Manufacturing Engineering and Technology

SIXTH EDITION

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Part I of this text begins by describing the behavior and engineering properties of materials, their manufacturing characteristics, and their applications, as well as their advantages and limitations that would influence their selection in the design and manufacture of products.

In order to emphasize the importance of the topics to be described, let's look at a typical automobile as an example of a common product that utilizes a wide variety of materials, as shown in Fig. I.1. These materials were selected primarily because, not only did they possess the desired properties and characteristics for the intended functions of specific parts, but also they were the ones that could be manufactured at the lowest cost.

For example, steel was chosen for much of the body because it is strong, easy to shape, and inexpensive. Plastics were used in many components because of characteristics such as light weight, resistance to corrosion, a wide selection of colors, and ease of manufacturing into complex shapes and at low cost. Glass was chosen for all the windows not only because it is transparent, but also because it is

![Diagram of a car showing various materials used](image-url)

**Figure I.1** Some of the metallic and nonmetallic materials used in a typical automobile.
hard (hence scratch resistant), easy to shape, and easy to clean. Numerous similar observations can be made about each component of an automobile, ranging from small screws to wheels. In recent years, fuel economy and the need for improved performance have driven the substitution of materials, such as aluminum, magnesium, and plastics for steel, and the use of composite materials for structural (load-bearing) components.

As stated in the General Introduction, the selection of materials for individual components in a product requires a thorough understanding of their properties, functions, and manufacturing costs. A typical automobile is an assemblage of some 15,000 parts; consequently, by saving just one cent on the cost per part, such as by selecting a different material or manufacturing process, the cost of an automobile would be reduced by $150. The task of engineers thus becomes very challenging, especially with the ever-increasing variety of materials that are now available, as outlined in Fig. I.2.

A general outline of the topics described in Part I is given in Fig. I.3. The fundamental knowledge presented on the behavior, properties, and characteristics of materials will help the reader understand their relevance to the manufacturing processes described in Parts II through IV. This knowledge will also make it possible for us to analyze the often complex interrelationships among materials, manufacturing processes, machinery and tooling, and the economics of manufacturing operations.

FIGURE I.2 An outline of the engineering materials described in Part I.
FIGURE 1.3 An outline of the behavior and the manufacturing properties of materials described in Part I.
As described throughout the rest of this book, several different methods are available to shape metals into useful products. One of the oldest processes is casting, which basically involves pouring molten metal into a mold cavity. Upon solidification, the metal takes the shape of the cavity. Examples of cast parts are shown in Figure II.1. Casting first was used around 4000 B.C. to make ornaments, arrowheads, and various other objects. A wide variety of products can be cast, and the process is capable of producing intricate shapes in one piece, including those with internal cavities, such as engine blocks. Figure II.2 shows cast components in a typical automobile, a product that was used in the introduction to Part I to illustrate the selection and use of a variety of materials. The casting processes developed over the years are shown in Fig. II.3.

**FIGURE II.1** Examples of cast parts. (a) A die-cast aluminum transmission housing. (b) A tree of rings produced through investment casting. *Source:* (a) Courtesy of North American Die Casting Association, (b) Courtesy of Romanoff, Inc.
Cast parts in a typical automobile.

Outline of metal-casting processes described in Part II.

As in all manufacturing operations, each casting process has its own characteristics, applications, advantages, limitations, and costs. Casting processes are most often selected over other manufacturing methods for the following reasons:

Casting can produce complex shapes and can incorporate internal cavities or hollow sections.
Very large parts can be produced in one piece.
Casting can utilize materials that are difficult or uneconomical to process by other means.
The casting process can be economically competitive with other manufacturing processes.

Almost all metals can be cast in (or nearly in) the final shape desired, often requiring only minor finishing operations. This capability places casting among the most important *net-shape manufacturing* technologies, along with net-shape forging (Chapter 14), stamping of sheet metal (Chapter 16), and powder metallurgy and metal-injection molding (Chapter 17). With modern processing techniques and the control of chemical composition, mechanical properties of castings can equal those made by other manufacturing processes.
We generally tend to take for granted many of the products that we use today and the materials and components from which they are made. However, when we inspect these products, we soon realize that a wide variety of materials and processes has been used in making them (Fig. III.1). Note also that some products consist of a few parts (mechanical pencils, light bulbs), while others consist of thousands of parts (automobiles, computers) or even millions of parts (airplanes, ships). Some products have simple shapes with smooth curvatures (ball bearings, bicycle handles), but others have complex configurations (engine blocks, pumps) and detailed surface features (coins, silverware). Some products are used in critical applications (elevator cables, turbine blades), whereas others are used in routine applications (paper clips, forks, knives). Some products are very thin (aluminum foil, plastic film), whereas others are very thick (ship hulls, boiler plates).

Note that the words forming and shaping are both used in the title of this part of the book. Although there are not always clear distinctions between the two terms, “forming” generally indicates changing the shape of an existing solid body. Thus, in

**FIGURE III.1** Formed and shaped parts in a typical automobile.
forming processes, the starting material (usually called the workpiece, stock, or blank) may be in the shape of a plate, sheet, bar, rod, wire, or tubing of various cross sections. For example, an ordinary wire coat hanger is made by forming a straight piece of wire by bending and twisting it into the shape of a hanger. As another example, the metal body for an automobile typically is made of cold-rolled, flat steel sheet which is then formed into various shapes (hood, roof, trunk, door panels) using a pair of large dies.

Shaping processes typically involve the molding and casting of soft or molten materials, and the finished product is usually at or near the final desired shape. It may require little or no further finishing. A plastic coat hanger, for example, is made by forcing molten plastic into a two-piece mold with a cavity in the shape of the hanger. Telephone receivers, refrigerator-door liners, computer housings, and countless other plastic products likewise are shaped by forcing the molten polymer into a mold and letting it solidify. Some of the forming and shaping operations produce long continuous products, such as plates, sheets, tubing, wire, and bars with various cross sections. Rolling, extrusion, and drawing processes (Chapters 13 and 15) are capable of making such products, which then are cut into desired lengths. On the other hand, processes such as forging (Chapter 14), sheet metal forming and stamping (Chapter 16), powder metallurgy compaction (Chapter 17), ceramic slip casting and glass pressing (Chapter 18), and processes involving plastics and reinforced plastics (Chapter 19) typically produce discrete products.

The initial material used in forming and shaping metals is usually molten metal, which is cast into individual ingots or continuously cast into slabs, rods, or pipes. Cast structures are converted to wrought structures by plastic-deformation processes. The raw material used also may consist of metal powders, which then are pressed and sintered (heated without melting) into individual products. For plastics, the starting material is usually pellets, flakes, or powder, and for ceramics, it is clays and oxides obtained from ores or produced synthetically.

The important factors involved in each forming and shaping process are described in this part of the text, along with how material properties and processes affect product quality (Table III.1). We also explain why some materials can be processed only by certain manufacturing methods and why parts with particular shapes can be processed only by certain techniques and not by others. The characteristics of the machinery and the equipment used in these processes also significantly affect product quality, production rate, and the economics of a particular manufacturing operation.
### General Characteristics of Forming and Shaping Processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rolling</td>
<td>Production of flat plate, sheet, and foil at high speeds; good surface finish, especially in cold rolling; very high capital investment; low-to-moderate labor cost</td>
</tr>
<tr>
<td>Flat</td>
<td></td>
</tr>
<tr>
<td>Shape</td>
<td>Production of various structural shapes (such as I-beams and rails) at high speeds; includes thread rolling; requires shaped rolls and expensive equipment; low-to-moderate labor cost; requires moderate operator skill</td>
</tr>
<tr>
<td>Forging</td>
<td>Production of discrete parts with a set of dies; some finishing operations usually required; usually performed at elevated temperatures, but also cold for smaller parts; die and equipment costs are high; moderate-to-high labor cost; requires moderate-to-high operator skill</td>
</tr>
<tr>
<td>Extrusion</td>
<td>Production of long lengths of solid or hollow shapes with constant cross section; product is then cut into desired lengths; usually performed at elevated temperatures; cold extrusion has similarities to forging and is used to make discrete products; moderate-to-high die and equipment cost; low-to-moderate labor cost; requires low-to-moderate operator skill</td>
</tr>
<tr>
<td>Drawing</td>
<td>Production of long rod and wire with various cross sections; good surface finish; low-to-moderate die, equipment, and labor costs; requires low-to-moderate operator skill</td>
</tr>
<tr>
<td>Sheet-metal forming</td>
<td>Production of a wide variety of shapes with thin walls and simple or complex geometries; generally low-to-moderate die, equipment, and labor costs; requires low-to-moderate operator skill</td>
</tr>
<tr>
<td>Powder metallurgy</td>
<td>Production of simple or complex shapes by compacting and sintering metal powders; moderate die and equipment cost; low labor cost and skill</td>
</tr>
<tr>
<td>Processing of plastics and composite materials</td>
<td>Production of a wide variety of continuous or discrete products by extrusion, molding, casting, and fabricating processes; moderate die and equipment costs; requires high operator skill in processing of composite materials</td>
</tr>
<tr>
<td>Forming and shaping of ceramics</td>
<td>Production of discrete products by various shaping, drying, and firing processes; low-to-moderate die and equipment cost; requires moderate-to-high operator skill</td>
</tr>
</tbody>
</table>
Machining Processes and Machine Tools

Parts manufactured by the casting, forming, and shaping processes described in Parts II and III, including many parts made by near-net or net-shape methods, often require further operations before the product is ready for use. Consider, for example, the following features on parts and whether they could be produced by the processes discussed thus far:

- Smooth and shiny surfaces, such as the bearing surfaces of the crankshaft shown in Fig. IV.1.
- Small-diameter deep holes in a part such as the injector nozzle shown in Fig. IV.2.
- Parts with sharp features, a threaded section, and specified close dimensional tolerances, such as the part shown in Fig. IV.3.
- A threaded hole or holes on different surfaces of a part for mechanical assembly with other components.
- Special surface finishes and textures for functional purposes or for appearance.

A brief review will indicate that none of the forming and shaping processes described thus far is capable of producing parts with such specific characteristics and that the parts will require further manufacturing operations. **Machining** is a general term describing a group of processes that consist of the **removal** of material and **modification** of the surfaces of a workpiece after it has been produced by various methods. Thus, machining involves **secondary** and **finishing** operations.

The very wide variety of shapes produced by machining can be seen clearly in an automobile, as shown in Fig. IV.4. It also should be recognized that some parts may be produced to final shape (net shape) and at high quantities by forming and shaping processes, such as die casting and powder metallurgy. However, machining may be more economical, provided that the number of parts required is relatively small or the material and shape allow the parts to be machined at high rates and quantities and with high dimensional accuracy. A good example is the production of brass screw-machine parts on multiple-spindle automatic screw machines.

**FIGURE IV.1** A forged crankshaft before and after machining the bearing surfaces. The shiny bearing surfaces of the part on the right cannot be made to their final dimensions and surface finish by any of the processes described in previous chapters of this book. Source: Courtesy of Wyman-Gordon Company.
In general, however, resorting to machining suggests that a part could not have been produced to the final desired specifications by the primary processes used in making them and that additional operations are necessary. We again emphasize the importance of net-shape manufacturing, as described in Section 1.5, to avoid these additional steps and reduce production costs.

Furthermore, in spite of their advantages, material-removal processes have the following disadvantages:

- They waste material (although the amount may be relatively small).
- The processes generally takes longer than other processes.
- They generally require more energy than do forming and shaping operations.
- They can have adverse effects on the surface quality and properties of the product.

As outlined in Fig. 1.6e in the General Introduction, machining consists of several major types of material-removal processes:

- Cutting, typically involving single-point or multipoint cutting tools, each with a clearly defined shape (Chapters 23 through 25).
- Abrasive processes, such as grinding and related processes (Chapter 26).
- Advanced machining processes utilizing electrical, chemical, laser, thermal, and hydrodynamic methods to accomplish this task (Chapter 27).

The machines on which these operations are performed are called machine tools. As described throughout Part IV, their construction and characteristics greatly influence these operations, as well as product quality, surface finish, and dimensional accuracy.
As can be seen in Table 1.2 in the General Introduction, the first primitive tools (dating back many millennia) were made for the main purpose of chipping away and cutting all types of natural materials (such as wood, stone, vegetation, and livestock) for the purpose of food and shelter. Note also that it was in the 1500s that progress began on manufacturing products by machining operations, particularly with the introduction of lathes. We now have available a wide variety of computer-controlled machine tools and modern techniques (using various materials and energy sources) and are capable of making functional parts as small as tiny insects and with cross sections smaller than a human hair.

As in other manufacturing operations, it is important to view machining operations as a system, consisting of the

- Workpiece
- Cutting tool
- Machine tool, and
- Production personnel.

Machining cannot be carried out efficiently or economically and also meet stringent part specifications without a thorough knowledge of the interactions among these four elements.

In the next seven chapters, the basic mechanics of chip formation in machining are described: tool forces, power, temperature, tool wear, surface finish and integrity, cutting tools, and cutting fluids. We then discuss specific machining processes—their capabilities, limitations, and typical applications—and identify important machine-tool characteristics for operations such as turning, milling, boring, drilling, and tapping. The features of machining centers—versatile machine tools controlled by computers and capable of efficiently performing a variety of operations—also are described.

The next processes described are those in which the removal of material (to a very high dimensional accuracy and surface finish) is carried out by abrasive processes and related operations. Common examples are grinding, wheels, coated abrasives, honing, lapping, buffing, polishing, shot-blasting, and ultrasonic machining.

For technical and economic reasons, some parts cannot be machined satisfactorily by cutting or abrasive processes. Since the 1940s, important developments have taken place in advanced machining processes, such as chemical, electrochemical, electrical-discharge, laser-beam, electron-beam, abrasive-jet, and hydrodynamic machining.

The knowledge gained in Part IV will enable us to assess the capabilities and limitations of material-removal processes; machine tools and related equipment; their proper selection for maximum efficiency, productivity, and low cost; and how these processes fit into the broader scheme of manufacturing operations.
Micromanufacturing and Fabrication of Microelectronic Devices

In order to appreciate the importance of the topics covered in the two chapters in this part of the book, consider the manufacture of a simple spur gear made of metal. If the gear is 100 mm in diameter, it can be produced by traditional means, such as starting with a cast or forged blank and machining it, as described in various chapters. A gear that is 2 mm in diameter, however, can be difficult to produce to the desired dimensional accuracy. If sufficiently thin, the gear could be made from sheet metal by very fine blanking or chemical etching, or by electroforming. If the gear is only a few micrometers in size, it can be produced with techniques involving optical lithography, wet and dry chemical etching, and related processes described in the next two chapters. A gear that is only a few nanometers in diameter would be extremely difficult to produce; indeed, such a gear would, at most, have only a few tens of atoms across its surface. The challenges faced in producing gears of increasingly smaller sizes is highly informative and can be put into proper perspective by referring to the illustration of length scales shown in Fig. V.1.

For most of the engineering profession's history, engineers have emphasized the design and manufacture of relatively large components. Conventional manufacturing processes, described in Chapters 11 through 27, typically produce parts that are larger than a millimeter or so and can be described as visible to the naked eye. The size of such parts generally are referred to as macroscale, the word "macro" being derived from the Greek _makros_, meaning "long". The processing of such parts is known as _macromanufacturing_. Numerous examples can be given, ranging from products found in a hardware store, to castings and forgings used in machinery, and to products as large as automobiles, aircraft, and ships. Macroscale is the most developed and best understood size range from a design and manufacturing standpoint, with a wide variety of processes available for producing components of that size. Note that all of the examples and case studies given thus far in this book have been examples of macromanufacturing.

The gear shown in Fig. V.1 is the size of a few tens of micrometers across and fits into the realm of micromanufacture. Micromanufacturing, which by definition refers to manufacturing on a microscopic scale (that is, not visible to the naked eye), has been developed mostly for electronic devices of all kinds, including computer processors and memory chips, sensors, and magnetic storage devices. For the most part, this type of manufacturing relies heavily on lithography approaches, wet and dry etching, and coating operations. In addition, the micromanufacturing of semiconductors exploits the unique ability of silicon to form oxides.
Illustration of the regimes of macro-, meso-, micro-, and nanomanufacturing, the range of common sizes of parts, and the capabilities of manufacturing processes in producing those parts.

Examples of products that rely upon micromanufacturing approaches are a wide variety of sensors and probes (see Fig. V.2), ink-jet printing heads, microactuators and associated devices, magnetic hard-drive heads, and microelectronic devices such as computer processors and memory chips. Micromanufacturing methods allow the production of a wide variety of features at these length scales, but most experience is with electronic devices. Microscale mechanical devices are still a relatively new technology, but one that has developed with surprising speed.

Mesomanufacturing overlaps macro- and micromanufacturing, as seen by the illustrations given in Fig. V.1. Examples of mesomanufacturing are extremely small motors, bearings, and components for miniature devices such as hearing aids; medical devices such as stents and valves; and mechanical watches, with components exactly the same as the gear shown in Fig. V.1.
In nanomanufacturing, parts are produced at nanometer length scales, that is, one billionth of a meter and typically between $10^{-6}$ and $10^{-9}$ m in length. Many of the features in integrated circuits are at this length scale, but very little else; molecularly engineered medicines and other forms of biomanufacturing are the only commercial examples. However, it is now recognized that many physical and biological processes act at the nanoscale and that this approach holds much promise for future innovations.

This part of the book emphasizes micro- and nanomanufacturing. Although these subdisciplines within the broad range of manufacturing engineering are now over five decades old, they have developed rapidly in the past two decades or so. Products made by micro- or nanomanufacturing have become very pervasive in modern society. Computers, communications, video, and control hardware of all types depend upon these manufacturing and material approaches.

In Chapter 28, we describe the manufacture of silicon wafers and microelectronic devices, which include a wide variety of computer processors, memory devices, and integrated circuits. Communication, entertainment, control, transportation, engineering design and manufacturing, and medicine have been changed greatly by the ready availability of metal-oxide-semiconductor (MOS) devices, usually based on single-crystal silicon. Microelectronics is the best known and commercially important example of micromanufacturing, with some aspects of the applications exemplifying nanomanufacturing. The techniques used in packaging and assembling integrated circuits onto printed circuit boards also are presented.

The production of microscale devices that are mechanical and electrical in nature is described in Chapter 29. Depending on their level of integration, these devices are called micromechanical devices or microelectromechanical systems (MEMS). While the historical origins of MEMS manufacture stem from the same processes used for microelectronic systems and from identical processes and production sequences that are still used, several unique approaches have been developed for the manufacture of microscale electromechanical devices and systems.
Joining Processes and Equipment

When inspecting various common products, note that some products, such as paper clips, nails, steel balls for bearings, staples, screws and bolts, are made of only one component. Almost all products, however, are assembled from components that have been manufactured as individual parts. Even relatively simple products consist of at least two different components joined by various means. For example, (a) some kitchen knives have wooden or plastic handles that are attached to the metal blade with fasteners; (b) cooking pots and pans have metal, plastic, or wooden handles and knobs that are attached to the pot by various methods; and (c) the eraser of an ordinary pencil is attached with a brass sleeve.

On a much larger scale, observe power tools, washing machines, motorcycles, ships, and airplanes and how their numerous components are assembled and joined so that they not only can function reliably, but also are economical to produce. As shown in Table I.1 in the General Introduction, a rotary lawn mower has about 300 parts and a grand piano has 12,000 parts. A C-5A transport plane has more than 4 million parts, and a Boeing 747-400 aircraft has more than 6 million parts. A typical automobile consists of 15,000 components, some of which are shown in Fig. VI.1.

Joining is an all-inclusive term covering processes such as welding, brazing, soldering, adhesive bonding, and mechanical fastening. These processes are an essential

![Diagram showing various parts of a typical automobile assembled by processes described in Part VI.]

**FIGURE VI.1** Various parts in a typical automobile that are assembled by the processes described in Part VI.
and important aspect of manufacturing and assembly operations, for one or more of the following reasons:

Even a relatively simple product may be impossible to manufacture as a single piece. Consider, for example, the tubular construction shown in Fig. VI.2a. Assume that each of the arms of this product is 5 m (15 ft) long, the tubes are 100 mm (4 in.) in diameter, and their wall thickness is 1 mm (0.04 in.). After reviewing all of the manufacturing processes described in the preceding chapters, one would conclude that manufacturing this product in one piece would be impossible or uneconomical.

The product, such as a cooking pot with a handle, is easier and more economical to manufacture as individual components, which are then assembled into a product.

Products such as hair dryers, appliances, and automobile engines need to be designed to be able to be taken apart for maintenance or replacement of their parts.

Different properties may be desirable for functional purposes of the product. For example, surfaces subjected to friction, wear, corrosion, or environmental attack generally require characteristics that differ significantly from those of the component's bulk. Examples are (a) masonry drills with carbide cutting tips brazed to the shank of a drill (Fig. VI.2b), (b) automotive brake shoes, and (c) grinding wheels bonded to a metal backing (Section 26.2).

Transporting the product in individual components and assembling them later may be easier and less costly than transporting the completed item. Metal or wood shelving, large toys, and machinery are assembled after the components or subassemblies have been transported to the appropriate site.

Although there are different ways of categorizing the wide variety of available joining processes, we will follow the classification by the American Welding Society.

Examples of parts utilizing joining processes. (a) A tubular part fabricated by joining individual components. This product cannot be manufactured in one piece by any of the methods described in the previous chapters if it consists of thin-walled, large-diameter, tubular-shaped long arms. (b) A drill bit with a carbide cutting insert brazed to a steel shank—an example of a part in which two materials need to be joined for performance reasons. (c) Spot welding of automobile bodies. Source: (c) Courtesy of Ford Motor Co.
(AWS). Accordingly, joining processes fall into three major categories (see Figs. VI.3 and I.7f):

- Welding
- Adhesive bonding
- Mechanical fastening.

