that *machine stiffness* is as important as any other parameter in machining. Low stiffness can cause *vibration* and *chatter* of the cutting tools and the machine components, and thus can have adverse effects on product quality. Vibration and chatter in machining are complex phenomena, and will be reviewed here briefly as a guide.

Uncontrolled vibration and chatter can result in:

- Poor surface finish, as shown in the right central region of Fig. 25.13
- Loss of dimensional accuracy of the workpiece
- Premature wear, chipping, and failure of the cutting tool, a critical consideration with brittle tool materials, such as ceramics, some carbides, and diamond
- Possible damage to the machine-tool components, from excessive vibration
- Objectionable noise, particularly if it is of high frequency, such as the squeal heard when turning brass on a lathe

There are two basic types of vibration in machining: forced and self-excited.

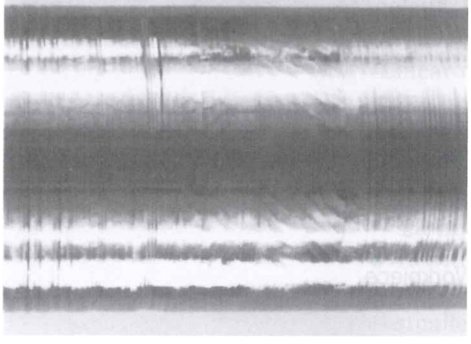

FIGURE 25.13 Chatter marks (right of center of photograph) on the surface of a turned part. *Source:* Courtesy of General Electric Company.

Forced Vibration. Forced vibration generally is caused by some *periodic* applied force that develops in the machine tool, such as that from gear drives, imbalance of the machine-tool components, misalignment, and motors and pumps. In operations such as the milling or turning of a splined shaft, or a shaft with a keyway or radial hole, forced vibrations are caused by the periodic engagement of the cutting tool with the workpiece surface (see, for example, Figs. 24.9 and 24.14).

The basic solution to forced vibration is to *isolate* or remove the forcing element. For example, if the forcing frequency is at or near the natural frequency of a machine-tool system component, one of these two frequencies may be raised or lowered. The amplitude of vibration can be reduced by increasing the stiffness or by damping the system.

The cutting parameters generally do not appear to greatly influence the magnitude of forced vibrations; however, changing the cutting speed and the tool geometry can be helpful. It is also recognized that the source of vibrations can be minimized by changing the configuration of the machine-tool components, as may be done when the driving forces are close to, or act through, the *center of gravity* of a particular component. This approach will reduce the bending moment on the component, thus reducing deflections and improving dimensional accuracy.

Self-excited Vibration. Generally called **chatter**, self-excited vibration is caused by the interaction of the chip-removal process with the structure of the machine tool. Self-excited vibrations usually have a very high amplitude, and are audible. Chatter typically begins with a disturbance in the cutting zone, such as by (a) the type of chips produced, (b) inhomogeneities in the workpiece material or its surface condition, and (c) variations in the frictional conditions at the tool–chip interface, as influenced by cutting fluids and their effectiveness.

The most important type of self-excited vibration is **regenerative chatter**, which is caused when a tool is cutting a surface that has a roughness or geometric disturbances developed from the previous cut (e.g., see Figs. 21.2 and 21.21). Thus, the depth of cut varies, and the resulting variations in the cutting force subject the tool to vibrations; the process continues repeatedly, hence the term *regenerative*. This type of vibration easily can be observed while driving a car over a rough road, the so-called *washboard effect*.

Self-excited vibrations generally can be controlled by:

- Increasing the *stiffness* and, especially, the *dynamic stiffness* of the system; the system includes not only the tool, tool holder, machine frame, etc., but also the *workpiece* and how it is supported
- *Damping* the system

Dynamic stiffness is defined as the ratio of the applied-force amplitude to the vibration amplitude. For example, recall that in the trepanning operation, shown in Fig. 23.23b, there are four machine components involved in the deflections that would cause vibrations: (a) spindle, (b) supporting arm for the cutting tool, (c) drill, and (d) cutting tool.

