Forming and Shaping Processes and Equipment

PART III

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

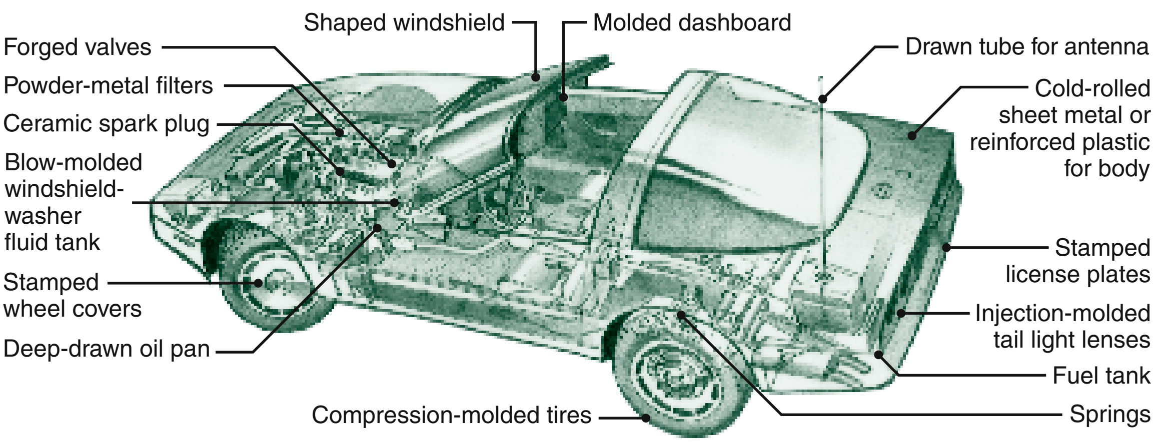


FIGURE III.1 Formed and shaped parts in a typical automobile.

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.

TABLE III.1

General Characteristics of Forming and Shaping Processes	
Process	**Characteristics**
Rolling	
Flat	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
Shape	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
Forging	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
Extrusion	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
Drawing	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
Sheet-metal forming	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
Powder metallurgy	Production of simple or complex shapes by compacting and sintering metal powders; moderate die and equipment cost; low labor cost and skill
Processing of plastics and composite materials	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
Forming and shaping of ceramics	Production of discrete products by various shaping, drying, and firing processes; low-to-moderate die and equipment cost; requires moderate-to-high operator skill

CHAPTER

13 Metal-Rolling Processes and Equipment

- This first chapter of Part III on the forming and shaping of metallic and non-metallic materials describes the rolling of metals, perhaps the most important metal-forming operation based on volume of metals rolled.
- The chapter begins with a description of the flat-rolling process, analyzing the force, torque, and power required in terms of relevant material and process parameters, as well as a review of defects and their causes in rolled products.
- Shape-rolling processes are then described, where workpieces are passed through a series of shaped rolls.
- Special rolling processes such as cross rolling, ring rolling, thread rolling, tube rolling, and tube piercing are also discussed.
- The chapter ends with a description of the characteristics of rolling mills and roll arrangements for specific products.

Typical products made by various rolling processes: Plates for ships, bridges, structures, machines; sheet metal for car bodies, aircraft fuselages, appliances, containers; foil for packaging; I-beams, railroad rails, architectural shapes, large rings, seamless pipe and tubing; bolts, screws, and threaded components.

Alternative processes: Continuous casting, extrusion, drawing, machining of threaded components.

13.1 Introduction

Rolling is the process of reducing the thickness or changing the cross section of a long workpiece by compressive forces applied through a set of **rolls** (Fig. 13.1). This process is similar to rolling dough with a rolling pin to reduce its thickness. Rolling, which accounts for about 90% of all metals produced by metalworking processes, was first developed in the late 1500s. Modern steelmaking practices and the production of various ferrous and nonferrous metals and alloys now generally involve combining continuous casting with rolling processes. This greatly improves productivity and lowers production costs, as described in Section 5.4. Nonmetallic materials also are rolled to reduce their thickness and enhance their properties. Typical applications are in the rolling of plastics, powder metals, ceramic slurry, and hot glass.