Table VI.1 lists the general relative characteristics of various joining processes. Welding processes, in turn, are generally classified into three basic categories:

- Fusion welding
- Solid-state welding
- Brazing and soldering.

As will be seen, some types of welding processes can be classified into both the fusion and the solid-state categories.

**Fusion welding** is defined as the *melting together and coalescing* of materials by means of heat, usually supplied by chemical or electrical means; filler metals may or may not be used. Fusion welding is composed of consumable- and nonconsumable-electrode arc welding and high-energy-beam welding processes. The welded joint undergoes important metallurgical and physical changes, which, in turn, have a major
### TABLE VI.1
Comparison of Various Joining Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Strength</th>
<th>Design</th>
<th>Small parts</th>
<th>Large parts</th>
<th>Tolerances</th>
<th>Reliability</th>
<th>Ease of manufacture</th>
<th>Ease of inspection</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arc welding</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Resistance welding</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Brazing</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Bolts and nuts</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Riveting</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Fasteners</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Seaming and crimping</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Adhesive bonding</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

*Note: 1 = very good; 2 = good; 3 = poor. For cost, 1 is the lowest.*

![Examples of joints](image)

**FIGURE VI.4** Examples of joints that can be made through the various joining processes described in Chapters 30 through 32.

Effect on the properties and performance of the welded component or structure. Some simple welded joints are shown in Fig. VI.4.

In **solid-state welding**, joining takes place without fusion; consequently, there is no liquid (molten) phase in the joint. The basic processes in this category are diffusion bonding and cold, ultrasonic, friction, resistance, and explosion welding. **Brazing** uses filler metals and involves lower temperatures than welding. **Soldering** uses similar filler metals (solders) and involves even lower temperatures.

**Adhesive bonding** has unique applications that require strength, sealing, thermal and electrical insulating, vibration damping, and resistance to corrosion between dissimilar metals. **Mechanical fastening** involves traditional methods of using various fasteners, especially bolts, nuts, and rivets. The joining of plastics can be accomplished by adhesive bonding, fusion by various external or internal heat sources, and mechanical fastening.
Surface Technology

Our first visual or tactile contact with the objects around us is through their surfaces. We can see or feel surface roughness, waviness, reflectivity, and other features, such as scratches, nicks, cracks, and discoloration. The preceding chapters described the properties of materials and manufactured components basically in terms of their bulk characteristics, such as strength, ductility, hardness, and toughness. Also included were some descriptions of the influences of surfaces on these properties—influences such as the effect of surface preparation on fatigue life and the sensitivity of brittle materials to surface scratches and defects.

Machinery and accessories have numerous members that slide against each other: slideways, bearings, tools and dies for cutting and forming, and pistons and cylinders. Close examination will reveal that (a) some of these surfaces are smooth while others are rough, (b) some are lubricated while others are dry, (c) some are subjected to heavy loads while others support light loads, (d) some are subjected to elevated temperatures while others are at room temperature, and (e) some surfaces slide against each other at high relative speeds while others move slowly.

In addition to possessing geometric features, a surface constitutes a thin layer on the bulk material. A surface's physical, chemical, metallurgical, and mechanical properties depend not only on the material and its processing history, but also on the environment to which the surface is exposed. The term surface integrity is used to describe the chemical, mechanical, and metallurgical characteristics of a surface.

Because of the various mechanical, physical, thermal, and chemical effects that result from its processing history, the surface of a manufactured part usually possesses properties and behavior that are significantly different from those of its bulk. Although the bulk material generally determines the component's overall mechanical properties, the component's surfaces directly influence the part's performance in the following areas (Fig. VII.1):

- Friction and wear of tools, molds, dies, and of the products made.
- Effectiveness of lubricants during the manufacturing process and throughout the part's service life.
- Appearance and geometric features of the part and their role in subsequent operations, such as welding, soldering, adhesive bonding, painting, and coating.
- Resistance to corrosion.
Crack initiation as a result of surface defects such as roughness, scratches, seams, and heat-affected zones, which can lead to weakening and premature failure of the part, through fatigue, for instance.

Thermal and electrical conductivity of contacting bodies. For example, rough surfaces have higher thermal and electrical resistances than smooth surfaces.

Following the outline shown in Fig. VII.2, this part of the book will present surface characteristics in terms of their structure and topography. The material and process variables that influence the friction and wear of materials will then be described. Several mechanical, thermal, electrical, and chemical methods can be used to modify surfaces for improved frictional behavior, effectiveness of lubricants, resistance to wear and corrosion, and surface finish and appearance.
The preceding chapters have described the techniques used to modify the surfaces of components and products to obtain certain desirable properties, discussing the advantages and limitations of each technique along the way. Although dimensional accuracies obtained in individual manufacturing processes were described, we have not yet described how parts are measured and inspected before they are assembled into products.

Dimensions and other surface features of a part are measured to ensure that it is manufactured consistently and within the specified range of dimensional tolerances. The vast majority of manufactured parts are components or a subassembly of a product, and they must fit and be assembled properly so that the product performs its intended function during its service life. For example, (a) a piston should fit into a cylinder within specified tolerances, (b) a turbine blade should fit properly into its slot on a turbine disk, and (c) the slideways of a machine tool must be produced with a certain accuracy so that the parts produced on that machine are accurate within their desired specifications.

Measurement of the relevant dimensions and features of parts is an integral aspect of interchangeable parts manufacturing, the basic concept behind standardization and mass production. For example, if a ball bearing in a machine is worn and has to be replaced, all one has to do is purchase a similar one with the same specification or part number. The same is now done with all products, ranging from bolts and nuts, to gears, to electric motors.

The first of the next two chapters describes the principles involved in, and the various instruments and modern machines used for, measuring dimensional features such as length, angle, flatness, and roundness. Testing and inspecting parts are important aspects of manufacturing operations; thus, the methods used for the nondestructive and destructive testing of parts are also described.

One of the most important aspects of manufacturing is product quality. Chapter 36 discusses the technological and economic importance of building quality into a product rather than inspecting the product after it is made, as has been done traditionally. This concept is even more significant in view of competitive manufacturing in a global economy.
Manufacturing in a Competitive Environment

In a highly competitive global marketplace for consumer and industrial goods, advances in manufacturing processes, machinery, tooling, and operations are being driven by goals that can be summarized as follows:

- Products must fully meet design and service requirements, specifications, and standards.
- Manufacturing activities must continually strive for higher levels of quality and productivity; quality must be built into the product at each stage of design and manufacture.
- Manufacturing processes and operations must have sufficient flexibility to respond rapidly to constantly changing market demands.
- The most economical methods of manufacturing must be explored and implemented.

Although numerical control of machine tools, beginning in the early 1950s, was a key factor in setting the stage for modern manufacturing, much of the progress in manufacturing activities stems from our ability to view these activities and operations as a large system with often complex interactions among all of its components. In implementing a systems approach to manufacturing, we can integrate and optimize various functions and activities that, for a long time, had been separate and distinct entities.

As the first of the four chapters in the final part of this book, Chapter 37 introduces the concept of automation and its implementation, in terms of key developments in numerical control and, later, in computer numerical control. This introduction is followed by a description of the advances made in automation and controls, involving major topics such as adaptive control, industrial robots, sensor technology, material handling and movement, and assembly systems and how they are all implemented in modern production.

Manufacturing systems and how their individual components and operations are integrated are described in Chapter 38, along with the critical role of computers and various enabling technologies as an aid in such activities as design, engineering, manufacturing, and process planning. The chapter also includes discussions on various enabling technologies, such as adaptive control, industrial robots, sensor technology, flexible fixturing, and assembly systems.
Computer-integrated manufacturing, with its various features, such as cellular manufacturing, flexible manufacturing systems, just-in-time production, lean manufacturing, and artificial intelligence, are then described in Chapter 39. Included also is the new concept of holonic manufacturing and the role and significance of communication networks.

The purpose of Chapter 40 is to highlight the importance of the numerous and often complex factors and their interactions that have a major effect on competitive manufacturing in a global marketplace. Among the factors involved are product design, quality, and product life cycle; selection of materials and processes and their substitution in economical production; process capabilities; and costs involved, including those of machinery, tooling, and labor.
General Introduction

1.1 What Is Manufacturing?

As you begin to read this chapter, take a few moments to inspect various objects around you: mechanical pencil, light fixture, chair, cell phone, and computer. You soon will note that all these objects, and their numerous individual components, are made from a variety of materials and have been produced and assembled into the items that you now see. You also will note that some objects, such as a paper clip, nail, spoon, and door key, are made of a single component. However, as shown in Table I.1, the vast majority of objects around us consist of numerous individual pieces that are built and assembled by a combination of processes called manufacturing.

The word manufacture first appeared in English in 1567 and is derived from the Latin manu factus, meaning “made by hand.” The word manufacturing first appeared in 1683, and the word production, which is often used interchangeably with the word manufacturing, first appeared sometime during the 15th century.

Manufacturing is concerned with making products. A manufactured product may itself be used to make other products, such as (a) a large press, to shape flat sheet metal into automobile bodies, (b) a drill, for producing holes, (c) industrial sawing machines, for making clothing at high rates, and (d) numerous pieces of machinery, to produce an endless variety of individual items, ranging from thin wire for guitars and electric motors to crankshafts and connecting rods for automotive engines (Fig. I.1).

Note that items such as bolts, nuts, and paper clips are discrete products, meaning individual items. By contrast, a roll of aluminum foil, a spool of wire, and metal or plastic tubing are continuous products, which are then cut into individual pieces of various lengths for specific purposes.

Because a manufactured item typically starts with raw materials, which are then subjected to a sequence of processes to make individual products, it has a certain value. For example, clay has some value as mined, but when it is made into a product such as cookware, pottery, an electrical insulator, or a cutting tool, value is added to the clay. Similarly, a nail has a value over and above the cost of the short piece of wire or rod from which it is made. Products such as computer chips, electric motors, and professional athletic shoes are known as high-value-added products.

A Brief History of Manufacturing. Manufacturing dates back to the period 5000–4000 B.C. (Table I.2), and thus, it is older than recorded history, the earliest forms of which were invented by the Sumerians around 3500 B.C. Primitive cave

EXAMPLES:

1.1 Incandescent Light Bulbs 6
1.2 Baseball Bats 17
1.3 U.S. Pennies 17
1.4 Saltshaker and Pepper Mill 26
1.5 Mold for Making Sunglasses Frames 28
TABLE 1.1

<table>
<thead>
<tr>
<th>Approximate Number of Parts in Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common pencil</td>
</tr>
<tr>
<td>Rotary lawn mower</td>
</tr>
<tr>
<td>Grand piano</td>
</tr>
<tr>
<td>Automobile</td>
</tr>
<tr>
<td>Boeing 747–400</td>
</tr>
</tbody>
</table>

FIGURE 1.1 Illustration of an automotive engine (the Duratec V-6), showing various components and the materials used in making them. Source: Courtesy of Ford Motor Company. Illustration by D. Kimball.

drawings, as well as markings on clay tablets and stone, needed (1) some form of a brush and some sort of “paint,” as in the prehistoric cave paintings in Lascaux, France, estimated to be 16,000 years old; (2) some means of scratching the clay tablets and baking them, as in cuneiform scripts and pictograms of 3000 B.C.; and (3) simple tools for making incisions and carvings on the surfaces of stone, as in the hieroglyphs in ancient Egypt.

The manufacture of items for specific uses began with the production of various household artifacts, which were typically made of either wood, stone, or metal. The materials first used in making utensils and ornamental objects included gold, copper, and iron, followed by silver, lead, tin, bronze (an alloy of copper and tin), and brass (an alloy of copper and zinc). The processing methods first employed involved mostly casting and hammering, because they were relatively easy to perform. Over the centuries, these simple processes gradually began to be developed into more and more complex operations, at increasing rates of production and higher levels of product quality. Note, for example, from Table 1.2 that lathes for cutting screw threads already were available during the period from 1600 to 1700, but it was not until some three centuries later that automatic screw machines were developed.
<table>
<thead>
<tr>
<th>Period</th>
<th>Dates</th>
<th>Metals and casting</th>
<th>Various materials and composites</th>
<th>Forming and shaping</th>
<th>Joining</th>
<th>Tools, machining, and manufacturing systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before 4000 B.C.</td>
<td></td>
<td>Gold, copper, meteoric iron</td>
<td>Earthenware, glazing, natural fibers</td>
<td>Hammering</td>
<td></td>
<td>Tools of stone, flint, wood, bone, ivory, composite tools</td>
</tr>
<tr>
<td>4000–3000 B.C.</td>
<td></td>
<td>Copper casting, stone and metal molds, lost-wax process, silver, lead, tin, bronze</td>
<td></td>
<td>Stamping, jewelry</td>
<td>Soldering (Cu–Au, Cu–Pb, Pb–Sn)</td>
<td>Corundum (alumina, emery)</td>
</tr>
<tr>
<td>3000–2000 B.C.</td>
<td></td>
<td>Bronze casting and drawing, gold leaf</td>
<td>Glass beads, potter's wheel, glass vessels</td>
<td>Wire by slitting sheet metal</td>
<td>Riveting, brazing</td>
<td>Hoe making, hammered axes, tools for ironmaking and carpentry</td>
</tr>
<tr>
<td>2000–1000 B.C.</td>
<td></td>
<td>Wrought iron, brass</td>
<td></td>
<td>Stamping of coins</td>
<td>Forging welding of iron and steel, gluing</td>
<td>Improved chisels, saws, files, woodworking lathes</td>
</tr>
<tr>
<td>1000–1 B.C.</td>
<td></td>
<td>Cast iron, cast steel</td>
<td>Glass pressing and blowing</td>
<td></td>
<td></td>
<td>Etching of armor</td>
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<tr>
<td>1–1000 A.D.</td>
<td></td>
<td>Zinc, steel</td>
<td>Venetian glass</td>
<td>Armor, coining, forging, steel swords</td>
<td></td>
<td>Sandpaper, windmill driven saw</td>
</tr>
<tr>
<td>1000–1500</td>
<td></td>
<td>Blast furnace, type metals, casting of bells, pewter</td>
<td>Crystal glass</td>
<td>Wire drawing, gold- and silversmith work</td>
<td></td>
<td>Hand lathe for wood</td>
</tr>
<tr>
<td>1500–1600</td>
<td></td>
<td>Cast-iron cannon, tinplate</td>
<td>Cast plate glass, flint glass</td>
<td>Waterpower for metalworking, rolling mill for coinage strips</td>
<td></td>
<td>Boring, turning, screw-cutting lathe, drill press</td>
</tr>
<tr>
<td>1600–1700</td>
<td></td>
<td>Permanent-mold casting, brass from copper and metallic zinc</td>
<td>Porcelain</td>
<td>Rolling (lead, gold, silver), shape rolling (lead)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(continued)
### Historical Development of Materials, Tools, and Manufacturing Processes

<table>
<thead>
<tr>
<th>Period</th>
<th>Dates</th>
<th>Metals and casting</th>
<th>Various materials and composites</th>
<th>Forming and shaping</th>
<th>Joining</th>
<th>Tools, machining, and manufacturing systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Industrial Revolution: ~1780 to 1850</td>
<td>1700–1800</td>
<td>Malleable cast iron, crucible steel (iron bars and rods)</td>
<td>Window glass from slit cylinder, light bulb, vulcanization, rubber processing, polyester, styrene, celluloid, rubber extrusion, molding</td>
<td>Extrusion (lead pipe), deep drawing, rolling</td>
<td></td>
<td>Shaping, milling, copying lathe for gunstocks, turret lathe, universal milling machine, vitrified grinding wheel</td>
</tr>
<tr>
<td></td>
<td>1800–1900</td>
<td>Centrifugal casting, Bessemer process, electrolytic aluminum, nickel steels, babbitt, galvanized steel, powder metallurgy, open-hearth steel</td>
<td></td>
<td>Steam hammer, steel rolling, seamless tube, steel-rail rolling, continuous rolling, electroplating</td>
<td></td>
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</tr>
<tr>
<td>WWI</td>
<td>1900–1920</td>
<td>Automatic bottle making, bakelite, borosilicate glass</td>
<td></td>
<td>Tube rolling, hot extrusion</td>
<td>Oxyacetylene; arc, electrical-resistance, and thermit welding</td>
<td>Geared lathe, automatic screw machine, hobbing, high-speed-steel tools, aluminum oxide and silicon carbide (synthetic)</td>
</tr>
<tr>
<td></td>
<td>1920–1940</td>
<td>Die casting</td>
<td>Development of plastics, casting, molding, polyvinyl chloride, cellulose acetate, polyethylene, glass fibers</td>
<td></td>
<td>Coated electrodes</td>
<td>Tungsten carbide, mass production, transfer machines</td>
</tr>
<tr>
<td>WWII</td>
<td>1940–1950</td>
<td>Lost-wax process for engineering parts</td>
<td>Acrylics, synthetic rubber, epoxies, photosensitive glass</td>
<td>Extrusion (steel), swaging, powder metals for engineering parts</td>
<td>Submerged arc welding</td>
<td>Phosphate conversion coatings, total quality control</td>
</tr>
<tr>
<td></td>
<td>1950–1960</td>
<td>Ceramic mold, nodular iron, semiconductors, continuous casting</td>
<td>Acrylonitrile-butadiene-styrene, silicones, fluorocarbons, polyurethane, float glass, tempered glass, glass ceramics</td>
<td>Cold extrusion (steel), explosive forming, thermomechanical processing</td>
<td>Gas metal arc, gas tungsten arc, and electroslag welding; explosion welding</td>
<td>Electrical and chemical machining, automatic control</td>
</tr>
<tr>
<td>Period</td>
<td>Dates</td>
<td>Metals and casting</td>
<td>Various materials and composites</td>
<td>Forming and shaping</td>
<td>Joining</td>
<td>Tools, machining, and manufacturing systems</td>
</tr>
<tr>
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<tr>
<td></td>
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<td></td>
<td>Acetals, polycarbonate, cold forming of plastics, reinforced plastics, filament winding</td>
<td>Hydroforming, hydrostatic extrusion, electroforming</td>
<td>Plasma-arc and electron-beam welding, adhesive bonding</td>
<td>Titanium carbide, synthetic diamond, numerical control, integrated circuit chip</td>
</tr>
<tr>
<td>Space</td>
<td>1960–1970</td>
<td>Squeeze casting, single-crystal turbine blades</td>
<td></td>
<td></td>
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<tr>
<td>age</td>
<td></td>
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<td></td>
<td>1970–1990</td>
<td>Compacted graphite, vacuum casting, organically bonded sand, automation of molding and pouring, rapid solidification, metal-matrix composites, semisolid metalworking, amorphous metals, shape-memory alloys (smart materials), computer simulation</td>
<td>Adhesives, composite materials, semiconductors, optical fibers, structural ceramics, ceramic-matrix composites, biodegradable plastics, electrically conducting polymers</td>
<td>Precision forging, isothermal forging, superplastic forming, dies made by computer-aided design and manufacturing, net-shape forging and forming, computer simulation</td>
<td>Laser beam, diffusion bonding (also combined with superplastic forming), surfacemount soldering</td>
<td>Cubic boron nitride, coated tools, diamond turning, ultraprecision machining, computer-integrated manufacturing, industrial robots, machining and turning centers, flexible manufacturing systems, sensor technology, automated inspection, expert systems, artificial intelligence, computer simulation and optimization</td>
</tr>
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<tr>
<td></td>
<td>1990–2000s</td>
<td>Rheocasting, computer-aided design of molds and dies, rapid tooling, TRIP and TWIP steels</td>
<td>Nanophase materials, metal foams, advanced coatings, high-temperature superconductors, machinable ceramics, diamondlike carbon, carbon nanotubes</td>
<td>Rapid prototyping, rapid tooling, environmentally friendly metalworking fluids</td>
<td>Friction stir welding, lead-free solders, laser butt-welded (tailored) sheet-metal blanks, electrically conducting adhesives</td>
<td>Micro- and nano fabrication, LIGA (a German acronym for a process involving lithography, electroplating, and molding), dry etching, linear motor drives, artificial neural networks, six sigma, three-dimensional computer chips</td>
</tr>
<tr>
<td>Information age</td>
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</tbody>
</table>

Although ironmaking began in the Middle East in about 1100 B.C., a major milestone was the production of steel in Asia during the period 600–800 A.D. A wide variety of materials continually began to be developed. Today, countless metallic and nonmetallic materials with unique properties are available, including engineered materials and various advanced materials. Among the available materials are industrial or high-tech ceramics, reinforced plastics, composite materials, and nanomaterials that are now used in an extensive variety of products, ranging from prosthetic devices and computers to supersonic aircraft.

Until the Industrial Revolution, which began in England in the 1750s and is also called the First Industrial Revolution, goods had been produced in batches and required much reliance on manual labor in all phases of their production. The Second Industrial Revolution is regarded by some as having begun in the mid-1900s with the development of solid-state electronic devices and computers (Table I.2). Mechanization began in England and other countries of Europe, basically with the development of textile machinery and machine tools for cutting metal. This technology soon moved to the United States, where it continued to be further developed.

A major advance in manufacturing occurred in the early 1800s with the design, production, and use of interchangeable parts, conceived by the American manufacturer and inventor Eli Whitney (1765–1825). Prior to the introduction of interchangeable parts, much hand fitting was necessary because no two parts could be made exactly alike. By contrast, it is now taken for granted that a broken bolt can easily be replaced with an identical one produced decades after the original. Further developments soon followed, resulting in countless consumer and industrial products that we now cannot imagine being without.