Experience and analysis of the system would indicate that, unless all of the machine components are sufficiently stiff, the trepanning operation likely will lead to chatter, beginning with torsional vibration around the spindle axis and twisting of the arm. Two similar examples are (a) long and slender drills that may undergo torsional vibrations and (b) cutting tools that are long or are not well supported, such as that shown schematically in Fig. 23.3.

Factors Influencing Chatter. It has been observed that the tendency for chatter during machining is proportional to the cutting forces and the depth and width of the cut. Because cutting forces increase with strength (hence with hardness of the workpiece material), the tendency to chatter generally increases as hardness increases. Thus, aluminum and magnesium alloys, for example, have a lower tendency to chatter than do martensitic and precipitation-hardening stainless steels, nickel alloys, and high-temperature and refractory alloys.

Another important factor in chatter is the type of chip produced during cutting operations. Continuous chips involve basically steady cutting forces, and such chips generally do not cause chatter; discontinuous chips and serrated chips (Fig. 21.5), on the other hand, may do so. These types of chips are produced periodically, and the resulting force variations during cutting can thus cause chatter. Other factors that may contribute to chatter are the use of dull tools or cutters, lack of cutting fluids, and worn machine-tool ways and components.

Damping. *Damping* is defined as the rate at which vibrations decay. This effect can be demonstrated on an automobile's shock absorbers, by pushing down on the car's front or rear end and observing how rapidly the vertical motion stops. Damping is a major factor in controlling machine-tool vibration and chatter; it consists of internal and external damping:

1. **Internal damping** results from the *energy loss* in materials during vibration; for example, composite materials have a higher damping capacity than gray cast iron, as shown in Fig. 25.14. The difference in the damping capacity of materials can easily be observed by striking them with a gavel and listening to the sound. For example, try striking a brass cymbal, a piece of concrete, and a piece of wood, and listen to the variations in their sound.

   Bolted joints in the structure of a machine tool also are a source of damping, their effectiveness depending on size, location, and the number of joints. Because friction dissipates energy, small relative movements along dry (unlubricated) joints increase damping. Because machine tools consist of a number of large and small components, assembled by various means, this type of damping is cumulative. Note in Fig. 25.15, for example, how overall damping increases as the number of components on a lathe and their contact areas increase. However, the overall stiffness of the machine tool will decrease as the number of joints increases. As described and illustrated in Fig. 23.17b, damping also can be accomplished by mechanical means, whereby energy is dissipated by the frictional resistance of the components within the structure of a boring bar.
2. **External damping** is accomplished with external dampers, similar to shock absorbers on automobiles or machinery. Special vibration absorbers have been developed and installed on machine tools for this purpose. Machinery can be installed on specially prepared floors and foundations to isolate forced vibrations, such as those from nearby machines on the same floor.

Guidelines for Reducing Vibration and Chatter. It is evident from the foregoing discussion that a balance must be achieved between the increased stiffness of a machine tool and the desirability of increased damping, particularly in the