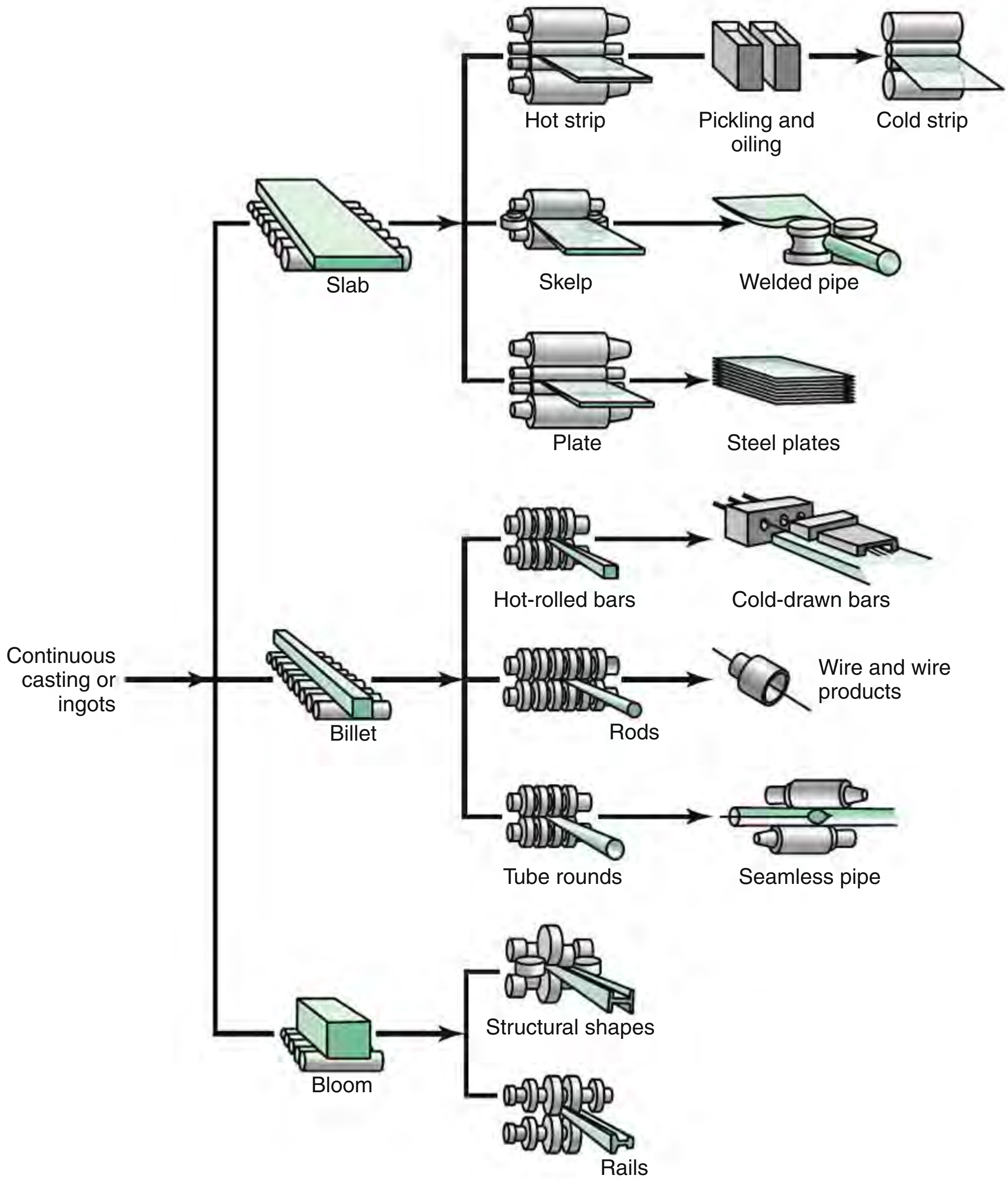


FIGURE 13.1 Schematic outline of various flat-rolling and shape-rolling processes. *Source*: After American Iron and Steel Institute.