Beginning in the early 1940s, several milestones were reached in all aspects of manufacturing, as can be observed by a detailed review of Table I.2. Note particularly the progress that has been made during the 20th century, compared with that achieved during the 40-century period from 4000 B.C. to 1 B.C.

For example, in the Roman Empire (ca. 500 B.C. to 476 A.D.), factories were available for the mass production of glassware; however, the methods used were generally very slow, and much manpower was involved in handling the parts and operating the machinery. Today, production methods have advanced to such an extent that (a) aluminum beverage cans are made at rates of more than 500 per minute, with each can costing about four cents to make, (b) holes in sheet metal are punched at rates of 800 holes per minute, and (c) incandescent light bulbs are made at rates of more than 2000 bulbs per minute (see Example I.1), each costing less than one dollar.

**EXAMPLE I.1 Incandescent Light Bulbs**

The first incandescent lamp was made by T.A. Edison (1847–1931) in New Jersey and was first lit in 1879. A typical bulb then had a life of only about 13.5 hours. Numerous improvements have since been made in both materials and production methods for making light bulbs, with the main purposes being increasing their life and reducing production costs. This example briefly describes the typical sequence of methods used in manufacturing incandescent light bulbs.

The basic components of an incandescent (meaning “glowing with heat”) light bulb are shown in Fig. I.2a. The light-emitting component is the filament, which, by the passage of current and due to its electrical resistance, is heated to incandescence to a temperature of 2200°–3000°C (4000°–5400°F). Edison’s first successful lamp had a carbon filament, although he and others also had experimented with carbonized paper and metals such as osmium, iridium,
FIGURE 1.2a Components of a common incandescent light bulb. Source: Courtesy of General Electric Company.

FIGURE 1.2b Manufacturing steps in making an incandescent light bulb. Source: Courtesy of General Electric Company.

and tantalum. However, none of these materials has the strength, resistance to high temperature, and long life as has tungsten (Section 16.8), which is now the most commonly used filament material.

The first step in manufacturing a light bulb is making the glass stem that supports the lead-in wires and the filament and connects them to the base of the bulb (Fig. 1.2b). All these components are positioned, assembled, and sealed while the glass is heated by gas flames. The filament is then attached to the lead-in wires. The filament is made by powder metallurgy techniques (Chapter 17), which involves first pressing tungsten powder into ingots and sintering it (heating it without its melting). Next, the ingot is shaped into round rods by rotary swaging (Section 14.4) and then drawing it through a set of dies into thin wire (Sections 15.8 and 15.10). The wire diameter for a 60-W, 120-V bulb is 0.045 mm (0.0018 in.). The diameter must be controlled precisely, because if it is only 1% less than the diameter specified, the life of the bulb would be
reduced by as much as 25% (because of the increased heat due to the higher electrical resistance of the wire).

Note from Fig. 1.2a, as well as by direct observation of a clear light bulb, that the filament wire is coiled; this is done in order to increase the light-producing capacity of the filament. The spacing between the coils must be precise, so as to prevent a localized buildup of heat that might short the filament during its use.

The completed stem assembly (called the mount) is transferred to a machine that lowers a glass bulb over the mount. Gas flames are used to seal the rim of the mount to the neck of the bulb. The air in the bulb is then exhausted through the exhaust tube (which is an integral part of the glass stem), and the bulb is either evacuated or filled with inert gas. For 40-W bulbs and higher, the gas used is typically a mixture of nitrogen and argon. The exhaust tube is then sealed. The filling gas must be pure, as otherwise the inside surfaces of the bulb will blacken. It has been observed that just one drop of water in the gas that is used for half a million bulbs will cause blackening in all of them.

The next step involves attaching the metal base to the glass bulb with a special cement. The machine that performs this operation also solders or welds the lead-in wires to the base, to provide the electrical connection. The lead-in wires are usually made of nickel, copper, or molybdenum, and the support wires are made of molybdenum (Section 6.8). The portion of the lead-in wire that is embedded in the stem is made from an iron–nickel alloy, which has essentially the same coefficient of thermal expansion as that of the glass (Table 3.1), as otherwise the thermal stresses that develop may cause cracking of the glass stem. The bulb base is generally made from aluminum, replacing the more expensive brass base that was used many years ago. To reduce friction and thus allow easy insertion of the bulb into a socket, the metal base is coated with a special compound.

Several types of glasses (Section 8.4) are used, depending on the bulb type. The bulbs are made by blowing molten glass into a mold (Section 18.3.3). The inside of the bulb either is left clear or is frosted (thus making it translucent), to better diffuse the light and to reduce glare.

1.2 Product Design and Concurrent Engineering

Product design involves the creative and systematic prescription of the shape and characteristics of an artifact to achieve specified objectives while simultaneously satisfying several constraints. Design is a critical activity, because it has been estimated that as much as 80% of the cost of product development and manufacture is determined by the decisions made in the initial stages of design. The product design process has been studied extensively; it is briefly introduced here because of the strong interactions between manufacturing and design activities.

Innovative approaches are essential in successful product design, as are clearly specified functions and a clear statement of the performance expected of the product, which may be new or a modified version of an existing product. The market for the product and its anticipated use(s) also must be clearly defined; this aspect involves the assistance of market analysts and sales personnel who will bring valuable and timely input to the manufacturer, especially regarding market trends.

The Design Process. Traditionally, design and manufacturing activities have taken place sequentially, as shown in Fig. 1.3a. This methodology may, at first, appear to be straightforward and logical; in practice, however, it is wasteful of resources. Consider the case of a manufacturing engineer who, for example, determines that, for a variety of reasons, it would be more desirable (a) to use a different material, such as a polymer or a ceramic, instead of a metal or (b) to use the same material, but in a different condition, such as a softer instead of a harder material or a
material with a smoother surface finish, or (c) to modify the design of a component in order to make it easier, faster, and less expensive to manufacture. Note that these decisions must take place at the material-specification stage (the sixth box from the top in Fig. I.3a).

Each of the modifications just described will necessitate a repeat of the design analysis stage (the third box from the top in Fig. I.3a) and the subsequent stages, to
ensure that the product will still meet all specified requirements and will function satisfactorily. A later change from, say, a forged to a cast component will likewise necessitate a repeat analysis. Such iterations obviously waste both time and the resources of a company.

**Concurrent Engineering.** Driven primarily by the consumer electronics industry, a continuing trend is taking place to bring products to the marketplace as rapidly as possible, so as to gain a higher percentage share of the market and thus higher profits. An important methodology aimed at achieving this end is concurrent engineering, which involves the product-development approach shown in Fig. I.3b. Note that, although this concept, also called simultaneous engineering, still has the same general product-flow sequence as in the traditional approach (Fig. I.3a), it now contains several deliberate modifications. From the earliest stages of product design and engineering, all relevant disciplines are now simultaneously involved. As a result, any iterations that may have to be made will require a smaller effort and thus result in much less wasted time than occurs in the traditional approach to design. It should be apparent that a critical feature of this approach is the recognition of the importance of communication among and within all disciplines.

Concurrent engineering can be implemented in companies large or small, which is particularly significant because 98% of all U.S. manufacturing companies have fewer than 500 employees. Such companies are generally referred to as small businesses. As an example of the benefits of concurrent engineering, one automotive company reduced the number of components in one of its engines by 30%, decreased the engine weight by 25%, and reduced its manufacturing time by 50%.

**Life Cycle.** In concurrent engineering, the design and manufacture of products are integrated with a view toward optimizing all elements involved in the life cycle of the product (see Section I.4). The life cycle of a new product generally consists of the following four stages:

1. Product start-up
2. Rapid growth of the product in the marketplace
3. Product maturity
4. Decline.

Consequently, life-cycle engineering requires that the entire life of a product be considered, beginning with the design stage and on through production, distribution, product use, and, finally, recycling or the disposal of the product.

**Role of Computers in Product Design.** Typically, product design first requires the preparation of analytical and physical models of the product for the purposes of visualization and engineering analysis. Although the need for such models depends on product complexity, constructing and studying these models have become highly simplified through the use of computer-aided design (CAD) and computer-aided engineering (CAE) techniques.

CAD systems are capable of rapid and complete analyses of designs, whether it be a simple shelf bracket or a shaft in large and complex structures. The Boeing 777 passenger airplane, for example, was designed completely by computers in a process known as paperless design, with 2000 workstations linked to eight design servers. Unlike previous mock-ups of aircraft, no prototypes or mock-ups were built and the 777 was constructed and assembled directly from the CAD/CAM software that had been developed.

Through computer-aided engineering, the performance of structures subjected, for example, to static or fluctuating loads or to temperature gradients also can be
simulated, analyzed, and tested, rapidly and accurately. The information developed is
stored and can be retrieved, displayed, printed, and transferred anytime and anywhere
within a company’s organization. Design modifications can be made and optimized
(as is often the practice in engineering, especially in the production of large structures)
directly, easily, and at any time.

Computer-aided manufacturing involves all phases of manufacturing, by utilizing
and processing the large amount of information on materials and processes gathered
and stored in the organization’s database. Computers greatly assist in organizing the
information developed and performing such tasks as (a) programming for numerical-
control machines and for robots for material-handling and assembly operations
(Chapter 37), (b) designing tools, dies, molds, fixtures, and work-holding devices
( Parts II, III, and IV), and (c) maintaining quality control ( Chapter 36).

On the basis of the models developed and analyzed in detail, product designers then
finalize the geometric features of each of the product’s components, including specifying
their dimensional tolerances and surface-finish characteristics. Because all components,
regardless of their size, eventually have to be assembled into the final product, dimen-
sional tolerances are a major consideration in manufacturing (Chapter 35). Indeed,
dimensional tolerances are equally important for small products as well as for car bodies
or airplanes. The models developed also allow the specification of the mechanical and
physical properties required, which in turn affect the selection of materials. (Section I.5).

Prototypes. A prototype is a physical model of an individual component or prod-
uct. The prototypes developed are carefully reviewed for possible modifications to
the original design, materials, or production methods. An important and continuously
evolving technology is rapid prototyping (RP, see Chapter 20). Using
CAD/CAM and various specialized technologies, designers can now make proto-
types rapidly and at low cost, from metallic or nonmetallic materials such as plastics
and ceramics.

Prototyping new components by means of traditional methods (such as casting,
forming, and machining) could cost an automotive company hundreds of millions of
dollars a year, with some components requiring a year or more to complete. Rapid
prototyping can significantly reduce costs and the associated product-development
times. Rapid-prototyping techniques are now advanced to such a level that they also
can be used for low-volume (in batches typically of fewer than 100 parts) economical
production of a variety of actual and functional parts to be assembled into products.

Virtual Prototyping. Virtual prototyping is a software-based method that uses
advanced graphics and virtual-reality environments to allow designers to view and
examine a part in detail. This technology, also known as simulation-based design,
uses CAD packages to render a part such that, in a 3-D interactive virtual environ-
ment, designers can observe and evaluate the part as it is being drawn and developed. Virtual prototyping has been gaining importance, especially because of the
availability of low-cost computers and simulation and analysis tools.

1.3 Design for Manufacture, Assembly,
Disassembly, and Service

Design for manufacture (DFM) is a comprehensive approach to integrating the de-
sign process with production methods, materials, process planning, assembly, test-
ing, and quality assurance. DFM requires a fundamental understanding of (1) the
characteristics, capabilities, and limitations of materials, manufacturing processes, machinery, equipment, and tooling and (2) variability in machine performance, dimensional accuracy and surface finish of the workpiece, processing time, and the effect of processing methods on product quality. Establishing quantitative relationships is essential in order to be able to analyze and optimize a design for ease of manufacturing and assembly at minimum product cost.

The concepts of design for assembly (DFA), design for manufacture and assembly (DFMA), and design for disassembly (DFD) are all important aspects of all manufacturing. Methodologies and computer software are now available for design for assembly, utilizing 3-D conceptual designs and solid models. Subassembly, assembly, and disassembly times and costs can now be minimized, while product integrity and performance are maintained. Experience has indicated that a product which is easy to assemble is usually also easy to disassemble.

Assembly is an important phase of manufacturing and requires a consideration of the ease, speed, and cost of putting together the numerous individual components of a product (Fig. 1.4). Assembly costs in manufacturing operations can be substantial, typically ranging from 20 to 60% of the total product cost. Disassembly of a product is an equally important consideration, for maintenance, servicing and recycling of individual components.

As described in Part VI, there are several methods of assembly of components, including the use of a wide variety of fasteners, adhesives, or joining techniques such as welding, brazing, or soldering. As is the case in all types of manufacturing, each of these operations has its own specific characteristics, assembly times, advantages and limitations, associated costs, and special design considerations. Individual parts may be assembled by hand or by a variety of automatic equipment and industrial robots. The choice depends on factors such as product complexity, the number of components to be assembled, the care and protection required to prevent damage to the surfaces of the parts, and the relative cost of labor compared with the cost of machinery required for automated assembly.

Design for Service. In addition to design for assembly and for disassembly, design for service is important in product design. Products often have to be disassembled to varying degrees in order to service and, if necessary, repair them. The design should take into account the concept that, for ease of access, components that are most likely to be in need of servicing be placed, as much as possible, at the outer layers of the product. This methodology can be appreciated by anyone who has had the experience of servicing machinery.

![Poor and Good Assembly](image)

**FIGURE 1.4** Redesign of parts to facilitate assembly. Source: After G. Boothroyd and P. Dewhurst.
1.4 Green Design and Manufacturing

In the United States alone, 9 million passenger cars, 300 million tires, 670 million compact fluorescent lamps, and more than 5 billion kilograms of plastic products are discarded each year. Every three months, industries and consumers discard enough aluminum to rebuild the U.S. commercial air fleet. Note that, as indicated subsequently, the term discarding implies that the products have reached the end of their useful life; it does not necessarily mean that they are wasted and dumped into landfills.

The particular manufacturing process and the operation of machinery can each have a significant environmental impact. Manufacturing operations generally produce some waste, such as:

a. Chips from machining and trimmed materials from sheet forming, casting, and molding operations.
b. Slag from foundries and welding operations.
c. Additives in sand used in sand-casting operations.
d. Hazardous waste and toxic materials used in various products.
e. Lubricants and coolants in metalworking and machining operations.
f. Liquids from processes such as heat treating and plating.
g. Solvents from cleaning operations.
h. Smoke and pollutants from furnaces and gases from burning fossil fuels.

The adverse effects of these activities, their damage to our environment and to the Earth’s ecosystem, and, ultimately, their effect on the quality of human life are now widely recognized and appreciated. Major concerns involve global warming, greenhouse gases (carbon dioxide, methane, and nitrous oxide), acid rain, ozone depletion, hazardous wastes, water and air pollution, and contaminant seepage into water sources. One measure of the adverse impact of human activities is called the carbon footprint, which quantifies the amount of greenhouse gases produced in our daily activities.

The term green design and manufacturing is now in common usage in all industrial activities, with a major emphasis on design for the environment (DFE). Also called environmentally conscious design and manufacturing, this approach considers all possible adverse environmental impacts of materials, processes, operations, and products, so that they can all be taken into account at the earliest stages of design and production.

These goals, which increasingly have become global, also have led to the concept of design for recycling (DFR). Recycling may involve one of two basic activities:

- Biological cycle: Organic materials degrade naturally, and in the simplest version, they lead to new soil that can sustain life. Thus, product design involves the use of (usually) organic materials. The products function well for their intended life and can then be safely discarded.
- Industrial cycle: The materials in the product are recycled and reused continuously. For example, aluminum beverage cans are recycled and reused after they have served their intended purpose. To demonstrate the economic benefits of this approach, it has been determined that producing aluminum from scrap, instead of from bauxite ore, reduces production costs by as much as 66% and reduces energy consumption and pollution by more than 90%.
One of the basic principles of design for recycling is the use of materials and product-design features that facilitate biological or industrial recycling. In the U.S. automotive industry, for example, about 75% of automotive parts (mostly metal) are now recycled, and there are continuing plans to recycle the rest as well, including plastics, glass, rubber, and foam. About 100 million of the 300 million discarded automobile tires are reused in various ways.

**Cradle-to-cradle Production.** A term coined in the 1970s and also called C2C, cradle-to-cradle production considers the impact of each stage of a product's lifecycle, from the time natural resources are mined and processed into raw materials, through each stage of manufacturing products, their use and, finally, recycling. Certification procedures for companies are now being developed for cradle-to-cradle production, as they have been for quality control (Section 40.4). Cradle-to-grave production, also called womb-to-tomb production, has a similar approach, but does not necessarily consider or take on the responsibility of recycling.

Cradle-to-cradle production especially emphasizes

1. Sustainable and efficient manufacturing activities, using clean technologies.
2. Waste-free production.
4. Reducing energy consumption.
5. Using renewable energy, such as wind and solar energy.
6. Maintaining ecosystems by minimizing the environmental impact of all activities.
7. Using materials and energy sources that are locally available, so as to reduce energy use associated with their transport, which, by and large, has an inherently high carbon footprint.
8. Continuously exploring the reuse and recycling of materials, thus perpetually trying to recirculate materials; also included is investigating the composting of materials whenever appropriate or necessary, instead of dumping them into landfills.

**Guidelines for Green Design and Manufacturing.** In reviewing the various activities described thus far, note that there are overarching relationships among the basic concepts of DFMA, DFD, DFE, and DFR. These relationships can be summarized as guidelines, now rapidly being accepted worldwide:

1. Reduce waste of materials, by refining product design, reducing the amount of materials used in products, and selecting manufacturing processes that minimize scrap (such as forming instead of machining).
2. Reduce the use of hazardous materials in products and processes.
3. Investigate manufacturing technologies that produce environmentally friendly and safe products and by-products.
4. Make improvements in methods of recycling, waste treatment, and reuse of materials.
5. Minimize energy use, and whenever possible, encourage the use of renewable sources of energy.
6. Encourage recycling by using materials that are a part of either industrial or biological cycling, but not both in the same product assembly. Ensure proper handling and disposal of all waste in the case of materials used that are not part of an industrial or biological cycle.
1.5 Selection of Materials

An increasingly wide variety of materials are now available, each type having its own (a) material properties and manufacturing characteristics, (b) advantages and limitations, (c) material and production costs, and (d) consumer and industrial applications (Part I). The selection of materials for products and their components is typically made in consultation with materials engineers, although design engineers may also be sufficiently experienced and qualified to do so. At the forefront of new materials usage are industries such as the aerospace and aircraft, automotive, military equipment, and sporting goods industries.

The general types of materials used, either individually or in combination with other materials, are the following:

- **Ferrous metals**: Carbon, alloy, stainless, and tool and die steels (Chapter 5)
- **Nonferrous metals**: Aluminum, magnesium, copper, nickel, titanium, superalloys, refractory metals, beryllium, zirconium, low-melting-point alloys, and precious metals (Chapter 6)
- **Plastics (polymers)**: Thermoplastics, thermosets, and elastomers (Chapter 7)
- **Ceramics, glasses, glass ceramics, graphite, diamond, and diamondlike materials** (Chapter 8)
- **Composite materials**: Reinforced plastics and metal-matrix and ceramic-matrix composites (Chapter 9)
- **Nanomaterials** (Section 8.8)
- **Shape-memory alloys** (also called **smart materials**), amorphous alloys, semiconductors, and superconductors (Chapters 6, 18 and 28).

As new developments continue, the selection of an appropriate material for a particular application becomes even more challenging. Also, there are continuously shifting trends in the substitution of materials, driven not only by technological considerations, but also by economics.

**Properties of Materials.** *Mechanical properties* of interest in manufacturing generally include strength, ductility, hardness, toughness, elasticity, fatigue, and creep resistance (Chapter 2). *Physical properties* are density, specific heat, thermal expansion and conductivity, melting point, and electrical and magnetic properties (Chapter 3). Optimum designs often require a consideration of a combination of mechanical and physical properties. A typical example is the strength-to-weight and stiffness-to-weight ratios of materials for minimizing the weight of structural members. Weight minimization is particularly important for aerospace and automotive applications, in order to improve performance and fuel economy.

*Chemical properties* include oxidation, corrosion, degradation, toxicity, and flammability. These properties play a significant role under both hostile (such as corrosive) and normal environments. *Manufacturing properties* indicate whether a particular material can be cast, formed, machined, joined, and heat treated with relative ease. As Table 1.3 illustrates, no one material has the same manufacturing characteristics. Another consideration is *appearance*, which includes such characteristics as color, surface texture, and feel, all of which can play a significant role in a product's acceptability by the public.

**Availability.** As will be emphasized throughout this book, the economic aspect of material selection is as important as technological considerations (Chapter 40). Thus, the availability of materials is a major concern in manufacturing. Furthermore, if materials are not available in the desired quantities, shapes, dimensions, and surface
### TABLE 1.3

<table>
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<th>Machinability</th>
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<td>Aluminum</td>
<td>E</td>
<td>F</td>
<td>E-G</td>
</tr>
<tr>
<td>Copper</td>
<td>G–F</td>
<td>F</td>
<td>G–F</td>
</tr>
<tr>
<td>Gray cast iron</td>
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<tr>
<td>White cast iron</td>
<td>G</td>
<td>VP</td>
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<td>Nickel</td>
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<td>Steels</td>
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</tr>
<tr>
<td>Zinc</td>
<td>E</td>
<td>D</td>
<td>E</td>
</tr>
</tbody>
</table>

*Note: E, excellent; G, good; F, fair; D, difficult; VP, very poor. The ratings shown depend greatly on the particular material, its alloys, and its processing history.*

texture, substitute materials or additional processing of a particular material may well be required, all of which can contribute significantly to product cost.