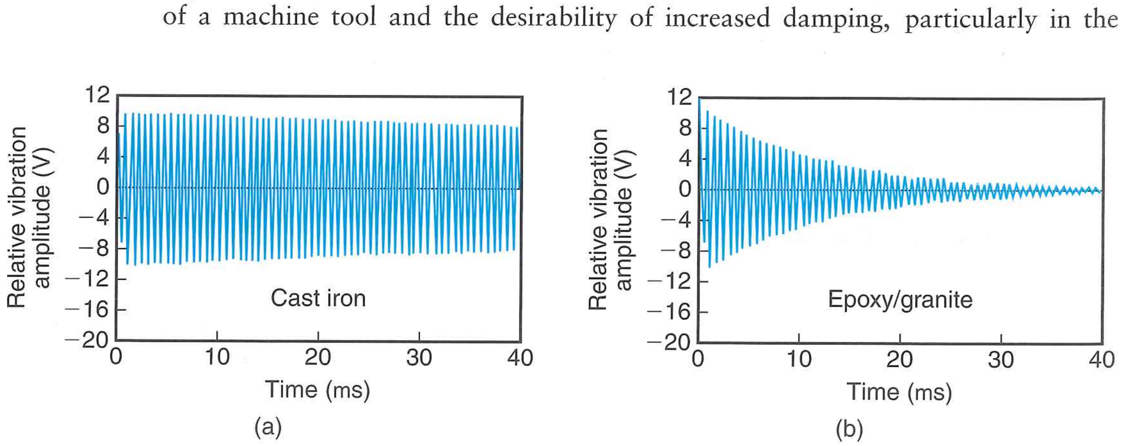

FIGURE 25.14 The relative damping capacity of (a) gray cast iron and (b) an epoxy–granite composite material. The vertical scale is the amplitude of vibration and the horizontal scale is time.

construction of high-precision machine tools. In various sections of Chapters 23 and 24, several guidelines were given for reducing vibration and chatter in machining operations. These basic guidelines may be summarized as:

- Minimize tool overhang
- Improve the stiffness of work-holding devices and support workpieces rigidly
- Modify tool and cutter geometry to minimize forces
- Change process parameters, such as cutting speed, feed, depth of cut, and cutting fluids
- Increase the stiffness of the machine tool and its components by improving their design, and by using larger cross-sections and materials with a higher elastic modulus
- Improve the damping capacity of the machine tool

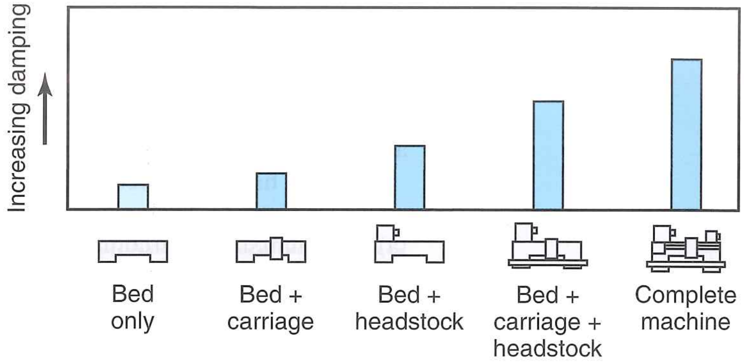

FIGURE 25.15 The damping of vibrations as a function of the number of components on a lathe. Joints dissipate energy; the greater the number of joints, the higher is the damping capacity of the machine. (See also Fig. 23.2.) *Source:* After J. Peters.

25.5 High-speed Machining

With continuing demands for higher productivity and lower production costs, the continuing trends are for increasing the cutting speed and the material-removal rate in machining operations, particularly in the aerospace and automotive industries.

The term "high" in *high-speed machining* (HSM) is somewhat relative; as a general guide, however, an approximate range of cutting speeds may be defined as:

1. **High speed:** 600–1800 m/min
2. **Very high speed:** 1800–18000 m/min
3. **Ultrahigh speed:** Higher than 18,000 m/min

Spindle rotational speeds in machine tools now range up to 50,000 rpm, although the automotive industry generally has limited them to 15,000 rpm for better reliability and less downtime should a failure occur. The *spindle power* required in high-speed machining is generally on the order of 0.004 W/rpm much less than in traditional machining, which typically is in the range from 0.2 to 0.4 W/rpm. Feed rates in high-speed machining are now up to 1 m/s and the acceleration rates of machine-tool components are very high.

Spindle designs for high speeds require *high stiffness* and *accuracy*, and generally involve an integral electric motor. The armature is built onto the shaft, and the stator is placed in the wall of the spindle housing. The bearings may be rolling elements or hydrostatic; the latter is more desirable because it requires less space than does the former. Because of *inertia* during the acceleration and deccelaration of machine-tool components, the use of lightweight materials, including ceramics and composite materials, is an important consideration.

The selection of appropriate cutting-tool materials is always a major consideration. On the basis of the discussions of tools and their selection in Chapter 22, and especially by reviewing Table 22.2, it is apparent that, depending on the workpiece material, multiphase coated carbides, ceramics, cubic-boron nitride, and diamond are all candidate tool materials for high-speed operations.