Rolling first is carried out at elevated temperatures (hot rolling). During this phase, the coarse-grained, brittle, and porous structure of the ingot (or the continuously cast metal) is broken down into a *wrought structure* having a finer grain size and enhanced properties, such as increased strength and hardness. Subsequently, rolling typically is carried out at room temperature (cold rolling), whereby the rolled product has higher strength and hardness and a better surface finish. However, it requires more energy (because of the higher strength of the material at room temperature) and will result in a product with anisotropic properties (due to preferred orientation or mechanical fibering; see Section 1.6).

Plates generally have a thickness of more than 6 mm (0.25 in.) and are used for structural applications, such as ship hulls, boilers, bridges, machinery, and nuclear vessels. Plates can be as thick as 300 mm (12 in.) for large structural supports, 150 mm (6 in.) for reactor vessels, and 100 to 125 mm (4 to 5 in.) for machinery frames and warships.

Sheets generally are less than 6 mm thick and typically are provided to manufacturing facilities as coils—weighing as much as 30,000 kg (33 tons)—or as flat sheets for further processing into various products. Sheets typically are used for automobile and aircraft bodies, appliances, food and beverage containers, and kitchen and office equipment. Commercial aircraft fuselages and trailer bodies usually are made of a minimum of 1-mm (0.04-in.) thick aluminum-alloy sheets. For example, the skin thickness of a Boeing 747 fuselage is 1.8 mm (0.07 in.) and of a Lockheed L1011 is 1.9 mm (0.075 in.). Steel sheets used for automobile and appliance bodies are typically about 0.7 mm (0.03 in.) thick. Aluminum beverage cans are made from sheets 0.28 mm (0.01 in.) thick. After processing into a can, this sheet metal becomes a cylindrical body with a wall thickness of 0.1 mm (0.004 in.). Aluminum **foil** (typically used for wrapping candy and chewing gum) has a thickness of 0.008 mm (0.0003 in.), although thinner foils down to 0.003 mm (0.0001 in.) also can be produced with a variety of metals.

This chapter describes the fundamentals of **flat-rolling** and various **shape-rolling** operations, examines the production of seamless tubing and pipe, and discusses the important factors involved in rolling practices.

13.2 The Flat-rolling Process

A schematic illustration of the *flat-rolling* process is shown in Fig. 13.2a. A metal strip of thickness h_0 enters the **roll gap** and is reduced to thickness h_f by a pair of rotating rolls, each powered individually by electric motors. The surface speed of the rolls is V_r. The velocity of the strip increases from its entry value of V_o as it moves through the roll gap; the velocity of the strip is highest at the exit from the roll gap and is denoted as V_f. The metal accelerates in the roll gap in the same manner as an incompressible fluid flowing through a converging channel.

Because the surface speed of the rigid roll is constant, there is *relative sliding* between the roll and the strip along the arc of contact in the roll gap, L. At one point along the contact length (called the **neutral point** or **no-slip point**) the velocity of the strip is the same as that of the roll. To the left of this point, the roll moves faster than the strip; to the right of this point, the strip moves faster than the roll. Consequently, the frictional forces—which oppose motion between two sliding bodies—act on the strip as shown in Fig. 13.2b.

The rolls pull the material into the roll gap through a *net frictional force* on the material. Thus, the net frictional force must be to the right in Fig. 13.2b. This also means that the frictional force to the left of the neutral point must be higher than the friction force to the right. Although friction is necessary for rolling materials (just as it is in driving a car on a road), energy is dissipated in overcoming friction. Thus, increasing friction also increases rolling forces and power requirements. Furthermore, high friction could damage the surface of the rolled product (or cause sticking, as can occur in rolling dough). Thus, a compromise is made in practice: Low and controlled friction is induced in rolling through the use of effective lubricants.