Reliability of supply is important in order to meet production schedules. In automotive industries, for example, materials must arrive at a plant at appropriate time intervals. (See also *just in time*, Section 1.7). Reliability of supply is also important, considering the fact that most countries import numerous raw materials. The United States, for example, imports most of the cobalt, titanium, chromium, aluminum, nickel, natural rubber, and diamond that it needs. Consequently, a country’s self-reliance on resources, especially energy, is an often-expressed political goal, but is challenging to achieve. Geopolitics (defined briefly as the study of the influence of a nation’s physical geography on its foreign policy) must thus be a consideration, particularly during periods of global hostility.

**Service Life.** We all have had the experience of a shortened service life of a product, which often can be traced to (a) improper selection of materials, (b) improper selection of production methods, (c) insufficient control of processing variables, (d) defective parts or manufacturing-induced defects, (e) poor maintenance, and (f) improper use of the product. Generally, a product is considered to have failed when it

- Stops functioning, due to the failure of one or more of its components, such as a broken shaft, gear, bolt, or turbine blade or a burned-out electric motor
- Does not function properly or perform within required specifications, due, for example, to worn gears or bearings
- Becomes unreliable or unsafe for further use, as in the erratic behavior of a switch, poor connections in a printed-circuit board, or delamination of a composite material.

Throughout various chapters, this text describes the types of failure of a component or a product resulting, for example, from (a) design deficiencies, (b) improper material selection, (c) incompatibility of materials in contact, which produces friction, wear, and galvanic corrosion, (d) defects in raw materials, (e) defects induced during manufacturing, (f) improper component assembly, and (g) improper product use.

**Material Substitution in Products.** For a variety of reasons, numerous substitutions are often made in materials, as evidenced by a simple inspection and comparison of common products such as home appliances, sports equipment, or automobiles. As a measure of the challenges faced in material substitution, consider the following examples: (a) metal vs. wooden handle for a hammer, (b) aluminum vs. cast-iron lawn
chair, (c) aluminum vs. copper wire, (d) plastic vs. steel car bumper, (e) plastic vs. metal toy, and (f) alloy steel vs. titanium submarine hull.

The two examples that follow give typical details of the major factors involved in material substitution in common products.

### EXAMPLE 1.2 Baseball Bats

Baseball bats for the major and minor leagues are generally made of wood from the northern white ash tree, a wood that has high dimensional stability, high elastic modulus and strength-to-weight ratio, and high shock resistance. Wooden bats can, however, break during their use and may cause serious injury. The wooden bats are made on semiautomatic lathes and then subjected to finishing operations for appearance and labeling. The straight uniform grain required for such bats has become increasingly difficult to find, particularly when the best wood comes from ash trees that are at least 45 years old.

For the amateur market and for high school and college players, aluminum bats (top portion of Fig. I.5) have been made since the 1970s as a cost-saving alternative to wood. The bats are made by various metalworking operations, described throughout Part III. Although, at first, their performance was not as good as that of wooden bats, the technology has advanced to a great extent. Metal bats are now made mostly from high-strength aluminum tubing, as well as other metal alloys. The bats are designed to have the same center of percussion (known as the sweet spot, as in tennis racquets) as wooden bats, and are usually filled with polyurethane or cork for improved sound damping and for controlling the balance of the bat.

Metal bats possess such desirable performance characteristics as lower weight than wooden bats, optimum weight distribution along the bat’s length, and superior impact dynamics. Also, as documented by scientific studies, there is a general consensus that metal bats outperform wooden bats.

![FIGURE I.5 Cross sections of baseball bats made of aluminum (top two) and composite material (bottom two).](image)

Developments in bat materials now include composite materials (Chapter 9) consisting of high-strength graphite and glass fibers embedded in an epoxy resin matrix. The inner woven sleeve (lower portion of Fig. I.5) is made of Kevlar fibers (an aramid), which add strength to the bat and dampen its vibrations. These bats perform and sound much like wooden bats.

*Source: Mizuno Sports, Inc.*

### EXAMPLE 1.3 U.S. Pennies

Billions of pennies are produced and put into circulation each year by the U.S. Mint. The materials used have undergone significant changes throughout history, largely because of periodic material shortages and the resulting fluctuating cost of appropriate raw materials. The following table shows the chronological development of material substitutions in pennies:

<table>
<thead>
<tr>
<th>Year Range</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1793–1837</td>
<td>100% copper</td>
</tr>
<tr>
<td>1837–1857</td>
<td>95% copper, 5% tin and zinc</td>
</tr>
<tr>
<td>1857–1863</td>
<td>88% copper, 12% nickel</td>
</tr>
<tr>
<td>1864–1962</td>
<td>95% copper, 5% tin and zinc</td>
</tr>
<tr>
<td>1943 (WW II years)</td>
<td>Steel, plated with zinc</td>
</tr>
<tr>
<td>1962–1982</td>
<td>95% copper, 5% zinc</td>
</tr>
<tr>
<td>1982–present</td>
<td>97.5% zinc, plated with copper</td>
</tr>
</tbody>
</table>
1.6 Selection of Manufacturing Processes

As will be described throughout this text, there is often more than one method that can be employed to produce a component for a product from a given material. The following broad categories of manufacturing methods are all applicable to metallic as well as nonmetallic materials:

a. Casting (Fig. I.6a): Expendable mold and permanent mold (Part II).

```
\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{casting_processes}
\caption{Schematic illustrations of various casting processes.}
\end{figure}
```
b. **Forming and shaping** (Figs. 1.6b through 1.6d): Rolling, forging, extrusion, drawing, sheet forming, powder metallurgy, and molding (Part III).

c. **Machining** (Fig. 1.6e): Turning, boring, drilling, milling, planing, shaping, broaching; grinding; ultrasonic machining; chemical, electrical, and electrochemical machining; and high-energy-beam machining (Part IV). This broad category also includes **micromachining** for producing ultraprecision parts (Part V).

d. **Joining** (Fig. 1.6f): Welding, brazing, soldering, diffusion bonding, adhesive bonding, and mechanical joining (Part VI).

e. **Finishing**: Honing, lapping, polishing, burnishing, deburring, surface treating, coating, and plating (Chapters 26 and 34).

f. **Microfabrication and nanofabrication**: Technologies that are capable of producing parts with dimensions at the micro (one-millionth of a meter) and nano (one-billionth of a meter) levels; fabrication of microelectromechanical

**FIGURE 1.6b** Schematic illustrations of various bulk-deformation processes.
systems (MEMS) and nanoelectromechanical systems (NEMS), typically involving processes such as lithography, surface and bulk micromachining, etching, LIGA, and various specialized processes (Chapters 28 and 29).

**Process Selection.** The selection of a particular manufacturing process or, more often, sequence of processes, depends on the geometric features of the parts to be produced, including the dimensional tolerances and surface texture required, and on numerous factors pertaining to the particular workpiece material and its manufacturing properties. To emphasize the challenges involved, consider the following two cases:

a. Brittle and hard materials cannot be shaped or formed without the risk of fracture, unless they are performed at elevated temperatures, whereas these materials can easily be cast, machined, or ground.
b. Metals that have been preshaped at room temperature become less formable during subsequent processing, which, in practice, is often required to complete the part; this is because the metals have become stronger, harder, and less ductile than they were prior to processing them further.

There is a constant demand for new approaches to production problems and, especially, for manufacturing cost reduction. For example, sheet-metal parts traditionally have been cut and fabricated using common mechanical tools such as punches and dies. Although still widely used, some of these operations are now being replaced by laser cutting, as shown in Fig. 1.7 on p. 24, thus eliminating the need for hard tools, which have only fixed shapes and can be expensive and time consuming to make.

The laser path in this cutting operation is computer controlled, thereby increasing the operation's flexibility and its capability of producing an infinite variety of
shapes accurately, repeatedly, and economically. However, because of the high heat involved in using lasers, the surfaces produced after cutting have very different characteristics (such as discoloration and a different surface texture) than those produced by traditional methods. This difference can have significant effects not only on the appearance of the material, but especially on its subsequent processing and in the
service life of the product. Moreover, the inherent flexibility of laser cutting is countered by the fact that it is a much slower operation than traditional punching.

In process selection, several factors can have a major role, such as the part size, shape complexity, and dimensional accuracy and surface finish required. For example,

- Flat parts and thin cross sections can be difficult to cast
- Complex parts generally cannot be shaped easily and economically by such metalworking techniques as forging, whereas, depending on the part size and the
level of complexity, the parts may be precision cast, fabricated from individual pieces, or produced by powder-metallurgy techniques.

- Dimensional tolerances and surface finish in hot-working operations are not as fine as those obtained in operations performed at room temperature (called cold working), because of the dimensional changes, distortion, warping, and surface oxidation that occur at the elevated temperatures involved.

The size of manufactured products, and the machinery and equipment involved in processing them, vary widely, ranging from microscopic gears and mechanisms of micrometer size, as illustrated in Fig. 1.8, to (a) the main landing gear for the Boeing 777 aircraft, which is 4.3 m (14 ft) high and includes three axles and six wheels; (b) the runner for the turbine for a hydroelectric power plant, which is 4.6 m (180 in.) in diameter and weighs 50,000 kg (110,000 lb); and (c) a large steam turbine rotor weighing 300,000 kg (700,000 lb).

**Process Substitution.** It is common practice in industry that, for a variety of reasons and after a review of all appropriate and applicable processes, a particular production method (that may have been employed in the past) may well have to be substituted with another. Consider, for example, the following products that can be produced by any of the sets of processes indicated: (a) cast vs. forged crankshaft, (b) stamped sheet-metal vs. forged or cast automobile wheels, (c) cast vs. stamped sheet-metal frying pan, (d) injection molded vs. extruded or cast polymer bracket, and (e) welded vs. riveted sheet-metal safety hood for a machine.

Many varieties of such products are widely available in the marketplace. However, a customer’s preference will depend on his or her particular needs, which include factors such as the product’s appeal to the customer, its cost, whether maintenance is required,
whether the product is for industrial or consumer use, the parameters to which the product will be subjected (such as temperatures and chemicals), and any environmental concerns that have to be addressed.

**Net-shape and Near-net-shape Manufacturing.** *Net-shape* and *near-net-shape manufacturing* together constitute an important methodology by which a part is made in only one operation at or close to the final desired dimensions, tolerances, and surface finish. The difference between net shape and near net shape is a matter of degree of how close the product is to its final dimensional characteristics.

The necessity for, and benefits of, net-shape manufacturing can be appreciated from the fact that, in the majority of cases, more than one additional operation is often necessary to produce the part. For example, a cast or forged gear or crankshaft generally will not have the necessary dimensional characteristics, thus requiring additional processing, such as machining or grinding. These additional operations can contribute significantly to the cost of a product.

Typical examples of net-shape manufacturing include precision casting (Chapter 11), forging (Chapter 14), forming sheet metal (Chapter 16), powder metallurgy and injection molding of metal powders (Chapter 17), and injection molding of plastics (Chapter 19).

**Ultraprecision Manufacturing.** Dimensional accuracies for some modern equipment and instrumentation are now reaching the magnitude of the atomic lattice. Various techniques, including the use of highly sophisticated technologies (see micromechanical and microelectromechanical device fabrication in Chapter 29), are rapidly being developed to attain such extreme accuracy. Also, mirrorlike surfaces on metals can now be produced by machining with a very sharp diamond with a nose radius of 250 micrometers as the cutting tool. The machine is highly specialized, with very high stiffness (to minimize deflections, as well as vibration and chatter, during machining) and is operated in a room where the ambient temperature is controlled to within 1°C in order to avoid thermal distortions of the machine.

**Types of Production.** The number of parts to be produced (e.g., the annual quantity) and the rate (number of pieces made per unit time) are important economic considerations in determining the appropriate processes and the types of machinery required. Note, for example, that light bulbs, beverage cans, fuel-injection nozzles, and hubcaps are produced in numbers and at rates that are much higher than those for jet engines and tractors.

Following is a brief outline of the general types of production, in increasing order of annual quantities produced:

a. **Job shops:** Small lot sizes, typically less than 100, using general-purpose machines such as lathes, milling machines, drill presses, and grinders, many now equipped with computer controls.

b. **Small-batch production:** Quantities from about 10 to 100, using machines similar to those in job shops.

c. **Batch production:** Lot sizes typically between 100 and 5000, using more advanced machinery with computer control.

d. **Mass production:** Lot sizes generally over 100,000, using special-purpose machinery, known as *dedicated machines*, and various automated equipment for transferring materials and parts in progress.
Example 1.4 Saltshaker and Pepper Mill

The saltshaker and pepper mill set shown in Fig. 1.9 consists of metallic as well as nonmetallic components. The main parts (the body) of the set are made by injection molding of a thermoplastic (Chapter 19), such as an acrylic, which has both transparency and other desirable characteristics for this application and is easy to mold. The round metal top of the saltshaker is made of sheet metal, has punched holes (Chapter 16), and is electroplated for improved appearance (Section 34.9).

The knob on the top of the pepper mill is made by machining (Chapter 23) and is threaded on the inside to allow it to be screwed and unscrewed. The square rod connecting the top portion of the pepper mill to the two pieces shown at the bottom of the figure is made by a rolling operation (Chapter 13). The two grinder components, shown at the bottom of the figure, are made of stainless steel. A design for manufacturing analysis indicated that casting or machining the two components would be too costly; consequently, it was determined that an appropriate and economical method would be the powder-metallurgy technique (Chapter 17).

Figure 1.9 A saltshaker and pepper mill set. The two metal pieces (at the bottom) for the pepper mill are made by powder-metallurgy techniques. Source: Reproduced with permission from Success Stories on P/M Parts, Metal Powder Industries Federation, Princeton, NJ, 1998.

1.7 Computer-integrated Manufacturing

Computer-integrated manufacturing (CIM), as the name suggests, integrates the software and hardware needed for computer graphics, computer-aided modeling, and computer-aided design and manufacturing activities, from initial product concept through its production and distribution in the marketplace. This comprehensive and integrated approach began in the 1970s and has been particularly effective because of its capability of making possible the following tasks:

- Responsiveness to rapid changes in product design modifications and to varying market demands
- Better use of materials, machinery, and personnel
- Reduction in inventory
- Better control of production and management of the total manufacturing operation.

The following is a brief outline of the various elements in CIM, all described in detail in Chapters 38 and 39:

1. **Computer numerical control** (CNC). First implemented in the early 1950s, this is a method of controlling the movements of machine components by the direct insertion of coded instructions in the form of numerical data.

2. **Adaptive control** (AC). The processing parameters in an operation are automatically adjusted to optimize the production rate and product quality.
and to minimize manufacturing cost. For example, machining forces, tempera-
ture, surface finish, and the dimensions of the part can be constantly moni-
tored; if they move outside the specified range, the system adjusts the
appropriate variables until the parameters are within the specified range.

3. **Industrial robots.** Introduced in the early 1960s, industrial robots (Fig. 1.10)
have rapidly been replacing humans, especially in operations that are repeti-
tive, dangerous, and boring. As a result, variability in product quality is
decreased and productivity improved. Robots are particularly effective in
assembly operations, and some (*intelligent robots*) have been developed with
sensory-perception capabilities and movements that simulate those of humans.

4. **Automated materials handling.** Computers have made possible highly efficient
handling of materials and components in various stages of completion (*work in progress*),
as in moving a part from one machine to another, and then to
points of inspection, to inventory, and finally, to shipment.

5. **Automated assembly systems.** These systems continue to be developed to re-
place assembly by human operators, although humans still have to perform
some operations. Assembly costs can be high, depending on the type of prod-
uct; consequently, products are now being designed so that they can be assem-
bled more easily, and faster by automated machinery, thus reducing the total
manufacturing cost.

6. **Computer-aided process planning** (CAPP). By optimizing process planning,
this system is capable of improving productivity, product quality, and consist-
tency and hence reducing costs. Functions such as cost estimating and moni-
toring work standards (time required to perform a certain operation) are also
incorporated into the system.

7. **Group technology** (GT). The concept behind group technology is that parts
can be grouped and produced by classifying them into families according to
similarities in design and the manufacturing processes employed to produce
them. In this way, part designs and process plans can be standardized and new
parts (based on similar parts made previously) can be produced efficiently and economically.

8. **Just-in-time production** (JIT). The principle behind JIT is that (1) supplies of raw materials and parts are delivered to the manufacturer just in time to be used, (2) parts and components are produced just in time to be made into sub-assemblies, and (3) products are assembled and finished just in time to be delivered to the customer. As a result, inventory carrying costs are low, defects in components are detected right away, productivity is increased, and high-quality products are made at low cost.

9. **Cellular manufacturing** (CM). This system utilizes workstations that consist of a number of **manufacturing cells**, each containing various production machines controlled by a central robot, with each machine performing a different operation on the part, including inspection.

10. **Flexible manufacturing systems** (FMS). These systems integrate manufacturing cells into a large production facility, with all of the cells interfaced with a central computer. Although very costly, flexible manufacturing systems are capable of producing parts efficiently, but in relatively small quantities, and of quickly changing manufacturing sequences required for different parts. Flexibility enables these systems to meet rapid changes in market demand for all types of products.

11. **Expert systems** (ES). Consisting basically of complex computer programs, these systems have the capability of performing various tasks and solving difficult real-life problems, much as human experts would, including expediting the traditional iterative process in design optimization.

12. **Artificial intelligence** (AI). Computer-controlled systems are now capable of learning from experience and of making decisions that optimize operations and minimize costs, ultimately replacing human intelligence.

13. **Artificial neural networks** (ANN). These networks are designed to simulate the thought processes of the human brain, with such capabilities as modeling and simulating production facilities, monitoring and controlling manufacturing processes, diagnosing problems in machine performance, and conducting financial planning and managing a company's manufacturing strategy.

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**EXAMPLE 1.5 Mold for Making Sunglasses Frames**

The metal mold used for injection molding of plastic sunglasses is made on a computer numerical-control milling machine, by using a cutter (called a ball-nosed end mill), as illustrated in Fig. I.11. First, a model of the sunglasses is made using a computer-aided design software package, from which a model of the mold is automatically generated. The geometric information is sent to the milling machine, and the machining steps are planned.

Next, an offset is added to each surface to account for the nose radius of the end mill during machining, thus determining the cutter path (i.e., the path followed by the center of rotation of the machine spindle). The numerical-control programming software executes this machining program on the milling machine, producing the die cavity with appropriate dimensions and tolerances. Electrical-discharge machining (Section 27.5) can also be used to make this mold; however, it was determined that the procedure was about twice as expensive as machining the mold by computer numerical control, and it produced molds with lower dimensional accuracy.

*Source: Courtesy of Mold Threads, Inc.*
1.8 Quality Assurance and Total Quality Management

*Product quality* is one of the most critical aspects of manufacturing, because it directly influences customer satisfaction, thus playing a crucial role in determining a product's success in the global marketplace (Chapter 36). The traditional approach of inspecting products after they are made has largely been replaced by the recognition that *quality must be built into the product* from its initial design through all subsequent stages of manufacture and assembly.

Because products are typically made through several manufacturing steps and operations, each step can involve its own significant variations in performance, which can occur even within a relatively short time. A production machine, for example, may perform differently when it is first turned on than when it warms up during its use or when the ambient temperature in the plant fluctuates. Consequently, *continuous control of processes* (known as *online monitoring*) is a critical factor in maintaining product quality, and the objective must be to control processes, not products.

*Quality assurance* and *total quality management* (TQM) are widely recognized as being the responsibility of everyone involved in the design and manufacture of products and their components. *Product integrity* is a term generally used to define the degree to which a product

- Functions reliably during its life expectancy, as shown in Table I.4,
- Is suitable for its intended purposes, and
- Can be maintained with relative ease.
As Table I.5 indicates, producing defective products can be very costly to the manufacturer, with costs varying by orders of magnitude.

Pioneers in quality control, particularly W.E. Deming (1900–1993), J.M. Juran (1904–2008), and G. Taguchi (1924–), all emphasized the importance of management's commitment to (a) product quality, (b) pride of workmanship at all levels of production, and (c) the necessity of using statistical process control (SPC) and control charts (Chapter 36). They also pointed out the importance of online monitoring and rapidly identifying the sources of quality problems in production, before even another defective part is produced. The major goal of control is to prevent defective parts from ever being made, rather than to inspect, detect, and reject defective parts after they have been made.

As an indication of strict quality control, computer chips are now made with such high quality that only a few out of a million chips may be defective. The level of defects is identified in terms of standard deviation, denoted by the symbol sigma. Three sigma in manufacturing would result in 2700 defective parts per million, which is much too high in modern manufacturing. In fact, it has been estimated that
at this level, no modern computer would function reliably. At six sigma, defective parts are reduced to only 3.4 per million parts made. This level has been reached through major improvements in manufacturing process capabilities in order to reduce variability in product quality.

Important developments in quality assurance include the implementation of experimental design, a technique in which the factors involved in a manufacturing process and their interactions are studied simultaneously. For example, the variables affecting dimensional accuracy or surface finish in a machining operation can be identified readily, thus making it possible for appropriate preventive on-time actions to be taken.

Quality Standards. Global manufacturing and competitiveness have led to an obvious need for international conformity and consensus in establishing quality control methods. This need resulted in the establishment of the ISO 9000 standards series on quality management and quality assurance standards, as well as of the QS 9000 standards (Section 36.6). A company’s registration for these standards, which is a quality process certification and not a product certification, means that the company conforms to consistent practices as specified by its own quality system. ISO 9000 and QS 9000 have permanently influenced the manner in which companies conduct business in world trade, and they are now the world standard for quality.