It also is important to note that high-speed machining should be considered primarily for operations in which **cutting time** is a significant portion of the total time in the overall machining operation. As described in Section 38.6 and Chapter 40, **noncutting time** and various other factors are important considerations in the overall assessment of the benefits of high-speed machining.

Studies have indicated that high-speed machining is economical for certain specific applications. As successful examples, it has been implemented in machining (a) aluminum structural components for aircraft; (b) submarine propellers 6 m in diameter, made of a nickel–aluminum–bronze alloy, and weighing 55,000 kg and (c) automotive engines, with 5–10 times the productivity of traditional machining. High-speed machining of complex three- and five-axis contours has been made possible by advances in CNC control technology, as described regarding *machining centers* in this chapter and in Chapter 37.

Another major factor in the adoption of high-speed machining has been the requirement to further improve dimensional tolerances. Note in Fig. 21.14 that as the cutting speed increases, a large percentage of the heat generated is removed by the chip, with the tool and the workpiece remaining closer to ambient temperature. This is beneficial, because there is no significant thermal expansion and thus warping of the workpiece during machining.

The important considerations in high-speed machining are summarized as:

1. Spindle design, for stiffness, accuracy, and balance at very high rotational speeds
2. Fast feed drives
3. Inertia of the components of the machine tool
4. Selection of appropriate cutting tools
5. Processing parameters and their computer control
6. Work-holding devices, which can withstand high centrifugal forces
7. Chip-removal systems, which are effective at very high rates of material removal

25.6 Hard Machining

It has been noted that as the hardness of the workpiece increases, its machinability decreases, and tool wear and fracture, surface finish, and surface integrity can become significant problems. However, it is still possible to machine hard metals and alloys by selecting an appropriate hard tool material and using machine tools with high stiffness, power, and precision.

An example is the finish machining of heat-treated steel (45–65 HRC) shafts, gears, pinions, and various automotive components, using polycrystalline cubic-boron nitride (PcBN), cermet, or ceramic cutting tools. Called *hard machining* or *hard turning*, this operation produces machined parts with good dimensional accuracy, surface finish (of as low as 25 μm), and surface integrity. The important factors are the (a) available power, (b) static and dynamic stiffness of the machine tool and its spindle, and (c) work-holding devices and fixturing.

As described in Section 25.3, trends in the design and construction of modern machine tools, especially for hard machining, include the use of hydrostatic bearings for the spindles and slideways. The headstock and the slanted bed in the machines (see Fig. 23.11a) can be made of *epoxy–granite composite materials*, which have unique properties, such as high stiffness-to-weight ratio, thermal stability, and good damping capacity. Cutting-tool selection and edge preparation also are important to avoid premature failure in hard machining.

From technical, economic, and ecological considerations, hard turning has been found to compete successfully with the *grinding* process (Chapter 26). For instance, in some specific cases, hard turning has been shown to be three times faster than grinding, requiring fewer operations to finish the part, and utilizing five times less energy. A detailed comparative example of hard turning versus grinding is presented in Example 26.4.

25.7 Ultraprecision Machining

Beginning in the 1960s, increasing demands have been made concerning the precision manufacturing of components for computer, electronic, nuclear, and defense applications. Some specific examples include optical mirrors and lenses, fiber optic connection components, computer memory disks, metrology equipment of all kinds, and drums for photocopying machines. Surface-finish requirements are in the nanometer (10^{-9} m) range, and dimensional tolerances and shape accuracies are in the micrometer (μm) and submicrometer range.

The trend toward ultraprecision manufacturing continues to grow. Modern **ultraprecision machine tools**, with advanced computer controls, can now position a cutting tool within an accuracy approaching 1 nm, as can be seen from Fig. 25.16. Also, note in this figure that higher precision is now being achieved by such processes as abrasive machining, ion-beam machining, and molecular manipulation.