The maximum possible **draft** is defined as the difference between the initial and final strip thicknesses, or $(h_o - h_f)$. It can be shown that this quantity is a function

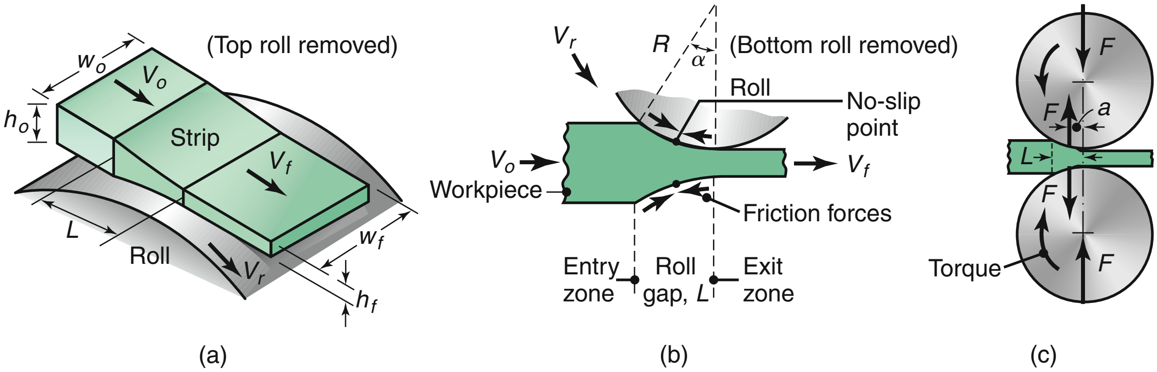


FIGURE 13.2 (a) Schematic illustration of the flat-rolling process. (b) Friction forces acting on strip surfaces. (c) Roll force, F, and torque, T, acting on the rolls. The width of the strip, w, usually increases during rolling, as shown later in Fig. 13.5.

of the roll radius, R, and the coefficient of friction, μ, between the strip and the roll by the following relationship:

$$h_o - h_f = \mu^2 R. \tag{13.1}$$

Thus, as expected, the higher the friction and the larger the roll radius, the greater the maximum possible draft becomes. Note that this situation is similar to the use of large tires (high R) and rough treads (high μ) on farm tractors and off-road earthmoving equipment, thus permitting the vehicles to travel over rough terrain without skidding.

13.2.1 Roll Force, Torque, and Power Requirements

The rolls apply pressure on the flat strip in order to reduce its thickness, resulting in a *roll force*, F, as shown in Fig. 13.2c. Note that this force appears in the figure as perpendicular to the plane of the strip, rather than at an angle. This is because, in practice, the arc of contact is very small compared with the roll radius, so we can assume that the roll force is perpendicular to the strip without causing significant error in calculations. The roll force in flat rolling can be estimated from the formula

$$F = LwY_{\text{avg}}, \tag{13.2}$$

where L is the roll-strip contact length, w is the width of the strip, and Y_{avg} is the average true stress (see Section 2.2) of the strip in the roll gap. Equation (13.2) is for a *frictionless* situation; however, an estimate of the *actual roll force*, including friction, may be made by increasing this calculated force by about 20%.

The *torque* on the roll is the product of F and a. The power required per roll can be estimated by assuming that F acts in the middle of the arc of contact; thus, in Fig. 13.2c, $a = L/2$. Therefore, the *total power* (for two rolls), in S.I. units, is

$$\text{Power (in kW)} = \frac{2\pi FLN}{60{,}000} \tag{13.3}$$

where F is in newtons, L is in meters, and N is the revolutions per minute of the roll. In traditional English units, the total power can be expressed as

$$\text{Power (in hp)} = \frac{2\pi FLN}{33{,}000} \tag{13.4}$$

where F is in pounds and L is in feet.

EXAMPLE 13.1 Calculation of Roll Force and Torque in Flat-rolling

An annealed copper strip 9 in. (228 mm) wide and 1.00 in. (25 mm) thick is rolled to a thickness of 0.80 in. (20 mm) in one pass. The roll radius is 12 in. (300 mm), and the rolls rotate at 100 rpm. Calculate the roll force and the power required in this operation.