Human-factors Engineering. This topic deals with human–machine interactions and thus is an important aspect of manufacturing operations in a plant, as well as of products in their normal use. The human-factors approach results in the design and manufacture of safe products; it emphasizes ergonomics, which is defined as the study of how a workplace and the machinery and equipment in it can best be designed for comfort, safety, efficiency, and productivity.

Some examples of the need for proper ergonomic considerations are represented by (a) a mechanism that is difficult to operate manually, causing injury to the worker, (b) a poorly designed keyboard that causes pain to the user’s hands and arms during its normal use (known as repetitive stress syndrome), and (c) a control panel on a machine that is difficult to reach or use safely and comfortably.

Product Liability. Designing and manufacturing safe products is among the essential aspects of a manufacturer’s responsibilities. All those involved with product design, manufacture, and marketing must fully recognize the consequences of a product’s failure, including failure due to foreseeable misuse of the product.

As is widely known, a product’s malfunction or failure can cause bodily injury or even death, as well as financial loss to an individual, to bystanders, or to an organization. This important topic is referred to as product liability, and the laws governing it generally vary from state to state and from country to country. Among the numerous examples of products that could involve liability are the following:

- A grinding wheel shatters and blinds a worker
- A cable supporting a platform snaps, allowing the platform to drop and cause bodily harm or death
- Automotive brakes suddenly become inoperative because of the failure of a particular component of the brake system
- Production machinery lacks appropriate safety guards
- Electric and pneumatic tools lack appropriate warnings and instructions for their safe use
- Aircraft landing gears fail to descend and lock properly.
1.9 Lean Production and Agile Manufacturing

Lean production is a methodology that involves a thorough assessment of each activity of a company, with the basic purpose of minimizing waste at all levels and calling for the elimination of unnecessary operations that do not provide any added value to the product being made. This approach, also called lean manufacturing, identifies all of a manufacturer's activities from the viewpoint of the customer and optimizes the processes used in order to maximize added value. Lean production focuses on (a) the efficiency and effectiveness of each and every manufacturing operation, (b) the efficiency of the machinery and equipment used, and (c) the activities of the personnel involved in each operation. This methodology also includes a comprehensive analysis of the costs incurred in each activity and those for productive and for nonproductive labor.

The lean production strategy requires a fundamental change in corporate culture, as well as an understanding of the importance of cooperation and teamwork among the company's workforce and management. Lean production does not necessarily require cutting back on a company's physical or human resources; rather, it aims at continually improving efficiency and profitability by removing all waste in the company's operations and dealing with any problems as soon as they arise.

Agile Manufacturing. The principle behind agile manufacturing is ensuring agility—and hence flexibility—in the manufacturing enterprise, so that it can respond rapidly and effectively to changes in product demand and the needs of the customer. Flexibility can be achieved through people, equipment, computer hardware and software, and advanced communications systems. As an example of this approach, it has been predicted that the automotive industry could configure and build a car in three days and that, eventually, the traditional assembly line will be replaced by a system in which a nearly custom made car will be produced by combining several individual modules.

The methodologies of both lean and agile production require that a manufacturer benchmark its operations. Benchmarking involves assessing the competitive position of other manufacturers with respect to one's own position (including product quality, production time, and manufacturing cost) and setting realistic goals for the future. Benchmarking thus becomes a reference point from which various measurements can be made and to which they can be compared.

1.10 Manufacturing Costs and Global Competition

Always critically important, the economics of manufacturing has become even more so with (a) ever-increasing global competition and (b) the demand for high-quality products, generally referred to as world-class manufacturing, at low prices. Typically, the manufacturing cost of a product represents about 40% of its selling price, which often is the overriding consideration in a product's marketability and general customer satisfaction. An approximate, but typical, breakdown of costs in modern manufacturing is given in Table I.6. The percentages indicated can, however, vary significantly depending on product type.

The total cost of manufacturing a product generally consists of the following components:

1. Materials. Raw-material costs depend on the material itself, as well as on supply and demand. Low cost may not be the deciding factor if the cost of processing a
TABLE I.6

<table>
<thead>
<tr>
<th>Typical Cost Breakdown in Manufacturing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
</tr>
<tr>
<td>Materials</td>
</tr>
<tr>
<td>Manufacturing</td>
</tr>
<tr>
<td>Direct labor</td>
</tr>
<tr>
<td>Indirect labor</td>
</tr>
</tbody>
</table>

particular material is higher than that for a more expensive material. For example, a low-cost piece of material may require more time to machine or form than one of higher cost, thus increasing production costs.

2. Tooling. Tooling costs include those for cutting tools, dies, molds, workholding devices, and fixtures. Some cutting tools cost as little as $2 and as much as about $100 for materials such as cubic boron nitride and diamond. Depending on their size and the materials involved in making them, molds and dies can cost from only a few hundred dollars to over $2 million for a set of dies for stamping sheet metal to make automobile fenders.

3. Fixed. Fixed costs include costs for energy, rent for facilities, insurance, and real-estate taxes.

4. Capital. Production machinery, equipment, buildings, and land are typical capital costs. Machinery costs can range from a few thousand to over a million dollars. Although the cost of computer-controlled machinery can be very high, such an expenditure may well be warranted in view of its long-range benefit of reducing labor costs.

5. Labor. Labor costs consist of direct and indirect costs. Direct labor, also called productive labor, concerns the labor that is directly involved in manufacturing products. Indirect labor pertains to servicing of the total manufacturing operation; it is also called nonproductive labor or overhead. Direct-labor costs may be only 10 to 15% of the total cost (Table I.6), but it can be as much as 60% for labor-intensive products. Reductions in the direct-labor share of manufacturing costs can be achieved by such means as extensive automation, computer control of all aspects of manufacturing, the implementation of modern technologies, and increased efficiency of operations.

As shown in Table I.7, there is a worldwide disparity in labor costs, by an order of magnitude. It is not surprising that today numerous consumer products are manufactured mostly in Pacific Rim countries, especially China, or they are assembled in Mexico. Likewise, software and information technologies are often much less costly to develop in countries such as India and China than in the United States or Europe. As living standards continue to rise, however, labor costs, too, are beginning to rise significantly in such countries.

Outsourcing. A more recent trend has been outsourcing, defined as the purchase by a company of parts or labor from an outside source, from either another company or another country, in order to reduce design and manufacturing costs. There is increasing evidence, however, that, depending on the type of product, manufacturing abroad can have significant challenges, including the rising cost of shipping. Another problem is the social impact and political implications of any ensuing lowered employment, especially in the European Union countries and the United States.
**TABLE 1.7**

Approximate Relative Hourly Compensation for Workers in Manufacturing in 2006 (United States = 100)

<table>
<thead>
<tr>
<th>Country</th>
<th>Relative Compensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norway</td>
<td>154</td>
</tr>
<tr>
<td>Germany</td>
<td>137</td>
</tr>
<tr>
<td>Denmark</td>
<td>127</td>
</tr>
<tr>
<td>Austria</td>
<td>122</td>
</tr>
<tr>
<td>Belgium</td>
<td>121</td>
</tr>
<tr>
<td>Switzerland</td>
<td>119</td>
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*Note: Compensation can vary significantly with benefits. Source: U.S. Department of Labor.*

### 1.1.1 General Trends in Manufacturing

Following are some general trends that have been observed regarding various aspects of manufacturing today:

**Global manufacturing trends**

1. Product variety and complexity continue to increase.
2. Product life cycles are becoming shorter.
3. Markets have become multinational and global competition has been increasing rapidly.
4. Market conditions fluctuate widely.
5. Customers are consistently demanding high-quality, low-cost products and on-time delivery.

**Materials**

6. Material composition, purity, and defects (impurities, inclusions, and flaws) are coming under more control in order to further enhance overall properties, manufacturing characteristics, reliability, and service life.
7. Developments have occurred in the selection of materials for improved recyclability.
8. Developments continue in nanomaterials, nanopowders, composites, superconductors, semiconductors, amorphous alloys, shape-memory alloys (smart materials), tool and die materials, and coatings.
9. Testing methods and equipment, including the use of advanced computers and software, particularly for ceramics, carbides, and composite materials, are continually being improved.
10. Increasing control over the thermal treatment of materials is resulting in more predictable and reliable properties.
11. Weight savings are being achieved with the use of materials with higher strength-to-weight and stiffness-to-weight ratios, particularly in the automotive and aerospace industries.

Manufacturing operations

12. Improvements are being made in predictive models of the effects of material-processing parameters on product integrity, applied during a product’s design stage.
13. Developments continue in ultraprecision manufacturing, micromanufacturing, and nanomanufacturing, approaching the level of atomic dimensions.
14. Computer simulation, modeling, and control strategies are being applied to all areas of manufacturing.
15. Rapid-prototyping technologies are increasingly being applied to the production of tooling and direct digital manufacturing.
16. Optimization of manufacturing processes and production systems are making them more agile.

Manufacturing systems

17. Advances in computer software and hardware are being applied to all aspects of production.
18. Developments have occurred in control systems, industrial robots, automated inspection, handling and assembly, and sensor technology.
19. Lean production and information technology are being implemented as tools to help meet major global challenges.

Goals in manufacturing

20. View manufacturing activities not as individual, separate tasks, but as making up a large system, with all its parts interrelated.
21. Meet all design requirements, product specifications, and relevant national and international standards for products.
22. Build quality into the product at each stage of its production.
23. Implement the most economical and environmentally friendly (green) manufacturing methods.
24. Continually evaluate advances in materials, production methods, and computer integration, with a view toward realizing their appropriate, timely, and economical implementation.
25. Adopt production methods that are sufficiently flexible in order to rapidly respond to changing global market demands and provide on-time delivery to the customer.
26. Continue efforts aimed at achieving higher levels of productivity and eliminating or minimizing waste with optimum use of an organization’s resources.
27. Cooperate with customers for timely feedback for continuous improvement of a company’s products.
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This chapter is an introduction to the fundamentals of the machining processes to be covered in subsequent chapters and, as such, presents the basic concepts relevant to all machining operations.

The chapter opens with a discussion of the mechanics of chip formation in machining and the model typically used for orthogonal cutting operations; the model and its oblique-cutting extensions allow the calculation of force and power in machining.

Temperature rise in chip and cutting tool are then discussed.

Mechanisms of tool wear and failure follow, with flank wear characterized by the Taylor tool-life equation.

Crater wear, nose wear, and other forms of wear are also described.

The chapter ends with a discussion of surface finish, the integrity of parts produced by machining, and the factors involved in the machinability of various metallic and nonmetallic materials.

21.1 Introduction

Cutting processes remove material from the surface of a workpiece by producing chips. Some of the more common cutting processes, illustrated in Fig. 21.1 (see also Fig. 1.6e), are as follows:

- **Turning**, in which the workpiece is rotated and a cutting tool removes a layer of material as the tool moves to the left, as in Fig. 21.1a.
- **Cutting off**, in which the cutting tool moves radially inward and separates the right piece from the bulk of the blank.
- **Slab milling**, in which a rotating cutting tool removes a layer of material from the surface of the workpiece.
- **End milling**, in which a rotating cutter travels along a certain depth in the workpiece and produces a cavity.

In the turning process, illustrated in greater detail in Fig. 21.2, the cutting tool is set at a certain depth of cut (mm or in.) and travels to the left with a certain velocity as the workpiece rotates. The *feed*, or *feed rate*, is the distance the tool travels...
horizontally per unit revolution of the workpiece (mm/rev or in./rev). This movement of the tool produces a chip, which moves up the face of the tool.

In order to analyze this process in detail, a two-dimensional model of it is presented in Fig. 21.3a. In this idealized model, a cutting tool moves to the left along the workpiece at a constant velocity, $V$, and a depth of cut, $t_0$. A chip is produced ahead of the tool by plastically deforming and shearing the material continuously along the shear plane. This phenomenon can be demonstrated by slowly scraping the surface of a stick of butter lengthwise with a sharp knife and observing the formation of a chip. Chocolate shavings used as decorations on cakes and pastries are produced in a similar manner.

In comparing Figs. 21.2 and 21.3, note that the feed in turning is equivalent to $t_0$, and the depth of cut in turning is equivalent to the width of cut (dimension perpendicular to the page) in the idealized model. These relationships can be visualized by rotating Fig. 21.3 clockwise by 90°. With this brief introduction as a background, the cutting process will now be described in greater detail.
21.2 Mechanics of Cutting

The factors that influence the cutting process are outlined in Table 21.1. In order to appreciate the contents of this table, let's now identify the major independent variables in the cutting process: (a) tool material and coatings; (b) tool shape, surface finish, and sharpness; (c) workpiece material and condition; (d) cutting speed, feed, and depth of cut; (e) cutting fluids; (f) characteristics of the machine tool; and (g) work holding and fixturing.

Dependent variables in cutting are those that are influenced by changes in the independent variables listed above, and include: (a) type of chip produced, (b) force and energy dissipated during cutting, (c) temperature rise in the workpiece, the tool, and the chip, (d) tool wear and failure, and (e) surface finish and surface integrity of the workpiece.
When machining operations yield unacceptable results, normal troubleshooting requires a systematic investigation. A typical question posed is which of the independent variables should be changed first, and to what extent, if (a) the surface finish of the workpiece being cut is unacceptable, (b) the cutting tool wears rapidly and becomes dull, (c) the workpiece becomes very hot, and (d) the tool begins to vibrate and chatter.

In order to understand these phenomena and respond to the question posed, let's first study the mechanics of chip formation—a subject that has been studied extensively since the early 1940s. Several models (with varying degrees of complexity) have been proposed. As is being done in other manufacturing processes (such as casting, molding, shaping, and forming), advanced machining models are being continuously developed. The methods used include computer simulation of the machining process, with the purpose of studying the complex interactions of the many variables involved while developing capabilities to optimize machining operations.

The simple model shown in Fig. 21.3a (referred to as the M.E. Merchant model, developed in the early 1940s) is sufficient for our purposes. This model is known as orthogonal cutting, because it is two dimensional and the forces involved (as we later show) are perpendicular to each other. The cutting tool has a rake angle of \( \alpha \) (positive, as shown in the figure) and a relief or clearance angle.

Microscopic examination of chips obtained in actual machining operations have revealed that they are produced by shearing (as modeled in Fig. 21.4a)—similar to the movement in a deck of cards sliding against each other. Shearing takes place in a shear zone (usually along a well-defined plane referred to as the shear plane) at an angle \( \phi \) (called the shear angle). Below the shear plane, the workpiece remains undeformed; above it, the chip that is already formed moves up the rake face of the tool. The dimension \( d \) in the figure is highly exaggerated to show the mechanism involved. In reality, this dimension is only on the order of \( 10^{-2} \) to \( 10^{-3} \) mm (\( 10^{-3} \) to \( 10^{-4} \) in.).

Some materials (notably cast irons at low speeds) do not shear along a well-defined plane but instead shear in a zone, as shown in Fig. 21.3b. Shearing in such a
(a) Schematic illustration of the basic mechanism of chip formation by shearing. (b) Velocity diagram showing angular relationships among the three speeds in the cutting zone.

Volume is not in itself objectionable, but it can lead to surface defects in the workpiece (as will be discussed later).

It can be seen that the chip thickness, \( t_o \), can be determined from the depth of cut, \( t_c \), the rake angle, \( \alpha \), and the shear angle, \( \phi \). The ratio of \( t_o / t_c \) is known as the cutting ratio (or chip-thickness ratio), \( r \), and is related to the two angles by the following relationships:

\[
\tan \phi = \frac{r \cos \alpha}{1 - r \sin \alpha}
\]  \hspace{1cm} (21.1a)

and

\[
r = \frac{t_o}{t_c} = \frac{\sin \phi}{\cos(\phi - \alpha)}
\]  \hspace{1cm} (21.1b)

Because the chip thickness is always greater than the depth of cut, the value of \( r \) is always less than unity. The reciprocal of \( r \) is known as the chip-compression ratio or chip-compression factor and is a measure of how thick the chip has become compared with the depth of cut; hence, the chip-compression ratio always is greater than unity. The depth of cut also is referred to as the undeformed chip thickness, as may be visualized by reviewing Fig. 21.3.

The cutting ratio is an important and useful parameter for evaluating cutting conditions. Since the undeformed chip thickness, \( t_o \), is a machine setting and is therefore known, the cutting ratio can be calculated easily by measuring the chip thickness with a micrometer. With the rake angle also known for a particular cutting operation (it is a function of the tool and workpiece geometry in use), Eq. (21.1I) allows calculation of the shear angle.

Although we have referred to \( t_o \) as the depth of cut, note that in a machining process such as turning, as shown in Fig. 21.2, this quantity is the feed. To visualize the situation, assume, for instance, that the workpiece in Fig. 21.2 is a thin-walled tube and the width of the cut is the same as the thickness of the tube. Then, by rotating Fig. 21.3 clockwise by 90°, note that it is now similar to the view in Fig. 21.2.
Shear Strain. Referring now to Fig. 21.4a, we can see that the shear strain, $\gamma$, that the material undergoes can be expressed as

$$\gamma = \frac{AB}{OC} = \frac{AO}{OC} + \frac{OB}{OC},$$

or

$$\gamma = \cot \phi + \tan(\phi - \alpha). \quad (21.2)$$

Note that large shear strains are associated with low shear angles or with low or negative rake angles. Shear strains of 5 or higher have been observed in actual cutting operations. Compared to forming and shaping processes, the workpiece material undergoes greater deformation during cutting, as is also seen in Table 2.4. Furthermore, deformation in cutting generally takes place within a very narrow zone. In other words, the dimension $d = OC$ in Fig. 21.4a is very small. Thus, the rate at which shearing takes place is high. (We discuss the nature and size of the deformation zone further in Section 21.3.)

The shear angle has great significance in the mechanics of cutting operations. It influences force and power requirements, chip thickness, and temperature. Consequently, much attention has been focused on determining the relationships among shear angle, cutting process variables, and workpiece material properties. One of the earliest analyses was based on the assumption that the shear angle adjusts itself to minimize the cutting force or that the shear plane is a plane of maximum shear stress. This analysis yielded the expression

$$\phi = 45^\circ + \frac{\alpha}{2} - \frac{\beta}{2}, \quad (21.3)$$

where $\beta$ is the friction angle and is related to the coefficient of friction, $\mu$, at the tool-chip interface by the expression $\mu = \tan \beta$. Among the many shear-angle relationships developed, another useful formula that generally is applicable is

$$\phi = 45^\circ + \alpha - \beta. \quad (21.4)$$

The coefficient of friction in metal cutting generally ranges from about 0.5 to 2, indicating that the chip encounters considerable frictional resistance while moving up the tool's rake face. Experiments have shown that $\mu$ varies considerably along the tool-chip interface because of large variations in contact pressure and temperature. Consequently, $\mu$ is also called the apparent mean coefficient of friction.

Equation (21.3) indicates that (a) as the rake angle decreases or the friction at the tool-chip interface (rake face) increases, the shear angle decreases and the chip becomes thicker; (b) thicker chips mean more energy dissipation because the shear strain is higher [see Eq. (21.2)]; and (c) because work done during cutting is converted into heat, the temperature rise is also higher. The effects of these phenomena are described throughout the rest of this chapter.

Velocities in the Cutting Zone. Note in Fig. 21.3 that (since the chip thickness is greater than the depth of cut) the velocity of the chip, $V_c$, has to be lower than the cutting speed, $V$. Since mass continuity has to be maintained,

$$Vt_o = V_c t_o, \quad \text{or} \quad V_c = Vt_o.$$  

Hence,

$$V_c = \frac{V \sin \phi}{\cos(\phi - \alpha)}. \quad (21.5)$$
A *velocity diagram* also can be constructed, as shown in Fig. 21.4b, in which, from trigonometric relationships, we obtain the equation

\[
\frac{V}{\cos(\phi - \alpha)} = \frac{V_s}{\cos \alpha} = \frac{V_c}{\sin \phi}
\]  

(21.6a)

where \( V_c \) is the velocity at which shearing takes place in the shear plane. Note also that

\[
r = \frac{t_0}{t_c} = \frac{V_c}{V'}
\]  

(21.6b)

These velocity relationships will be utilized further in Section 21.3 in describing power requirements in cutting operations.

**Types of Chips Produced in Metal Cutting**

The types of metal chips commonly observed in practice and their photomicrographs are shown in Fig. 21.5. The four main types are as follows:

Basic types of chips produced in orthogonal metal cutting, their schematic representation, and photomicrographs of the cutting zone: (a) continuous chip with narrow, straight, and primary shear zone; (b) continuous chip with secondary shear zone at the chip–tool interface; (c) built-up edge; (d) segmented or nonhomogeneous chip; and (e) discontinuous chip. *Source:* After M.C. Shaw, P.K. Wright, and S. Kalpakjian.
Continuous chips usually are formed with ductile materials that are machined at high cutting speeds and/or high rake angles (Fig. 21.5a). The deformation of the material takes place along a narrow shear zone called the primary shear zone. Continuous chips may develop a secondary shear zone (Fig. 21.5b) because of high friction at the tool–chip interface; this zone becomes thicker as friction increases.

Deformation in continuous chips also may take place along a wide primary shear zone with curved boundaries (see Fig. 21.3b), unlike that shown in Fig. 21.5a. Note that the lower boundary of the deformation zone in Fig. 21.3b projects below the machined surface, subjecting it to distortion, as depicted by the distorted vertical lines in the machined subsurface. This situation occurs generally in machining soft metals at low speeds and low rake angles. It usually results in a poor surface finish and induces surface residual stresses, which may be detrimental to the properties of the machined part in their service life.