The cutting tool for *ultraprecision machining* applications is almost exclusively a single-crystal diamond, where the process is called **diamond turning**. The diamond tool has a polished cutting edge, with a radius as small as a few nanometers. Wear of the diamond can be a significant problem, and more recent advances include **cryogenic diamond turning**, in which the tooling system is cooled by liquid nitrogen, to a temperature of about −120°C.

The workpiece materials for ultraprecision machining include copper alloys, aluminum alloys, silver, gold, electroless nickel, infrared materials, and plastics (acrylics). With depths of cut in the nm range, hard and brittle materials produce continuous chips, in a process known as **ductile-regime cutting** (see Section 26.3.4); deeper cuts in brittle materials produce discontinuous chips.

The machine tools for ultraprecision machining are built with very high precision and high stiffness of the machine, spindle, and work-holding devices. These machines have components that are made of structural materials with low thermal expansion and good dimensional stability (see Section 25.3). They are located in a dust-free environment (*clean rooms*; Section 28.2), where the temperature is controlled to within a fraction of one degree.

Vibrations from internal machine sources, as well as from external sources such as nearby machines on the same floor, must be avoided. Laser metrology (Section 35.5) is used for feed and position control, and

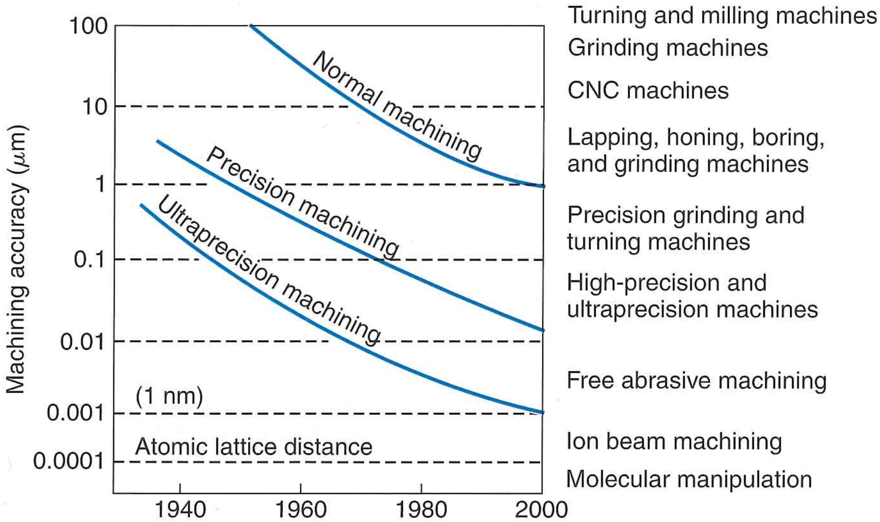

FIGURE 25.16 Improvements in machining accuracy over the years, using ultraprecision machining technologies. *Source:* After C.J. McKeown, N. Taniguchi, G. Byrne, D. Dornfeld, and B. Denkena.

the machines are equipped with highly advanced computer-control systems and with thermal and geometric error-compensating features.

General Considerations for Precision Machining. There are several important factors in precision and ultraprecision machining and machine tools, somewhat similar to those in high-speed machining:

1. Machine-tool design, construction, and assembly, including the spindle, must provide stiffness, damping, and geometric accuracy
2. Motion control of various machine components, both linear and rotational
3. Thermal expansion of the machine tool, compensation for thermal expansion, and control of the machine-tool environment, especially ambient temperature
4. Real-time performance and control of the machine tool, and implementation of a tool-condition monitoring system

25.8 Machining Economics

The material and process parameters that are relevant to efficient machining operations have been described in the preceding three chapters. In analyzing the *economics* of machining, several other factors also have to be considered. These factors include the costs involved in (a) the machine tools, work-holding devices and fixtures, and cutting tools; (b) labor and overhead associated with indirect costs; (c) the time required in setting up the machine for a particular operation; (d) material handling and movement, such as loading the blank and unloading the machined part; (e) gaging for dimensional accuracy and surface finish; and (f) cutting times and noncutting times.