Solution The roll force is determined from Eq. (13.2), in which L is the roll-strip contact length. It can be shown from simple geometry that this length is given approximately by

$$L = \sqrt{R(h_o - h_f)} = \sqrt{12(1.00 - 0.80)} = 1.55 \text{ in.}$$

The average true stress, Y_{avg}, for annealed copper is determined as follows: First note that the absolute value of the true strain that the strip undergoes in this operation is

$$\varepsilon = \ln\left(\frac{1.00}{0.80}\right) = 0.223.$$

Referring to Fig. 2.6, note that annealed copper has a true stress of about 12,000 psi in the unstrained condition, and at a true strain of 0.223, the true stress is 40,000 psi. Thus, the average true stress is (12,000 + 40,000)/2 = 26,000 psi. We can now define the roll force as

$$F = LwY_{avg} = (1.55)(9)(26{,}000)$$
$$= 363{,}000 \text{ lb} = 1.6 \text{ MN}.$$

The total power is calculated from Eq. (13.4), with $N = 100$ rpm. Thus,

$$\text{Power} = \frac{2\pi FLN}{33{,}000} = \frac{2\pi(363{,}000)(1.55/12)(100)}{33{,}000}$$
$$= 898 \text{ hp} = 670 \text{ kW}.$$

Exact calculation of the force and the power requirements in rolling is difficult because of the uncertainties involved in (a) determining the exact contact geometry between the roll and the strip and (b) accurately estimating both the coefficient of friction and the strength of the material in the roll gap, particularly for hot rolling because of the sensitivity of the strength of the material to strain rate (see Section 2.2.7.)

Reducing Roll Force. Roll forces can cause significant deflection and flattening of the rolls (as it does in a rubber tire). Such changes in turn will affect the rolling operation. Also, the columns of the **roll stand** (including the housing, chocks, and bearings, as shown in Fig. 13.3) may deflect under high roll forces to such an extent that the roll gap can open up significantly. Consequently, the rolls have to be set closer than originally calculated in order to compensate for this deflection and to obtain the desired final thickness.

Roll forces can be reduced by the following means:

- Reducing friction at the roll–workpiece interface
- Using smaller diameter rolls to reduce the contact area
- Taking smaller reductions per pass to reduce the contact area
- Rolling at elevated temperatures to lower the strength of the material
- Applying front and/or back tensions to the strip

Among these strategies, the last requires some elaboration. An effective method of reducing roll forces is to apply longitudinal **tension** to the strip during rolling (as a result of which the compressive stresses required to plastically deform the material become smaller). Because they require high roll forces, tensions are important particularly in rolling high-strength metals. Tensions can be applied to the strip at either the entry zone (**back tension**), the exit zone (**front tension**), or both. Back tension is applied to the sheet by applying a braking action to the reel that supplies the sheet into the roll gap (*pay-off reel*) by some suitable means. Front tension is applied by increasing the rotational speed of the *take-up reel*. Although it has limited and specialized applications, rolling also can be carried out by front tension only, with no power supplied to the rolls—a process known as **Steckel rolling**.