Although they generally produce a good surface finish, continuous chips are not necessarily desirable, particularly with computer-controlled machine tools in wide use, as they tend to become tangled around the toolholder, the fixture, and the workpiece, as well as around the chip-disposal systems (see Section 23.3.7). The operation may have to be stopped to clear away the chips. This problem can be alleviated with chip breakers (discussed shortly), by changing parameters such as cutting speed, feed, and depth of cut, or by using cutting fluids.

Built-up Edge Chips. A built-up edge (BUE) consists of layers of material from the workpiece that gradually are deposited on the tool tip—hence the term built-up (Fig. 21.5c). As it grows larger, the BUE becomes unstable and eventually breaks apart. Part of the BUE material is carried away by the tool side of the chip; the rest is deposited randomly on the workpiece surface. The cycle of BUE formation and destruction is repeated continuously during the cutting operation until corrective measures are taken. In effect, a built-up edge changes the geometry of the cutting edge and dulls it (Fig. 21.6a).

Built-up edge commonly is observed in practice. It is a major factor that adversely affects surface finish, as can be seen in Figs. 21.5c and 21.6b and c. However, a thin, stable BUE usually is regarded as desirable because it reduces tool wear by protecting its rake face. Cold-worked metals generally have less of a tendency to form BUE than when in their annealed condition. Because of work hardening and deposition of successive layers of material, the BUE hardness increases significantly (Fig. 21.6a). As the cutting speed increases, the size of the BUE decreases; in fact it may not form at all.

The tendency for BUE formation can be reduced by one or more of the following means:

- Increase the cutting speeds
- Decrease the depth of cut
- Increase the rake angle
- Use a sharp tool
- Use an effective cutting fluid
- Use a cutting tool that has lower chemical affinity for the workpiece material.
Serrated chips (also called segmented or nonhomogeneous chips, see Fig. 21.5d) are semicontinuous chips with large zones of low shear strain and small zones of high shear strain, hence the latter zone is called shear localization. Metals with low thermal conductivity and strength that decreases sharply with temperature (thermal softening) exhibit this behavior, most notably titanium. The chips have a sawtooth-like appearance. (This type of chip should not be confused with the illustration in Fig. 21.4a, in which the dimension d is highly exaggerated.)

Discontinuous chips consist of segments that may be attached firmly or loosely to each other (Fig. 21.5e). Discontinuous chips usually form under the following conditions:

- Brittle workpiece materials, because they do not have the capacity to undergo the high shear strains involved in cutting
- Workpiece materials that contain hard inclusions and impurities or have structures such as the graphite flakes in gray cast iron
- Very low or very high cutting speeds
- Large depths of cut
- Low rake angles
- Lack of an effective cutting fluid
- Low stiffness of the toolholder or the machine tool, thus allowing vibration and chatter to occur.

Because of the discontinuous nature of chip formation, forces continually vary during cutting. Consequently, the stiffness or rigidity of the cutting-tool holder, the
work-holding devices, and the machine tool are important in cutting with serrated chips as well as with discontinuous chips. If it is not sufficiently stiff, the machine tool may begin to vibrate and chatter, as discussed in detail in Section 25.4. This, in turn, adversely affects the surface finish and dimensional accuracy of the machined part and may cause premature wear or damage to the cutting tool—even to the components of the machine tool if the vibration is excessive.

**Chip Curl.** In all cutting operations performed on metals, as well as nonmetallic materials such as plastics and wood, chips develop a curvature (*chip curl*) as they leave the workpiece surface (Fig. 21.5). Among the factors affecting the chip curl are the following:

- The distribution of stresses in the primary and secondary shear zones
- Thermal effects
- Work-hardening characteristics of the workpiece material
- The geometry of the cutting tool
- Cutting fluids.

Process variables also affect chip curl. Generally, as the depth of cut decreases, the radius of curvature decreases; that is, the chip becomes curlier. Also, cutting fluids can make chips become more curly (the radius of curvature decreases), thus reducing the tool–chip contact area and concentrating the heat closer to the tip of the tool. As a result, tool wear increases.

**Chip Breakers.** As stated previously, continuous and long chips are undesirable, as they tend to become entangled, severely interfere with machining operations, and also become a potential safety hazard. If all of the process variables are under control, the usual procedure employed to avoid such a situation is to break the chip intermittently with cutting tools that have *chip-breaker* features, as shown in Fig. 21.7.

Chip breakers, traditionally pieces of metal clamped to the tool's rake face, bend and break the chip. However, most modern cutting tools and inserts (see Fig. 22.2) now have built-in chip-breaker features of various designs (Fig. 21.7). Chips also can be broken by changing the tool geometry to control chip flow, as in the turning operations shown in Fig. 21.8. Experience indicates that the ideal chip size to be broken is in the shape of either the letter C or the number 9 and fits within a 25-mm (1-in.) square space.

With soft workpiece materials (such as pure aluminum or copper), chip breaking by the means just described may not be effective, in which case machining may be done in small increments (pausing so that a chip is not generated) or by reversing the feed by small increments. In interrupted-cutting operations (such as milling), chip breakers generally are not necessary, since the chips already have finite lengths.

**Controlled Contact on Tools.** Cutting tools can be designed so that the tool–chip contact length is reduced by recessing the rake face of the tool some distance away from its tip. This reduction in contact length affects chip-formation mechanics. Primarily, it reduces the cutting forces and thus the energy and temperature. Determining an optimum length is important, as too small a contact length would concentrate the heat at the tool tip, thus increasing wear.

**Cutting Nonmetallic Materials.** A variety of chips are encountered in cutting thermoplastics, depending on the type of polymer and process parameters, such as depth
(a) Schematic illustration of the action of a chip breaker. Note that the chip breaker decreases the radius of curvature of the chip and eventually breaks it. (b) Chip breaker clamped on the rake face of a cutting tool. (c) Grooves in cutting tools acting as chip breakers. Most cutting tools used now are inserts with built-in chip-breaker features.

Chips produced in turning: (a) tightly curled chip; (b) chip hits workpiece and breaks; (c) continuous chip moving radially away from workpiece; and (d) chip hits tool shank and breaks off. Source: After G. Boothroyd.

of cut, tool geometry, and cutting speed. Many of the discussions concerning metals also are applicable to polymers. Because they are brittle, thermosetting plastics and ceramics generally produce discontinuous chips. For characteristics of other machined materials (such as wood, ceramics, and composite materials) see Section 21.7.3.

Oblique Cutting

The majority of machining operations involve tool shapes that are three dimensional; thus, the cutting is oblique. The basic difference between oblique and orthogonal cutting can be seen in Fig. 21.9a. Whereas in orthogonal cutting the chip slides directly up the face of the tool, in oblique cutting the chip is helical and at an angle \( \theta \), called
the inclination angle (Fig. 21.9b). Note the lateral direction of chip movement in oblique cutting—a situation that is similar to a snowplow blade, that throws the snow sideways. It can be seen that such a helical chip moves sideways and away from the cutting zone and doesn’t obstruct it as it would in orthogonal cutting.

Note that the chip in Fig. 21.9a flows up the rake face of the tool at angle $\alpha$, (the chip flow angle), which is measured in the plane of the tool face. Angle $\alpha$ is the normal rake angle and is a basic geometric property of the tool. This is the angle between line $oz$ normal to the workpiece surface and line $oa$ on the tool face.

The workpiece material approaches the cutting tool at a velocity $V$ and leaves the surface (as a chip) with a velocity $V_c$. The effective rake angle, $\alpha_e$, is calculated in the plane of these two velocities. Assuming that the chip flow angle, $\alpha$, is equal to the inclination angle, $i$ (and this assumption has been verified experimentally), the effective rake angle, $\alpha_e$, is

$$\alpha_e = \sin^{-1}(\sin^2 i + \cos^2 i \sin \alpha).$$ (21.7)

Since both $i$ and $\alpha$ can be measured directly, the effective rake angle can be calculated. Note that, as $i$ increases, the effective rake angle increases, the chip becomes thinner and longer, and, as a consequence, the cutting force decreases. The influence of the inclination angle on chip shape is shown in Fig. 21.9c.

A typical single-point turning tool used on a lathe is shown in Fig. 21.10a. Note the various angles involved, each of which has to be selected properly for efficient cutting. Although these angles usually can be produced by grinding, the majority of cutting tools are now available as inserts, as shown in Fig. 21.10b and described in detail in Chapter 22. (Various three-dimensional cutting tools, including those for drilling, tapping, milling, planing, shaping, broaching, sawing, and filing, are described in greater detail in Chapters 23 and 24.

Shaving and Skiving. Thin layers of material can be removed from straight or curved surfaces by a process similar to the use of a plane to shave wood. Shaving is useful particularly in improving the surface finish and dimensional accuracy of sheared parts and punched slugs (Fig. 16.9). Another application of shaving is in finishing gears with a cutter that has the shape of the gear tooth (see Section 24.7). Parts that are long or have a combination of shapes are shaved by skiving with a specially shaped cutting tool that moves tangentially across the length of the workpiece.
21.3 Cutting Forces and Power

Knowledge of the cutting forces and power involved in machining operations is important for the following reasons:

- Data on cutting forces is essential so that
  a. Machine tools can be properly designed to minimize distortion of the machine components, maintain the desired dimensional accuracy of the machined part, and help select appropriate toolholders and work-holding devices.
  b. The workpiece is capable of withstanding these forces without excessive distortion.
  c. Power requirements must be known in order to enable the selection of a machine tool with adequate electric power.

The forces acting in orthogonal cutting are shown in Fig. 21.11a. The cutting force, $F_c$, acts in the direction of the cutting speed, $V$, and supplies the energy required for cutting. The ratio of the cutting force to the cross-sectional area being cut (i.e., the product of width of cut and depth of cut) is referred to as the specific cutting force.

The thrust force, $F_t$, acts in a direction normal to the cutting force. These two forces produce the resultant force, $R$, as can be seen from the force circle shown in Fig. 21.11b. Note that the resultant force can be resolved into two components on the tool face: a friction force, $F$, along the tool–chip interface and a normal force, $N$, perpendicular to it. It can also be shown that

$$ F = R \sin \beta $$  \hspace{1cm} (21.8a)

and

$$ N = R \cos \beta. $$  \hspace{1cm} (21.8b)

Note that the resultant force is balanced by an equal and opposite force along the shear plane and is resolved into a shear force, $F_s$, and a normal force, $F_n$. It can
be shown that these forces can be expressed, respectively, as

\[ F_s = F_c \cos \phi - F_r \sin \phi \]  \hspace{1cm} (21.9)

and

\[ F_n = F_c \sin \phi + F_r \cos \phi. \]  \hspace{1cm} (21.10)

Because the area of the shear plane can be calculated by knowing the shear angle and the depth of cut, the shear and normal stresses in the shear plane can be determined.

The ratio of \( F \) to \( N \) is the **coefficient of friction**, \( \mu \), at the tool–chip interface, and the angle \( \beta \) is the **friction angle** (as in Fig. 21.11). The magnitude of \( \mu \) can be determined as

\[ \mu = \frac{F}{N} = \frac{F_r + F_c \tan \alpha}{F_c - F_r \tan \alpha}. \]  \hspace{1cm} (21.11)

Although the magnitude of forces in actual cutting operations is generally on the order of a few hundred newtons, the **local stresses** in the cutting zone and the **pressures** on the tool are very high because the contact areas are very small. For example, the tool–chip contact length (see Fig. 21.3) is typically on the order of 1 mm (0.04 in.). Consequently, the tool tip is subjected to very high stresses, which lead to wear and, sometimes, chipping and fracture of the tool.

**Thrust Force.** A knowledge of the **thrust force** in cutting is important because the toolholder, the work-holding devices, and the machine tool must be sufficiently stiff to support that force with minimal deflections. For example, if the thrust force is too high or if the machine tool is not sufficiently stiff, the tool will be pushed away from the workpiece surface being machined. This movement will, in turn, reduce the depth of cut, resulting in less dimensional accuracy in the machined part.

We also can show the effect of rake angle and friction angle on the direction of thrust force by noting from Fig. 21.11b that

\[ F_t = R \sin(\beta - \alpha), \]  \hspace{1cm} (21.12a)

or

\[ F_t = F_c \tan(\beta - \alpha). \]  \hspace{1cm} (21.12b)
Note that the magnitude of the cutting force, \( F_c \), is always positive, as shown in Fig. 21.11, because it is this force that supplies the work required in cutting. However, the sign of the thrust force, \( F_t \), can be either positive or negative, depending on the relative magnitudes of \( \beta \) and \( \alpha \). When \( \beta > \alpha \), the sign of \( F_t \) is positive (that is, downward), and when \( \beta < \alpha \), the sign is negative (that is, upward). Therefore, it is possible to have an upward thrust force under the conditions of (a) high rake angles, (b) low friction at the tool–chip interface, or (c) both. A negative thrust force can have important implications in the design of machine tools and work holders and in the stability of the cutting process.

**Power.** Power is the product of force and velocity. Thus, from Fig. 21.11, the power input in cutting is

\[
\text{Power} = F \cdot V.
\]  
(21.13)

This power is dissipated mainly in the shear zone (due to the energy required to shear the material) and on the rake face of the tool (due to tool–chip interface friction).

From Figs. 21.4b and 21.11, it can be seen that the power dissipated in the shear plane is

\[
\text{Power for shearing} = F_s \cdot V_s.
\]  
(21.14)

Denoting the width of cut as \( w \), the specific energy for shearing, \( u_s \), is given by

\[
u_s = \frac{F_s \cdot V_s}{w \cdot t_o \cdot V'}
\]  
(21.15)

Similarly, the power dissipated in friction is

\[
\text{Power for friction} = F \cdot V_c,
\]  
(21.16)

and the specific energy for friction, \( u_f \), is

\[
u_f = \frac{F \cdot V_c}{w \cdot t_o \cdot V'} = \frac{F_r}{w \cdot t_o}.
\]  
(21.17)

The total specific energy, \( u_t \), is thus

\[
u_t = u_s + u_f.
\]  
(21.18)

Because of the many factors involved, reliable prediction of cutting forces and power still is based largely on experimental data, such as given in Table 21.2. The wide range of values shown can be attributed to differences in strength within each material group and to various other factors, such as friction, use of cutting fluids, and processing variables.

The sharpness of the tool tip also influences forces and power. Because the tip rubs against the machined surface and makes the deformation zone ahead of the tool larger, duller tools require higher forces and power.

**Measuring Cutting Forces and Power.** Cutting forces can be measured using a force transducer (typically with quartz piezoelectric sensors), a dynamometer, or a load cell (with resistance-wire strain gages placed on octagonal rings) mounted on the cutting-tool holder. Transducers have a much higher natural frequency and stiffness than dynamometers, which are prone to excessive deflection and vibration. Also, it is possible to calculate the cutting force from the power consumption during cutting, provided that the mechanical efficiency of the machine tool is known or can be determined. The specific energy in cutting (such as that shown in Table 21.2) also can be used to calculate cutting forces.
### TABLE 21.2

Approximate Range of Energy Requirements in Cutting Operations at the Drive Motor of the Machine Tool (for Dull Tools, Multiply by 1.25)

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific energy</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W · s/mm³</td>
<td>hp · min/in³</td>
</tr>
<tr>
<td>Aluminum alloys</td>
<td>0.4–1</td>
<td>0.15–0.4</td>
</tr>
<tr>
<td>Cast irons</td>
<td>1.1–5.4</td>
<td>0.4–2</td>
</tr>
<tr>
<td>Copper alloys</td>
<td>1.4–3.2</td>
<td>0.5–1.2</td>
</tr>
<tr>
<td>High-temperature alloys</td>
<td>3.2–8</td>
<td>1.2–3</td>
</tr>
<tr>
<td>Magnesium alloys</td>
<td>0.3–0.6</td>
<td>0.1–0.2</td>
</tr>
<tr>
<td>Nickel alloys</td>
<td>4.8–6.7</td>
<td>1.8–2.5</td>
</tr>
<tr>
<td>Refractory alloys</td>
<td>3–9</td>
<td>1.1–3.5</td>
</tr>
<tr>
<td>Stainless steels</td>
<td>2–5</td>
<td>0.8–1.9</td>
</tr>
<tr>
<td>Steels</td>
<td>2–9</td>
<td>0.7–3.4</td>
</tr>
<tr>
<td>Titanium alloys</td>
<td>2–5</td>
<td>0.7–2</td>
</tr>
</tbody>
</table>

### EXAMPLE 21.1 Relative Energies in Cutting

In an orthogonal cutting operation, \( t_o = 0.005 \text{ in.} \), \( V = 400 \text{ ft/min} \), \( \alpha = 10^\circ \), and the width of cut = 0.25 in. It is observed that \( t_c = 0.009 \text{ in.} \), \( F_c = 125 \text{ lb} \), and \( F_t = 50 \text{ lb} \). Calculate the percentage of the total energy that goes into overcoming friction at the tool–chip interface.

**Solution** The percentage of the energy can be expressed as

\[
\frac{\text{Friction energy}}{\text{Total energy}} = \frac{FV_c}{F_c V} = \frac{F}{F_c}
\]

and

\[
R = \sqrt{F_t^2 + F_c^2} = \sqrt{50^2 + 125^2} = 135 \text{ lb.}
\]

Thus,

\[125 = 135 \cos(\beta - 10),\]

so

\[\beta = 32^\circ\]

and

\[F = 135 \sin 32^\circ = 71.5 \text{ lb.}\]

Hence,

\[
\text{Percentage} = \frac{(71.5)(0.555)}{125} = 0.32, \text{ or } 32%.
\]

### 21.4 Temperatures in Cutting

As in all metalworking processes where plastic deformation is involved, the energy dissipated in cutting is converted into heat that, in turn, raises the temperature in the cutting zone. *Temperature rise* is a very important factor in machining because of its major adverse effects, such as the following:

- Excessive temperature lowers the strength, hardness, stiffness, and wear resistance of the cutting tool; tools also may soften and undergo plastic deformation; thus, tool shape is altered.
• Increased heat causes uneven dimensional changes in the part being machined, making it difficult to control its dimensional accuracy and tolerances.
• An excessive temperature rise can induce thermal damage and metallurgical changes in the machined surface, adversely affecting its properties.

From the preceding sections, it can be seen that the main sources of heat in machining are: (a) the work done in shearing in the primary shear zone, (b) energy dissipated as friction at the tool–chip interface, and (c) heat generated as the tool rubs against the machined surface, especially for dull or worn tools. Much effort has been expended in establishing relationships among temperature and various material and process variables in cutting. A comprehensive expression for the mean temperature, \( T_{\text{mean}} \), in orthogonal cutting is

\[
T = \frac{1.2 Y_f}{\rho c} \sqrt[3]{V t_c K},
\]

where the mean temperature is in \(^\circ\)F, \( Y_f \) is the flow stress in psi, \( \rho c \) is the volumetric specific heat in in.-lb/in.\(^3\).\(^\circ\)F, and \( K \) is the thermal diffusivity (ratio of thermal conductivity to volumetric specific heat) in in.\(^2\)/s. Because the material parameters in this equation depend on temperature, it is important to use appropriate values that are compatible with the predicted temperature range. It can be seen from Eq. (21.19a) that the mean cutting temperature increases with workpiece strength, cutting speed, and depth of cut, and decreases with increasing specific heat and thermal conductivity of the workpiece material.

An expression for the mean temperature in turning on a lathe is given by

\[
T_{\text{mean}} \propto V^{a} f^{b},
\]

where \( V \) is the cutting speed and \( f \) is the feed of the tool, as shown in Fig. 21.2. Approximate values of the exponents \( a \) and \( b \) are \( a = 0.2 \) and \( b = 0.125 \) for carbide tools and \( a = 0.5 \) and \( b = 0.375 \) for high-speed steel tools.

**Temperature Distribution.** Because the sources of heat generation in machining are concentrated in the primary shear zone and at the tool–chip interface, it is to be expected that there will be severe temperature gradients in the cutting zone. A typical temperature distribution is shown in Fig. 21.12. Note the presence of severe gradients and that the maximum temperature is about halfway up the tool–chip interface. From the preceding discussions, it will be apparent that the particular temperature pattern depends on several factors pertaining to material properties and cutting conditions, including the type of cutting fluid (if any) used during machining.

The temperatures developed in a turning operation on 52100 steel are shown in Fig. 21.13. The temperature distribution along the flank surface of the tool is shown in Fig. 21.13a, for \( V = 60, 90, \) and 170 m/min, respectively, as a function of the distance from the tip of the tool. The temperature distributions at the tool–chip interface for the same three cutting speeds are shown in Fig. 21.13b as a function of the fraction of the contact length. Thus, zero on the abscissa represents the tool tip, and 1.0 represents the end of the tool–chip contact length.

---

**Figure 21.12** Typical temperature distribution in the cutting zone. Note the severe temperature gradients within the tool and the chip, and that the workpiece is latively cool. *Source: After G. Vierecke.*
FIGURE 21.13 Temperatures developed in turning 52100 steel: (a) flank temperature distribution and (b) tool–chip interface temperature distribution. Source: After B.T. Chao and K.J. Trigger.

Note that the temperature increases with cutting speed and that the highest temperature is almost 1100°C (2000°F). The presence of such high temperatures in machining can be verified simply by observing the dark-bluish color of the chips (caused by oxidation) produced at high cutting speeds. Chips can become red hot and create a safety hazard for the operator.

From Eq. (21.19b) and the values for the exponent a, it can be seen that the cutting speed, V, greatly influences temperature. The explanation is that, as speed increases, the time for heat dissipation decreases, and hence the temperature rises (eventually becoming almost an adiabatic process). This effect of speed can be demonstrated easily by rubbing your hands together faster and faster.