Actual machining time is an important consideration, and recall also the discussion in Section 25.5 regarding the role of noncutting time in high-speed machining. Thus, unless noncutting time is a significant portion of the floor-to-floor time, high-speed machining should not be considered, unless it has other benefits.

Economic analysis is based on the ability to achieve a desired outcome, such as tolerance and surface finish, and, as such, requires that a machining process be robust and under control (see Section 36.5.1). For example, if a milling cutter is mounted such that the exposed spindle length varies randomly with every tool change, then this alone could result in high tolerances. The same analysis for different machine tools, whose dynamic stiffness and damping ability may differ (see Section 25.3), the use of cutters with different numbers of inserts, or loss of ambient temperature control, etc., all can result in variations that can significantly affect the ability to machine accurately.

Full-factorial design of experiments can be used to characterize the machine-tool/workpiece/operator system, but this approach is complex and has its own limitations. This section will assume that a process has been carefully designed to be robust, so that variations in these contributing factors can be ignored, and the effect of cutting speed on economics and productivity can be explored.

Minimizing Machining Cost per Piece. As in all manufacturing processes and operations, the relevant parameters in machining can be selected and specified in such a manner that the *machining cost per piece*, as well as *machining time per piece*, is minimized. Various methods and approaches have been developed over the years to accomplish this goal, a task that has now become easier with the increasing use of computers and user-friendly software. In order for the results of the methods used to be reliable, however, it is essential that input data be accurate and up to date.

Described next is one of the simpler and more commonly used methods of analyzing machining costs and uses a *turning* operation to demonstrate the approach.

In machining a part by turning, the total machining cost per piece, C_p, is

$$C_p = C_m + C_s + C_l + C_t, \tag{25.1}$$

where

C_m = Machining cost
C_s = Cost of setting up for machining, including mounting the cutter, setting up fixtures, and preparing the machine tool for the operation
C_l = Cost of loading, unloading, and machine handling
C_t = Tooling cost, often only about 5% of the total machining operation; consequently, using the least expensive tool is not necessarily the proper way of reducing machining costs

The **machining cost** is given by

$$C_m = T_m (L_m + B_m), \tag{25.2}$$

where T_m is the machining time per piece, L_m is the labor cost of production personnel per hour, and B_m is the *burden rate*, or *overhead charge*, of the machine, including depreciation, maintenance, and indirect labor.

The **setup cost** is a fixed figure in dollars per piece. The **loading, unloading,** and **machine-handling cost** is

$$C_l = T_l (L_m + B_m), \tag{25.3}$$

where T_l is the time involved in loading and unloading the part, in changing speeds and feed rates, and making any other adjustments before machining. The **tooling cost** is

$$C_t = \frac{1}{N_i}\left[T_c (L_m + B_m) + D_i\right] + \frac{1}{N_f}\left[T_i (L_m + B_m)\right], \tag{25.4}$$

where N_i is the number of parts machined per cutting tool insert, N_f is the number of parts that can be produced per insert edge, T_c is the time required to change the insert, T_i is the time required to index the insert, and D_i is the depreciation of the insert, in dollars.

The time required to machine one part is

$$T_p = T_l + T_m + \frac{T_c}{N_i} + \frac{T_i}{N_f}, \tag{25.5}$$

where T_m has to be calculated for each particular operation on the part. For example, let's consider a turning operation, where the machining time (see Section 23.2) is given by

$$T_m = \frac{L}{fN} = \frac{\pi LD}{fV}, \tag{25.6}$$

where L is the length of cut, f is the feed, N is the angular speed (rpm) of the workpiece, D is the workpiece diameter, and V is the cutting speed. (Note that appropriate units must be used in all these equations.)