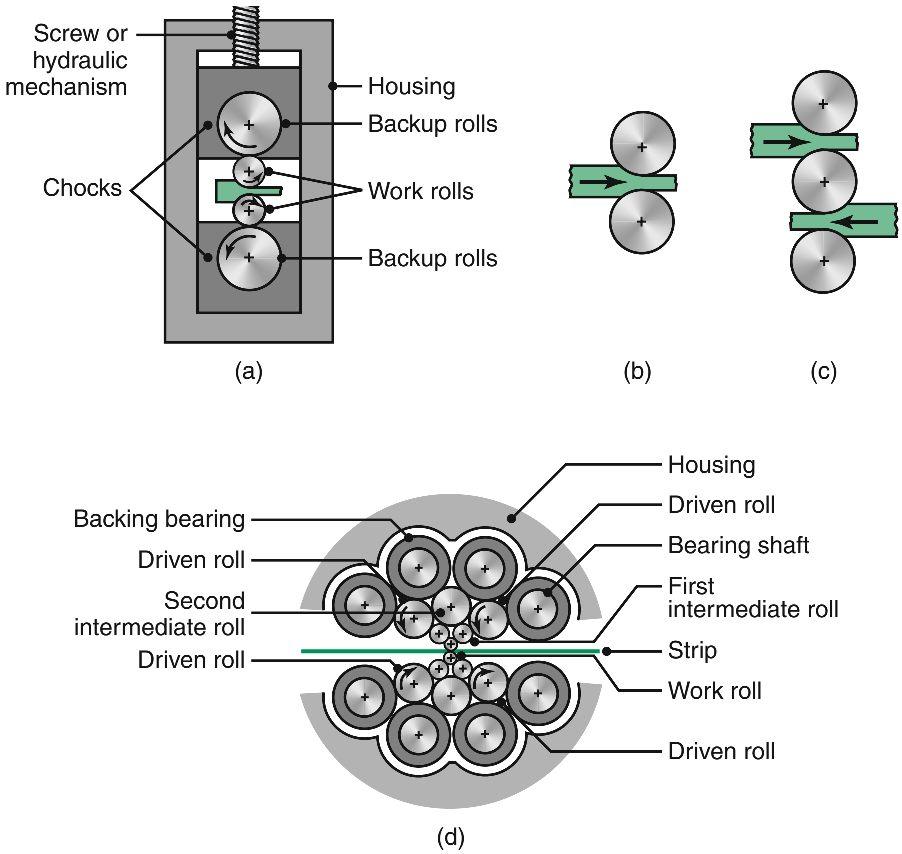


FIGURE 13.3 Schematic illustration of various roll arrangements: (a) four-high rolling mill showing various features. The stiffness of the housing, the rolls, and the roll bearings are all important in controlling and maintaining the thickness of the rolled strip; (b) two-high mill; (c) three-high mill; and (d) cluster (or *Sendzimir*) mill.

13.2.2 Geometric Considerations

Because of the forces acting on them, rolls undergo changes in shape during rolling. Just as a straight beam deflects under a transverse load, roll forces tend to bend the rolls *elastically* during rolling (Fig. 13.4a). As expected, the higher the elastic modulus of the roll material, the smaller the roll deflection.

As a result of roll bending, the rolled strip tends to be thicker at its center than at its edges (**crown**). The usual method of avoiding this problem is to grind the rolls in such a way that their diameter at the center is slightly larger than at their edges (**camber**). Thus, when the roll bends, the strip being rolled now has a constant thickness along its width (Fig. 13.4b). For rolling sheet metals, the radius of the maximum camber point is generally 0.25 mm (0.01 in.) greater than that at the edges of the roll. However, as expected, a particular camber is correct only for a certain load and strip width. To reduce the effects of deflection, the rolls also can be subjected to external bending by applying moments at their bearings

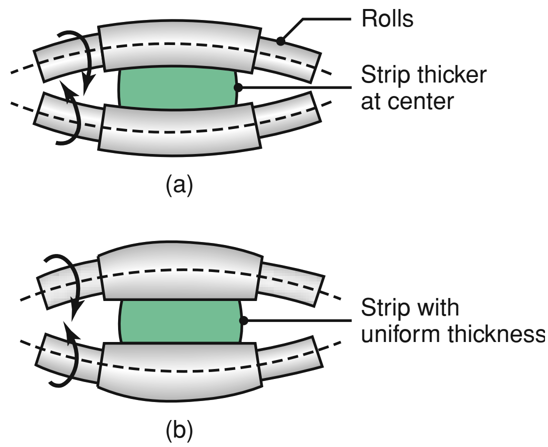


FIGURE 13.4 (a) Bending of straight cylindrical rolls caused by roll forces. (b) Bending of rolls ground with camber, producing a strip with uniform thickness through the strip width. Deflections have been exaggerated for clarity.

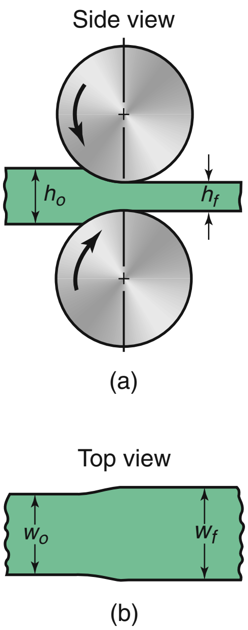


FIGURE 13.5 Spreading in flat rolling. Note that similar spreading can be observed when dough is rolled with a rolling pin.

(a technique demonstrated simply by bending a wooden stick at its ends, a manipulation that simulates camber).