As can be seen from Fig. 21.14, the chip carries away most of the heat generated. It has been estimated that 90% of the energy is removed by the chip during a typical machining operation, with the rest by the tool and the workpiece. Note in this figure that, as the cutting speed increases, a larger proportion of the total heat generated is carried away by the chip, and less heat goes into the workpiece or the tool. This is one reason that machining speeds have been increasing significantly over the years (see high-speed machining, Section 25.5). The other main benefit is associated with the favorable economics in reducing machining time, as described in Section 25.8.

Techniques for Measuring Temperature. Temperatures and their distribution in the cutting zone may be determined from thermocouples embedded in the tool or the workpiece. This technique has been used successfully, although it involves considerable effort. It is easier to determine the mean temperature with the thermal emf (electromotive force) at the tool–chip interface, which acts as a hot junction between two different materials (i.e., tool and chip). Infrared radiation

FIGURE 21.14 Proportion of the heat generated in cutting transferred to the tool, workpiece, and chip as a function of the cutting speed. Note that the chip removes most of the heat.
from the cutting zone may be monitored with a radiation pyrometer. However, this technique indicates only surface temperatures; the accuracy of the results depends on the emissivity of the surfaces, which is difficult to determine accurately.

### 21.5 Tool Life: Wear and Failure

We have seen that cutting tools are subjected to (a) high localized stresses at the tip of the tool, (b) high temperatures, especially along the rake face, (c) sliding of the chip along the rake face, and (d) sliding of the tool along the newly cut workpiece surface. These conditions induce tool wear, which is a major consideration in all machining operations, as are mold and die wear in casting and metalworking. Tool wear adversely affects tool life, the quality of the machined surface and its dimensional accuracy, and, consequently, the economics of cutting operations.

Wear is a gradual process, much like the wear of the tip of an ordinary pencil. The rate of tool wear depends on tool and workpiece materials, tool geometry, process parameters, cutting fluids, and the characteristics of the machine tool. Tool wear and the changes in tool geometry during cutting manifest themselves in different ways, generally classified as flank wear, crater wear, nose wear, notching, plastic deformation of the tool tip, chipping, and gross fracture (Fig. 21.15).

![Diagram of tool wear](image)

**Figure 21.15** (a) Features of tool wear in a turning operation. The VB indicates average flank wear. (b)–(e) Examples of wear in cutting tools: (b) flank wear, (c) crater wear, (d) thermal cracking, and (e) flank wear and built-up edge. Source: (a) Terms and definitions reproduced with the permission of the International Organization for Standardization, ISO, copyright remains with ISO. (b)–(e) Courtesy of Kennametal Inc.
21.5.1 Flank Wear

Flank wear occurs on the relief (flank) face of the tool (Fig. 21.15a, b, and e). It generally is attributed to (a) rubbing of the tool along the machined surface, thereby causing adhesive or abrasive wear (see Section 33.5) and (b) high temperatures, which adversely affect tool-material properties.

In a classic study by F.W. Taylor on the machining of steels conducted in the early 1890s, the following approximate relationship for tool life, known as the Taylor tool life equation, was established:

\[ VT^n = C. \quad (21.20a) \]

Here, \( V \) is the cutting speed, \( T \) is the time (in minutes) that it takes to develop a certain flank wear land (shown as \( VB \) in Fig. 21.15a), \( n \) is an exponent that depends on tool and workpiece materials and cutting conditions, and \( C \) is a constant. Each combination of workpiece and tool materials and each cutting condition have their own \( n \) and \( C \) values, both of which are determined experimentally. Generally, however, \( n \) depends on the tool material, as shown in Table 21.3, and \( C \) on the workpiece material. Note that the magnitude of \( C \) is the cutting speed at \( T = 1 \) min.

To appreciate the importance of the exponent \( n \), Eq. (21.20) can be rewritten as

\[ T = \left( \frac{C}{V} \right)^{\frac{1}{n}}, \quad (21.20b) \]

where it can be seen that for constant values of \( C \), the smaller the value of \( n \), the lower is the tool life.

Cutting speed is the most important process variable associated with tool life, followed by depth of cut and feed, \( f \). For turning, Eq. (21.20) can be modified to

\[ VT^n d^x f^y = C, \quad (21.21) \]

where \( d \) is the depth of cut and \( f \) is the feed in mm/rev or in./rev, as shown in Fig. 21.2. The exponents \( x \) and \( y \) must be determined experimentally for each cutting condition. Taking \( n = 0.15 \), \( x = 0.15 \), and \( y = 0.6 \) as typical values encountered in machining practice, it can be seen that cutting speed, feed rate, and depth of cut are of decreasing importance.

We can rewrite Eq. (21.21) as

\[ T = C^{1/n} V^{-1/n} d^{-x} f^{-y/n}, \quad (21.22) \]

or, using typical values, as

\[ T \approx C^{7} V^{-7} d^{-1} f^{-4}. \quad (21.23) \]

| Table 21.3 |
|-------------------|-----------------|
| Ranges of \( n \) Values for the Taylor Equation (21.20a) for Various Tool Materials |
| High-speed steels | 0.08–0.2        |
| Cast alloys       | 0.1–0.15        |
| Carbides          | 0.2–0.5         |
| Coated carbides   | 0.4–0.6         |
| Ceramics          | 0.5–0.7         |
FIGURE 21.16  Effect of workpiece hardness and microstructure on tool life in turning ductile cast iron. Note the rapid decrease in tool life (approaching zero) as the cutting speed increases. Tool materials have been developed that resist high temperatures, such as carbides, ceramics, and cubic boron nitride, as described in Chapter 22.

To obtain a constant tool life, the following observations can be made from Eq. (21.23): (a) If the feed or the depth of cut is increased, the cutting speed must be decreased (and vice versa), and (b) depending on the exponents, a reduction in speed can result in an increase in the volume of the material removed because of the increased feed or depth of cut.

**Tool-life Curves.** Tool-life curves are plots of experimental data obtained by performing cutting tests on various materials under different cutting conditions, such as cutting speed, feed, depth of cut, tool material and geometry, and cutting fluids. Note in Fig. 21.16, for example, that (a) tool life decreases rapidly as the cutting speed increases, (b) the condition of the workpiece material has a strong influence on tool life, and (c) there is a large difference in tool life for different workpiece-material microstructures.

Heat treatment of the workpiece is important, due largely to increasing workpiece hardness. For example, ferrite has a hardness of about 100 HB, pearlite 200 HB, and martensite 300 to 500 HB. Impurities and hard constituents in the material or on the surface of the workpiece (such as rust, scale, and slag) also are important factors, because their abrasive action reduces tool life.

The exponent \( n \) can be determined from tool-life curves (Fig. 21.17). Note that the smaller the \( n \) value, the faster the tool life decreases with increasing cutting speed. Although tool-life curves are somewhat linear over a limited range of cutting speeds, they rarely are linear over a wide range. Moreover, the exponent \( n \) can indeed become negative at low cutting speeds, meaning that tool-life curves actually can reach a maximum and then curve downward. Because of this possibility, caution should be exercised in using tool-life equations beyond the range of cutting speeds to which they are applicable.

Because temperature has a major influence on the physical and mechanical properties of materials, it is understandable that it also strongly influences wear. Thus, as temperature increases, flank wear rapidly increases.
EXAMPLE 21.2 Increasing Tool Life by Reducing the Cutting Speed

Using the Taylor Equation (21.20a) for tool life and letting $n = 0.5$ and $C = 400$, calculate the percentage increase in tool life when the cutting speed is reduced by 50%.

Solution Since $n = 0.5$, the Taylor equation can be rewritten as $VT^{0.5} = 400$. Let’s denote $V_1$ as the initial speed and $V_2$ the reduced speed; thus, $V_2 = 0.5V_1$. Because $C$ is the constant 400, we have the relationship

$$0.5V_1\sqrt{\frac{T_2}{T_1}} = V_1\sqrt{T_1}.$$

Simplifying this equation, $T_2/T_1 = 1/0.25 = 4$. This indicates that the change in tool life is

$$\frac{T_2 - T_1}{T_1} = \left(\frac{T_2}{T_1}\right) - 1 = 4 - 1 = 3,$$

or that tool life is increased by 300%. Thus, a reduction in cutting speed has resulted in a major increase in tool life. Note also that, for this problem, the magnitude of $C$ is not relevant.

Allowable Wear Land. We realize that we have to sharpen a knife or a pair of scissors when the quality of the cut deteriorates or the forces required are too high. Similarly, cutting tools need to be replaced (or resharpened) when (a) the surface finish of the machined workpiece begins to deteriorate, (b) cutting forces increase significantly, or (c) the temperature rises significantly. The allowable wear land ($VB$ in Fig. 21.15a) for various machining conditions is given in Table 21.4. For improved dimensional accuracy, tolerances, and surface finish, the allowable wear land may be smaller than the values given in the table.

The recommended cutting speed for a high-speed steel tool is generally the one that yields a tool life of 60 to 120 min, and for a carbide tool, it is 30 to 60 min. However, depending on the particular workpiece, the operation, and the high-productivity considerations due to the use of modern, computer-controlled machine tools, the cutting speeds selected can vary significantly from these values.

Optimum Cutting Speed. We have noted that as cutting speed increases, tool life is reduced rapidly. On the other hand, if the cutting speed is low, tool life is long, but the rate at which material is removed is also low. Thus, there is an optimum cutting speed. Because it involves several other parameters, we will describe this topic further in Section 25.8.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Allowable wear land (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High-speed steel tools</td>
</tr>
<tr>
<td>Turning</td>
<td>1.5</td>
</tr>
<tr>
<td>Face milling</td>
<td>1.5</td>
</tr>
<tr>
<td>End milling</td>
<td>0.3</td>
</tr>
<tr>
<td>Drilling</td>
<td>0.4</td>
</tr>
<tr>
<td>Reaming</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Note: Allowable wear for ceramic tools is about 50% higher. Allowable notch wear, $VB_{max}$ is about twice that for $VB$. 

Section 21.5 Tool Life: Wear and Failure
EXAMPLE 21.3  Effect of Cutting Speed on Material Removal

The effect of cutting speed on the volume of metal removed between tool changes (or resharpenings) can be appreciated by analyzing Fig. 21.16. Assume that a material is being machined in the “one” condition (that is, as cast with a hardness of 265 HB). We note that when the cutting speed is 60 m/min, tool life is about 40 min. Thus, the tool travels a distance of 60 m/min × 40 min = 2400 m before it has to be replaced. However, when the cutting speed is increased to 120 m/min, the tool life is reduced to about 5 min and the tool travels 120 m/min × 5 min = 600 m before it has to be replaced.

Since the volume of material removed is directly proportional to the distance the tool has traveled, it can be seen that by decreasing the cutting speed, more material is removed between tool changes. It is important to note, however, that the lower the cutting speed, the longer is the time required to machine a part, which has a significant economic impact on the operation (see Section 25.8).

21.5.2 Crater Wear

Crater wear occurs on the rake face of the tool, as shown in Fig. 21.15a, and c, and Fig. 21.18, which illustrates various types of tool wear and failures. It readily can be seen that crater wear changes the tool–chip interface contact geometry. The most significant factors influencing crater wear are (a) the temperature at the tool–chip interface and (b) the chemical affinity between the tool and workpiece materials. Additionally, the factors influencing flank wear may affect crater wear.

![Diagram showing types of wear](image_url)

**FIGURE 21.18** (a) Schematic illustrations of types of wear observed on various cutting tools. (b) Schematic illustrations of catastrophic tool failures. A wide range of parameters influence these wear and failure patterns. *Source: Courtesy of V.C. Venkatesh.*
Crater wear generally is attributed to a diffusion mechanism—that is, the movement of atoms across the tool–chip interface. Since diffusion rate increases with increasing temperature, crater wear increases as temperature increases. Note in Fig. 21.19, for example, how rapidly crater wear increases within a narrow range of temperatures. Applying protective coatings to tools is an effective means of slowing the diffusion process and thus reducing crater wear. Typical coatings are titanium nitride, titanium carbide, titanium carbonitride, and aluminum oxide and are described in greater detail in Section 22.6.

In comparing Figs. 21.12 and 21.15a, it can be seen that the location of the maximum depth of crater wear, KT, coincides with the location of the maximum temperature at the tool–chip interface. An actual cross section of this interface, for steel cut at high speeds, is shown in Fig. 21.20. Note that the crater-wear pattern on the tool coincides with its discoloration pattern, which is an indication of the presence of high temperatures.

21.5.3 Other Types of Wear, Chipping, and Fracture

We now describe the factors involved in other types of cutting-tool wear and fracture.

Nose wear (Fig. 21.15a) is the rounding of a sharp tool due to mechanical and thermal effects. It dulls the tool, affects chip formation, and causes rubbing of the tool over the workpiece, raising its temperature and possibly inducing residual stresses on the machined surface. A related phenomenon is edge rounding, as shown in Fig. 21.15a.

An increase in temperature is particularly important for high-speed steel tools, as can be appreciated from Fig. 22.1. Tools also may undergo plastic deformation because of temperature rises in the cutting zone, where temperatures can easily reach 1000°C (1800°F) in machining steels and can be higher in stronger materials.

Notches or grooves observed on cutting tools, as shown in Figs. 21.15a and 21.18, have been attributed to the fact that the region they occupy is the boundary where the chip is no longer in contact with the tool. Known as the depth-of-cut line (DOC) with a depth VN, this boundary oscillates because of inherent variations in the cutting operation. Furthermore, the region is in contact with the machined surface generated during the previous cut; the thin work-hardened layer that can develop will contribute to the formation of the wear groove. If sufficiently deep, the notch can lead to gross chipping of the tool tip because of its reduced cross section, as well as the notch sensitivity of the tool material.

Scale and oxide layers on a workpiece surface also contribute to notch wear, because these layers are hard and abrasive. Thus, light cuts should not be taken on rusted workpieces, and the depth of cut should be greater than the thickness of the oxide film or the work-hardened layer. In Fig. 21.3, for example, the depth of cut, \( t_w \), should be greater than the thickness of the scale on the workpiece.

In addition to being subject to wear, tools may undergo chipping, in which a small fragment from the cutting edge of the tool breaks away. This phenomenon,
which typically occurs in brittle tool materials such as ceramics, is similar to chipping the tip of a pencil if it is too sharp. The chipped fragments from the cutting tool may be very small (microchipping or macrochipping), or they may be relatively large, in which case they are variously called gross chipping, gross fracture, and catastrophic failure (Fig. 21.18).

Chipping also may occur in a region of the tool where a small crack or defect already exists. Unlike wear, which is a gradual process, chipping is a sudden loss of tool material and a corresponding change in its shape. As can be expected, chipping has a major detrimental effect on surface finish, surface integrity, and the dimensional accuracy of the workpiece.

Two main causes of chipping are the following:

- **Mechanical shock** (i.e., impact due to interrupted cutting, as in turning a splined shaft on a lathe)
- **Thermal fatigue** (i.e., cyclic variations in the temperature of the tool in interrupted cutting).

*Thermal cracks* usually are perpendicular to the cutting edge of the tool, as shown on the rake face of the carbide tool in Figs. 21.15d and 21.18a. Major variations in the composition or structure of the workpiece material also may cause chipping.

Chipping can be reduced by selecting tool materials with high impact and thermal-shock resistance, as described in Chapter 22. High positive rake angles can contribute to chipping because of the small included angle of the tool tip, as can be visualized from Fig. 21.3. Also, it is possible for the crater-wear region to progress toward the tool tip, thus weakening the tip because of reduced material volume and causing chipping.

### 21.5.4 Tool-condition Monitoring

With computer-controlled machine tools and automated manufacturing, the reliable and repeatable performance of cutting tools is a critical consideration. As described in Chapters 23 through 25, modern machine tools operate with little direct supervision by a machine operator and generally are enclosed, making it impossible or difficult to monitor the machining operation and the condition of the tool. It is therefore essential to continuously and indirectly monitor the condition of the cutting tool so as to note, for example, wear, chipping, or gross tool failure.

In modern machine tools, tool-condition monitoring systems are integrated into computer numerical control and programmable logic controllers. Techniques for tool-condition monitoring typically fall into two general categories: direct and indirect.

The **direct method** for observing the condition of a cutting tool involves optical measurements of wear, such as the periodic observation of changes in the tool profile. This is a common and reliable technique and is done with a microscope (toolmakers' microscope). However, this requires that the cutting operation be stopped for tool observation. Another direct method involves programming the tool to contact a sensor after every machining cycle; this approach allows the detection of broken tools. Usually, the sensor has the appearance of a pin that must be depressed by the tool tip.

**Indirect methods** of observing tool conditions involve the correlation of the tool condition with parameters such as cutting forces, power, temperature rise, workpiece surface finish, vibration, and chatter. A powerful technique is **acoustic emission** (AE), which utilizes a piezoelectric transducer mounted on a toolholder. The transducer picks up acoustic emissions (typically above 100 kHz), which result from the stress waves generated during cutting. By analyzing the signals, tool wear and chipping can be monitored. This technique is effective particularly in precision-machining
operations, where cutting forces are low because of the small amounts of material removed. Another effective use of AE is in detecting the fracture of small carbide tools at high cutting speeds.

A similar indirect tool-condition monitoring system consists of transducers that are installed in original machine tools or are retrofitted on existing machines. They continually monitor torque and forces during cutting. The signals are preamplified, and a microprocessor analyzes and interprets their content. The system is capable of differentiating the signals that come from different sources, such as tool breakage, tool wear, a missing tool, overloading of the machine tool, or colliding with machine components. The system also can compensate automatically for tool wear and thus improve the dimensional accuracy of the part being machined.

The design of transducers must be such that they are (a) nonintrusive to the machining operation, (b) accurate and repeatable in signal detection, (c) resistant to abuse and the shop-floor environment, and (d) cost effective. Continued progress is being made in the development of sensors, including the use of infrared and fiber-optic techniques for temperature measurement during machining.

In lower cost computer numerical-control machine tools, monitoring is done by tool-cycle time. In a production environment, once the life expectancy of a cutting tool or insert has been determined, it can be entered into the machine control unit, so that the operator is prompted to make a tool or cutter change when that time is reached. This process is inexpensive and fairly reliable, although not totally so, because of the inherent statistical variation in tool life.

## 21.6 Surface Finish and Integrity

Surface finish influences not only the dimensional accuracy of machined parts but also their properties and their performance in service. The term surface finish describes the geometric features of a surface (see Chapter 33), and surface integrity pertains to material properties, such as fatigue life and corrosion resistance, that are strongly influenced by the nature of the surface produced.

With its significant effect on the tool-tip profile, the built-up edge has the greatest influence on surface finish. Figure 21.21 shows the surfaces obtained in two

![Figure 21.21](image-url) Machined surfaces produced on steel (highly magnified), as observed with a scanning-electron microscope: (a) turned surface and (b) surface produced by shaping. Source: Courtesy of J T. Black and S. Ramalingam.
different cutting operations. Note the considerable damage to the surfaces from BUE; its damage is manifested in the scuffing marks, which deviate from the straight grooves that would result from normal machining, as seen in Fig. 21.2. Ceramic and diamond tools generally produce a better surface finish than other tools, largely because of their much lower tendency to form a BUE.

A dull tool has a large radius along its edges, just as the tip of a dull pencil or the cutting edge of a knife. Figure 21.22 illustrates the relationship between the radius of the cutting edge and the depth of cut in orthogonal cutting. Note that at small depths of cut, the rake angle effectively can become negative and the tool simply may ride over the workpiece surface instead of cutting it and producing chips. This is a phenomenon similar to trying to scrape a thin layer from the surface of a stick of butter with a dull knife.

If the tip radius of the tool (not to be confused with the radius $R$ in Fig. 21.15a) is large in relation to the depth of cut, the tool simply will rub over the machined surface. Rubbing will generate heat and induce residual surface stresses, which in turn may cause surface damage, such as tearing and cracking. Consequently, the depth of cut should be greater than the radius on the cutting edge.

In a turning operation, as in other cutting processes, the tool leaves a spiral profile (feed marks) on the machined surface as it moves across the workpiece, as shown in Figs. 21.2 and 21.23. We can see that the higher the feed, $f$, and the smaller the tool-nose radius, $R$, the more prominent these marks will be. It can be shown that the surface roughness for such a case is given by

$$R_t = \frac{f^2}{8R},$$

(21.24)

where $R_t$ is the roughness height, as described in Section 33.3. Although not significant in rough machining operations, feed marks are important in finish machining. (Further details on surface roughness are given for individual machining processes as they are discussed.)

**Vibration and chatter** are described in detail in Section 25.4. For now, it should be recognized that if the tool vibrates or chatter during cutting, it will affect the workpiece surface finish adversely. The reason is that a vibrating tool periodically changes the dimensions of the cut. Excessive chatter also can cause chipping and premature failure of the more brittle cutting tools, such as ceramics and diamond.

Factors influencing **surface integrity** are as follows:

- Temperatures generated during processing and possible metallurgical transformations
- Surface residual stresses
- Severe plastic deformation and strain hardening of the machined surfaces, tearing, and cracking.

Each of these factors can have major adverse effects on the machined part but can be taken care of by careful selection and maintenance of cutting tools and control of process variables.
The difference between *finish machining* and *rough machining* should be emphasized. In finish machining it is important to consider the surface finish to be produced, whereas in rough machining the main purpose is to remove a large amount of material at a high rate. Surface finish is not a primary consideration, since it will be improved during finish machining. Of course, it is important that there be no subsurface-damage results from rough machining that cannot be removed during finish machining (see Fig. 21.21).

## 21.7 Machinability

The *machinability* of a material is usually defined in terms of four factors:

1. Surface finish and surface integrity of the machined part.
2. Tool life.
3. Force and power required.
4. The level of difficulty in chip control.