From Eq. (21.25) for tool life we have

$$T = \left(\frac{C}{V}\right)^{1/n}, \tag{25.7}$$

where T is the time, in minutes, required to reach a flank wear of certain dimension, after which the tool has to be reground or changed. Note that the tool may have to be replaced due to other reasons as well, such as crater wear, built-up edge, or nose wear. This analysis is restricted to *flank wear* as the important tool-failure criterion, but could be made more elaborate to include other variables. The number of pieces machined per insert edge follows from the Taylor equation, Eq. 21.25, as

$$N_f = \frac{T}{T_m}, \tag{25.8}$$

and the number of pieces per insert is given by

$$N_i = mN_f = \frac{mT}{T_m}. \tag{25.9}$$

Sometimes not all of the edges are used before the insert is discarded; thus, it should be recognized that m corresponds to the number of edges that are actually used, not the number provided per insert. Combining Eqs. (25.6) through (25.9) yields

$$N_i = \frac{mfC^{1/n}}{\pi LDV^{(1/n)-1}}. \tag{25.10}$$

The cost per piece, C_p in Eq. (25.1), can now be defined in terms of several variables. To find the optimum cutting speed and the optimum tool life for **minimum cost**, C_p must be differentiated with respect to V and set to zero. Thus,

$$\frac{\partial C_p}{\partial V} = 0. \tag{25.11}$$

The *optimum cutting speed*, V_o, is

$$V_o = \frac{C\,(L_m + B_m)^n}{\left(\dfrac{1}{n} - 1\right)^n \left\{\dfrac{1}{m}\left[T_c\,(L_m + B_m) + D_i\right] + T_i\,(L_m + B_m)\right\}^n} \tag{25.12}$$

and the *optimum tool life*, T_o, is

$$T_o = \left(\frac{1}{n} - 1\right)\frac{\dfrac{1}{m}\left[T_c\,(L_m + B_m) + D_i\right] + T_i\,(L_m + B_m)}{L_m + B_m}. \tag{25.13}$$

To find the optimum cutting speed and the optimum tool life for **maximum production**, T_p must be differentiated with respect to V and set to zero. Thus,

$$\frac{\partial T_p}{\partial V} = 0. \tag{25.14}$$

The **optimum cutting** speed then is

$$V_o = \frac{C}{\left[\left(\dfrac{1}{n} - 1\right)\left(\dfrac{T_c}{m} + T_i\right)\right]^n}, \tag{25.15}$$

and the **optimum tool life** is

$$T_o = \left(\frac{1}{n} - 1\right)\left(\frac{T_c}{m} + T_i\right). \tag{25.16}$$

Qualitative plots of *minimum cost per piece* and *minimum time per piece* (hence the *maximum production rate*) are given in Figs. 25.17a and b. It should be noted that the cost of machining a part also depends on the surface finish required; the additional cost increases rapidly with finer surface finish, as shown in Fig. 26.35.

The preceding analysis indicates the importance of identifying all relevant parameters in a machining operation, determining various cost factors, obtaining relevant tool-life curves for the particular operation, and properly measuring the various time intervals involved in the overall operation. The importance of obtaining accurate data is shown in Fig. 25.17; note that small changes in cutting speed can have a significant effect on the minimum cost or minimum time per piece. The speeds