Thus, good machinability indicates good surface finish and surface integrity, a long tool life, and low force and power requirements. As for chip control, and as stated earlier regarding continuous chips, long, thin, stringy, and curled chips can interfere severely with the cutting operation by becoming entangled in the cutting zone.

Because of the complex nature of cutting operations, it is difficult to establish relationships that quantitatively define the machinability of a particular material. In machining practice, tool life and surface roughness generally are considered to be the most important factors in machinability. Although not used much anymore due to their qualitative and misleading nature, approximate *machinability ratings* (indexes) have been available for many years for each type of material and its condition.

In these ratings, the standard material is AISI 1112 steel (resulfurized), with a rating of 100. This means that, for a tool life of 60 min, this steel should be machined at a cutting speed of 100 ft/min (30 m/min). Examples of typical ratings are 3140 steel at 55; free-cutting brass at 300; 2011 wrought aluminum at 200; pearlitic gray iron at 70; and precipitation-hardening 17-7 steel at 20.

These qualitative aspects of machinability are not sufficient (of course) to guide a machine operator in determining the machining parameters in order to produce an acceptable part economically. Hence, in subsequent chapters, we present several tables in which, for various groups of materials, *specific recommendations* are given regarding such parameters as cutting speed, feed, depth of cut, cutting tools and their shape, and type of cutting fluids.

### 21.7.1 Machinability of Ferrous Metals

This section describes the machinability of steels, alloy steels, stainless steels, and cast irons.

**Steels.** Because steels are among the most important engineering materials (as also noted in Chapter 5) their machinability has been studied extensively. Carbon steels have a wide range of machinability, depending on their ductility and hardness. If a carbon steel is too ductile, chip formation can produce built-up edge, leading to poor surface finish; if the steel is too hard, it can cause abrasive wear of the tool because of the presence of carbides in the steel. Cold-worked carbon steels are desirable from a machinability standpoint.
An important group of steels is **free-machining steels**, containing sulfur and phosphorus. Sulfur forms manganese-sulfide inclusions (second-phase particles), which act as stress raisers in the primary shear zone. As a result, the chips produced break up easily and are small, thus improving machinability. The size, shape, distribution, and concentration of these inclusions significantly influence machinability. Elements such as tellurium and selenium, both of which are chemically similar to sulfur, act as inclusion modifiers in resulfurized steels.

Phosphorus in steels has two major effects: (a) It strengthens the ferrite, causing increased hardness and resulting in better chip formation and surface finish, and (b) it increases hardness and thus causes the formation of short chips instead of continuous stringy ones, thereby improving machinability. Note that soft steels can be difficult to machine because of their tendency for built-up edge formation and the resulting poor surface finish.

In **leaded steels**, a high percentage of lead solidifies at the tips of manganese-sulfide inclusions. In nonresulfurized grades of steel, lead takes the form of dispersed fine particles. Lead is insoluble in iron, copper, and aluminum and their alloys. Because of its low shear strength, lead acts as a *solid* lubricant and is smeared over the tool–chip interface during cutting.

When the temperature developed is sufficiently high, such as at high cutting speeds and feeds, the lead melts directly in front of the tool, acting as a *liquid* lubricant. In addition to having this effect, lead lowers the shear stress in the primary shear zone, thus reducing cutting forces and power consumption. Lead can be used with every grade of steel and is identified by the letter “L” between the second and third numerals in steel identification (e.g., 10L45). (Note that in stainless steels, a similar use of the letter L means “low carbon,” a condition that improves their corrosion resistance.)

However, because lead is a well-known *toxin* and a pollutant, there are serious environmental concerns about its use in steels (estimated at 4500 tons of lead consumption every year in the production of steels). Consequently, there is a continuing trend toward eliminating the use of lead in steels (lead-free steels). Bismuth and tin are substitutes for lead in steels, although their performance is not as good.

**Calcium-deoxidized steels** contain oxide flakes of calcium silicates (CaSO) that reduce the strength of the secondary shear zone and decrease tool–chip interface friction and wear. Increases in temperature are reduced correspondingly. Consequently, these steels produce less crater wear, especially at high cutting speeds.

**Alloy steels** can have a wide variety of compositions and hardnesses. Consequently, their machinability cannot be generalized, although they have higher levels of hardness and other mechanical properties. An important trend in machining these steels is *hard turning*, as described in detail in Section 25.6. Alloy steels at hardness levels of 45 to 65 HRC can be machined with polycrystalline cubic boron-nitride cutting tools, producing good surface finish, integrity, and dimensional accuracy.

**Effects of Various Elements in Steels.** The presence of *aluminum* and *silicon* in steels is always harmful, because these elements combine with oxygen to form aluminum oxide and silicates, which are hard and abrasive. As a result, tool wear increases and machinability is reduced.

*Carbon* and *manganese* have various effects on the machinability of steels, depending on their composition. Plain low-carbon steels (less than 0.15% C) can produce poor surface finish by forming a built-up edge. Cast steels are more abrasive, although their machinability is similar to that of wrought steels. Tool and die steels
are very difficult to machine and usually require annealing prior to machining. The machinability of most steels is improved by cold working, which hardens the material and reduces the tendency for built-up edge formation.

Other alloying elements (such as nickel, chromium, molybdenum, and vanadium) that improve the properties of steels generally reduce machinability. The effect of boron is negligible. Gaseous elements such as hydrogen and nitrogen can have particularly detrimental effects on the properties of steel. Oxygen has been shown to have a strong effect on the aspect ratio of the manganese-sulfide inclusions: The higher the oxygen content, the lower the aspect ratio, and the higher the machinability.

In improving the machinability of steels, however, it is important to consider the possible detrimental effects of the alloying elements on the properties and strength of the machined part in service. At elevated temperatures, for example, lead causes embrittlement of steels (liquid-metal embrittlement and hot shortness; see Section 1.5.2), although at room temperature it has no effect on mechanical properties.

Sulfur can reduce the hot workability of steels severely because of the formation of iron sulfide (unless sufficient manganese is present to prevent such formation). At room temperature, the mechanical properties of resulfurized steels depend on the orientation of the deformed manganese-sulfide inclusions (anisotropy). Rephosphorized steels are significantly less ductile and are produced solely to improve machinability.

Stainless Steels. Austenitic (300 series) steels generally are difficult to machine. Chatter can be a problem, necessitating machine tools with high stiffness. Ferritic stainless steels (also 300 series) have good machinability. Martensitic (400 series) steels are abrasive, tend to form a built-up edge, and require tool materials with high hot hardness and crater-wear resistance. Precipitation-hardening stainless steels are strong and abrasive, thus requiring hard and abrasion-resistant tool materials.

Cast Irons. Gray irons generally are machinable, but they can be abrasive depending on composition, especially pearlite. Free carbides in castings reduce their machinability and cause tool chipping or fracture. Nodular and malleable irons are machinable with hard tool materials.

21.7.2 Machinability of Nonferrous Metals

Following is a summary of the machinability of nonferrous metals and alloys, in alphabetic order:

- **Aluminum** is generally very easy to machine, although the softer grades tend to form a built-up edge, resulting in poor surface finish. Thus, high cutting speeds, high rake angles, and high relief angles are recommended. Wrought aluminum alloys with high silicon content and cast aluminum alloys are generally abrasive; hence, they require harder tool materials. Dimensional tolerance control may be a problem in machining aluminum, because it has a high thermal expansion coefficient and a relatively low elastic modulus.

- **Beryllium** generally is machinable, but because the fine particles produced during machining are toxic, it requires machining in a controlled environment.

- **Cobalt-based alloys** are abrasive and highly work hardening. They require sharp, abrasion-resistant tool materials and low feeds and speeds.
Copper in the wrought condition can be difficult to machine because of built-up edge formation, although cast copper alloys are easy to machine. brasses are easy to machine, especially with the addition of lead \((\text{leaded free-machining brass})\). Note, however, the toxicity of lead and associated environmental concerns. Bronzes are more difficult to machine than brass.

Magnesium is very easy to machine, with good surface finish and prolonged tool life. However, care should be exercised because of its high rate of oxidation \((\text{pyrophonic})\) and the danger of fire.

Molybdenum is ductile and work hardening. It can produce poor surface finish; thus, sharp tools are essential.

Nickel-based alloys and superalloys are work hardening, abrasive, and strong at high temperatures. Their machinability depends on their condition and improves with annealing.

Tantalum is very work hardening, ductile, and soft. It produces a poor surface finish, and tool wear is high.

Titanium and its alloys have very poor thermal conductivity (the lowest of all metals), causing a significant temperature rise and built-up edge. They are highly reactive and can be difficult to machine.

Tungsten is brittle, strong, and very abrasive; hence, its machinability is low, although it improves greatly at elevated temperatures.

Zirconium has good machinability, but it requires a coolant-type cutting fluid because of the danger of explosion and fire.

**Machinability of Miscellaneous Materials**

Thermoplastics generally have low thermal conductivity and a low elastic modulus, and they are thermally softening. Consequently, machining them requires sharp tools with positive rake angles (to reduce cutting forces), large relief angles, small depths of cut and feed, relatively high speeds, and proper support of the workpiece. External cooling of the cutting zone may be necessary to keep the chips from becoming gummy and sticking to the tools. Cooling usually can be achieved with a jet of air, a vapor mist, or water-soluble oils.

Thermosetting plastics are brittle and sensitive to thermal gradients during cutting; machining conditions generally are similar to those of thermoplastics.

Polymer-matrix composites are very abrasive because of the fibers that are present; hence, they are difficult to machine. Fiber tearing, pulling, and edge delamination are significant problems and can lead to severe reduction in the load-carrying capacity of the machined component. Machining of these materials requires careful handling and removal of debris to avoid contact with and inhaling of the fibers.

Metal-matrix and ceramic-matrix composites can be difficult to machine, depending on the properties of the matrix material and the reinforcing fibers.

Graphite is abrasive; it requires sharp, hard, and abrasion-resistant tools.

Ceramics have a steadily improved machinability, particularly with the development of machinable ceramics and nanoceramics (Section 8.2.5) and with the selection of appropriate processing parameters, such as ductile-regime cutting (described in Section 25.7).

Wood is an orthotropic material with properties varying with its grain direction. Consequently, the type of chips and the surfaces produced also vary significantly, depending on the type of wood and its condition. Woodworking, which dates
back to 3000 B.C., remains largely an art. Two basic requirements are generally sharp tools and high cutting speeds.

21.7.4 Thermally Assisted Machining

Metals and alloys that are difficult to machine at room temperature can be machined more easily at elevated temperatures. In thermally assisted machining (also called hot machining), a source of heat (such as a torch, induction coil, electric current, laser-beam, electron-beam, or plasma arc) is focused onto an area just ahead of the cutting tool. First investigated in the early 1940s, this operation typically is carried out above the homologous temperature of $T/T_m = 0.5$ (see Section 1.7, and Tables 1.2 and 3.1). Thus, steels are hot machined above a temperature range of 650° to 750°C (1200° to 1400°F). Although difficult and complicated to perform in production plants, the general advantages of hot machining are (a) reduced cutting forces, (b) increased tool life, (c) higher material-removal rates, and (d) a reduced tendency for vibration and chatter.

SUMMARY

- The Merchant model of orthogonal cutting, although a simple model, nonetheless takes into account all of the major process parameters in machining. Central to the model is that machining takes place through localized deformation occurring on the shear plane.
- Machining processes are often necessary to impart the desired dimensional accuracy, geometric features, and surface-finish characteristics to components, particularly those with complex shapes that cannot be produced economically with other shaping techniques. On the other hand, these processes generally take more time, waste some material in the form of chips, and may have adverse effects on surfaces produced.
- Commonly observed chip types in machining are continuous, built-up edge, discontinuous, and serrated. Important process variables in machining are tool shape and tool material; cutting conditions such as speed, feed, and depth of cut; the use of cutting fluids; and the characteristics of the workpiece material and the machine tool. Parameters influenced by these variables are forces and power consumption, tool wear, surface finish and surface integrity, temperature rise, and dimensional accuracy of the workpiece.
- Temperature rise is an important consideration, since it can have adverse effects on tool life, as well as on the dimensional accuracy and surface integrity of the machined part.
- Two principal types of tool wear are flank wear and crater wear. Tool wear depends on workpiece and tool material characteristics; cutting speed, feed, depth of cut, and cutting fluids; and the characteristics of the machine tool. Tool failure also may occur by notching, chipping, and gross fracture.
- The surface finish of machined components can affect product integrity adversely. Important variables are the geometry and condition of the cutting tool, the type of chip produced, and process variables.
- Machinability generally is defined in terms of surface finish, tool life, force and power requirements, and chip control. The machinability of materials depends on their composition, properties, and microstructure. Thus, proper selection and control of process variables are important.
KEY TERMS

Acoustic emission  
Allowable wear land  
Built-up edge  
Chip  
Chip breaker  
Chip curl  
Chipping of tool  
Clearance angle  
Continuous chip  
Crater wear  
Cutting force  
Cutting ratio  
Depth-of-cut line  
Diffusion  
Discontinuous chip  
Feed marks  
Flank wear  
Friction angle  
Hot machining  
Inclination angle  
Machinability  
Machinability ratings  
Machine tool  
Machining  
Notch wear  
Oblique cutting  
Orthogonal cutting  
Primary shear zone  
Rake angle  
Relief angle  
Rephosphorized steel  
Resulfurized steel  
Secondary shear zone  
Serrated chip  
Shaving  
Shear angle  
Shear plane  
Skiving  
Specific energy  
Surface finish  
Surface integrity  
Taylor equation  
Thrust force  
Tool-condition monitoring  
Tool life  
Turning  
Wear land

BIBLIOGRAPHY

Astakhov, V.P., Metal Cutting Mechanics, CRC Press, 1998.  
Machinery's Handbook, revised periodically, Industrial Press.  

REVIEW QUESTIONS

21.1. Explain why continuous chips are not necessarily desirable.
21.2. Name the factors that contribute to the formation of discontinuous chips.
21.3. Explain the difference between positive and negative rake angles. What is the importance of the rake angle?
21.4. Comment on the role and importance of the relief angle.
21.5. Explain the difference between discontinuous chips and segmented chips.
21.6. Why should we be interested in the magnitude of the thrust force in cutting?
21.7. What are the differences between orthogonal and oblique cutting?
21.8. Is there any advantage to having a built-up edge on a tool? Explain.
21.9. What is the function of chip breakers? How do they function?
21.10. Identify the forces involved in a cutting operation. Which of these forces contributes to the power required?
21.11. Explain the characteristics of different types of tool wear.
21.12. List the factors that contribute to poor surface finish in cutting.
21.13. Explain what is meant by the term machinability and what it involves. Why does titanium have poor machinability?
QUALITATIVE PROBLEMS


21.15. Is material ductility important for machinability? Explain.

21.16. Explain why studying the types of chips produced is important in understanding cutting operations.

21.17. Why do you think the maximum temperature in orthogonal cutting is located at about the middle of the tool–chip interface? (*Hint: Note that the two sources of heat are (a) shearing in the primary shear plane and (b) friction at the tool–chip interface.*)

21.18. Tool life can be almost infinite at low cutting speeds. Would you then recommend that all machining be done at low speeds? Explain.

21.19. Explain the consequences of allowing temperatures to rise to high levels in cutting.

21.20. The cutting force increases with the depth of cut and decreasing rake angle. Explain why.

21.21. Why is it not always advisable to increase the cutting speed in order to increase the production rate?

21.22. What are the consequences if a cutting tool chips?

21.23. What are the effects of performing a cutting operation with a dull tool? A very sharp tool?

21.24. To what factors do you attribute the difference in the specific energies in machining the materials shown in Table 21.2? Why is there a range of energies for each group of materials?

21.25. Explain why it is possible to remove more material between tool sharpenings by lowering the cutting speed.

21.26. Noting that the dimension \( d \) in Fig. 21.4a is very small, explain why the shear strain rate in metal cutting is so high.

21.27. Explain the significance of Eq. (21.7).


21.29. Describe the consequences of exceeding the allowable wear land (Table 21.4) for various cutting-tool materials.

21.30. Comment on your observations regarding the hardness variations shown in Fig. 21.6a.

21.31. Why does the temperature in cutting depend on the cutting speed, feed, and depth of cut? Explain in terms of the relevant process variables.

21.32. You will note that the values of \( a \) and \( b \) in Eq. (21.19b) are higher for high-speed steels than for carbides. Why is this so?

21.33. As shown in Fig. 21.14, the percentage of the total cutting energy carried away by the chip increases with increasing cutting speed. Why?

21.34. Describe the effects that a dull tool can have on cutting operations.

21.35. Explain whether it is desirable to have a high or low (a) \( n \) value and (b) \( C \) value in the Taylor tool-life equation.

21.36. The tool-life curve for ceramic tools in Fig. 21.17 is to the right of those for other tool materials. Why?

21.37. Why are tool temperatures low at low cutting speeds and high at high cutting speeds?

21.38. Can high-speed machining be performed without the use of a cutting fluid?

21.39. Given your understanding of the basic metal-cutting process, what are the important physical and chemical properties of a cutting tool?

QUANTITATIVE PROBLEMS

21.40. Let \( n = 0.5 \) and \( C = 300 \) in the Taylor equation for tool wear. What is the percent increase in tool life if the cutting speed is reduced by (a) 50% and (b) 75%?

21.41. Assume that, in orthogonal cutting, the rake angle is 25° and the coefficient of friction is 0.2. Using Eq. (21.3), determine the percentage increase in chip thickness when the friction is doubled.

21.42. Derive Eq. (21.11).

21.43. Taking carbide as an example and using Eq. (21.19b), determine how much the feed should be reduced in order to keep the mean temperature constant when the cutting speed is doubled.

21.44. Using trigonometric relationships, derive an expression for the ratio of shear energy to frictional energy in orthogonal cutting, in terms of angles \( \alpha \), \( \beta \), and \( \phi \) only.

21.45. An orthogonal cutting operation is being carried out under the following conditions: \( t_o = 0.1 \) mm, \( t_c = 0.2 \) mm, width of cut = 5 mm, \( V = 2 \) m/s, rake angle = 10°, \( F_c = 500 \) N, and \( F_t = 200 \) N. Calculate the percentage of the total energy that is dissipated in the shear plane.

21.46. Explain how you would go about estimating the \( C \) and \( n \) values for the four tool materials shown in Fig. 21.17.


21.48. Assume that, in orthogonal cutting, the rake angle, \( \alpha \), is 20° and the friction angle, \( \beta \), is 35° at the chip–tool interface. Determine the percentage change in chip thickness when the friction angle is 50°. (*Note: do not use Eq. (21.3) or Eq. (21.4)).

21.49. Show that, for the same shear angle, there are two rake angles that give the same cutting ratio.
21.50. With appropriate diagrams, show how the use of a cutting fluid can change the magnitude of the thrust force, \( F_n \), in Fig. 21.11.

21.51. For a turning operation using a ceramic cutting tool, if the speed is increased by 50%, by what factor must the feed rate be modified to obtain a constant tool life? Use \( n = 0.5 \) and \( y = 0.6 \).

21.52. In Example 21.3, if the cutting speed \( V \) is doubled, will the answer be different? Explain.

21.53. Using Eq. (21.24), select an appropriate feed for \( R = 1 \) mm and a desired roughness of 1 \( \mu \)m. How would you adjust this feed to allow for nose wear of the tool during extended cuts? Explain your reasoning.

21.54. With a carbide tool, the temperature in a cutting operation is measured as 1200°F when the speed is 300 ft/min and the feed is 0.002 in./rev. What is the approximate temperature if the speed is doubled? What speed is required to lower the maximum cutting temperature to 900°F?

21.55. Assume that you are an instructor covering the topics described in this chapter and you are giving a quiz on the numerical aspects to test the understanding of the students. Prepare two quantitative problems and supply the answers.

SYNTHESIS, DESIGN, AND PROJECTS

21.56. As we have seen, chips carry away the majority of the heat generated during machining. If chips did not have this capacity, what suggestions would you make in order to be able to carry out machining processes without excessive heat? Explain.

21.57. Tool life is increased greatly when an effective means of cooling and lubrication is implemented. Design methods of delivering this fluid to the cutting zone and discuss the advantages and limitations of your design.

21.58. Design an experimental setup whereby orthogonal cutting can be simulated in a turning operation on a lathe.

21.59. Describe your thoughts on whether chips produced during machining can be used to make useful products. Give some examples of possible products, and comment on their characteristics and differences if the same products were made by other manufacturing processes. Which types of chips would be desirable for this purpose?

21.60. Recall that cutting tools can be designed so that the tool-chip contact length is reduced by recessing the rake face of the tool some distance away from its tip. Explain the possible advantages of such a tool.

21.61. Recall that the chip-formation mechanism also can be observed by scraping the surface of a stick of butter with a sharp knife. Using butter at different temperatures, including frozen butter, conduct such an experiment. Keep the depth of cut constant and hold the knife at different angles (to simulate the tool rake angle), including oblique scraping. Describe your observations regarding the type of chips produced. Also, comment on the force that your hand feels while scraping and whether you observe any chatter when the butter is very cold.

21.62. Experiments have shown that it is possible to produce thin, wide chips, such as 0.08 mm (0.003 in.) thick and 10 mm (4 in.) wide, which would be similar to the dimensions of a rolled sheet. Materials have been aluminum, magnesium, and stainless steel. A typical setup would be similar to orthogonal cutting, by machining the periphery of a solid round bar with a straight tool moving radially inward. Describe your thoughts regarding producing thin metal sheets by this method, taking into account the metal’s surface characteristics and properties.

21.63. Describe your thoughts regarding the recycling of chips produced during machining in a plant. Consider chips produced by dry cutting versus those produced by machining with a cutting fluid.