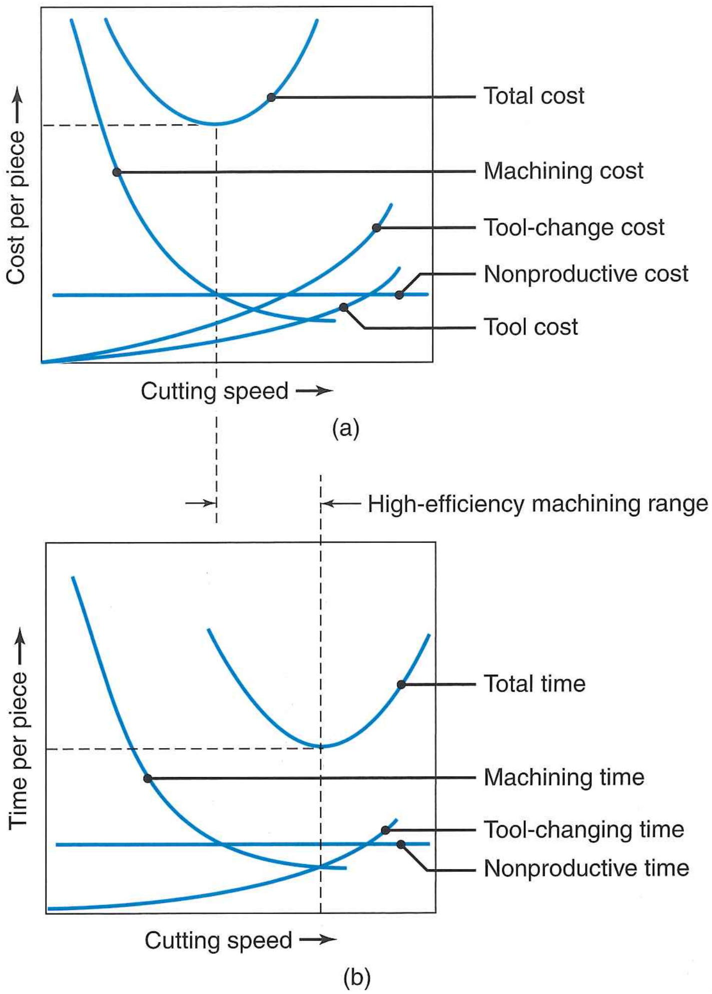

FIGURE 25.17 Graphs showing (a) cost per piece and (b) time per piece in machining; note the optimum speeds for both cost and time. The range between the two is known as the *high-efficiency machining range*.

and feeds recommended in Tables 23.4 and 24.2 generally lie in the *high-efficiency machining range*, which is between the speeds that yield the highest economy and highest production rate.

For many applications, such as finish machining of surfaces on soft metal castings, the machining cost per piece is fairly insensitive to cutting speed within this range; that is, the curve in Fig. 25.17 is fairly flat. With difficult-to-machine materials, however, as are routinely encountered in the medical products and aerospace industries, the cost per piece is very sensitive to cutting speed. Consequently, greater care is taken to ensure that machining takes place near the desired speed. Moreover, it should be recognized that the data given in Tables 23.4 and 24.2 are a summary for various tool and material grades; specific data is often available for machining particular alloys.

Such an economic analysis is typically done for all manufacturing operations, and it also can be a valuable tool for guiding process selection. For example, the cost per part in a sand-casting process to produce blanks, and in a machining operation to achieve final dimensional tolerances, can be calculated from an equation similar to Eq. (25.1), but including costs associated with sand casting, such as the cost of mold production, pattern depreciation, etc. A similar calculation can be made on a processing approach that uses powder metallurgy (thus increasing die and machinery costs), but requires less machining because of its ability to produce net-shape parts and with tighter tolerances, thereby reducing machining costs. A comparison of cost estimates can then help determine a processing strategy, as discussed in greater detail in Section 40.9.

SUMMARY

- Because they are versatile and capable of performing a variety of machining operations on small or large workpieces of various shapes, machining centers are now among the most important machine tools. Their selection depends on such factors as part complexity, the number and type of machining operations to be performed, the number of cutting tools required, and the dimensional accuracy and production rate specified.
- Vibration and chatter in machining are important considerations for workpiece dimensional accuracy, surface finish, and tool life. Stiffness and damping capacity of machine tools are major factors in controlling vibration and chatter.
- The economics of machining operations depends on factors such as nonproductive costs, machining costs, tool-change costs, and tool costs. Optimum cutting speeds can be determined for both minimum machining time per piece and minimum machining cost per piece.

KEY TERMS

Automatic pallet changer
Automatic tool changer
Chatter
Chip collection
Damping
Dynamic stiffness
Forced vibration
Hard machining
Hexapods
High-efficiency machining range
High-speed machining
Machining center
Modular construction
Pallet
Reconfigurable machines
Regenerative chatter
Self-excited vibration
Stiffness
Tool-exchange arm
Tool- and part-checking station
Touch probes
Turning center
Ultraprecision machining
Universal machining center
Work envelope