Because of the heat generated by plastic deformation during rolling, rolls can become slightly barrel shaped (**thermal camber**). Unless compensated for by some means, this condition can produce strips that are thinner at the center than at the edges. Consequently, the total (or final) camber can be controlled by adjusting the location and the flow rate of the coolant along the length of the rolls during hot rolling.

Roll forces also tend to *flatten* the rolls elastically, producing an effect much like the flattening of automobile tires under load. Flattening of the rolls is undesirable, as it results, in effect, in a larger roll radius. This, in turn, means a larger contact area for the same draft, and the roll force increases because of the now larger contact area.

Spreading. In rolling plates and sheets with high width-to-thickness ratios, the width of the strip remains effectively constant during rolling. However, with smaller ratios (such as a strip with a square cross section), its width increases significantly as it passes through the rolls (an effect commonly observed in the rolling of dough with a rolling pin). This increase in width is called *spreading* (Fig. 13.5). In the calculation of the roll force, the width w in Eq. (13.2) then is taken as an average width.

It can be shown that spreading increases with (a) decreasing width-to-thickness ratio of the entering strip (because of reduction in the width constraint), (b) increasing friction, and (c) decreasing ratio of the roll radius to the strip thickness. The last two effects are due to the increased longitudinal constraint of the material flow in the roll gap. Spreading can be prevented also by using additional rolls (with vertical axes) in contact with the edges of the rolled product in the roll gap (*edger mills*), thus providing a physical constraint to spreading.

13.2.3 Vibration and Chatter

Vibration and *chatter* can have significant effects on product quality and the productivity of metalworking operations. Chatter, generally defined as *self-excited vibration*, can occur in rolling as well as in extrusion, drawing, machining, and grinding operations. In rolling, it leads to periodic variations in the thickness of the rolled sheet and in its surface finish and, consequently, can lead to excessive scrap (see Table 40.3). Chatter in rolling has been found to occur predominantly in *tandem mills*. Chatter is very detrimental to productivity; it has been estimated, for example, that modern rolling mills could operate at up to 50% higher speeds were it not for chatter.

Chatter is a very complex phenomenon (see also Section 25.4) and results from interactions between the structural dynamics of the mill stand and the dynamics of the rolling operation. Rolling speed and lubrication are found to be the two most important parameters. Although not always practical to implement, it also has been suggested that chatter can be reduced by increasing the distance between the stands of the rolling mill, increasing the strip width, decreasing the reduction per pass (draft), increasing the roll radius, increasing the strip-roll friction, and incorporating dampers in the roll supports.

13.3 Flat-rolling Practice

The initial rolling steps (*breaking down*) of the material typically is done by **hot rolling** (above the recrystallization temperature of the metal; see Section 1.7). As described in Section 10.2 and illustrated in Fig. 10.2, a **cast structure** typically is dendritic, and it

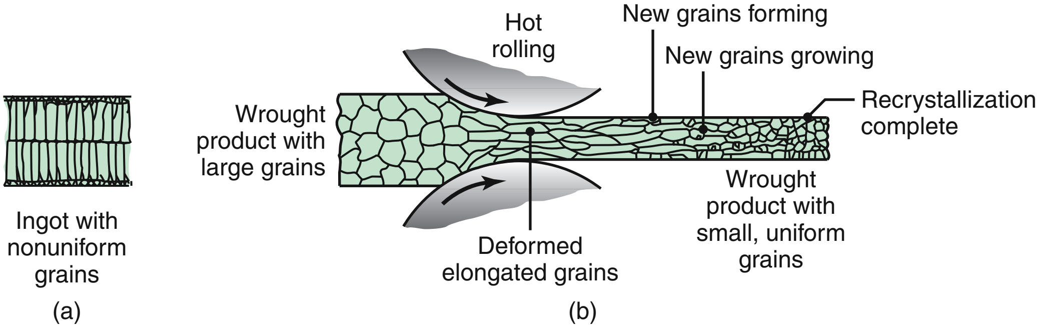


FIGURE 13.6 Changes in the grain structure of cast or of large-grain wrought metals during hot rolling. Hot rolling is an effective way to reduce grain size in metals for improved strength and ductility. Cast structures of ingots or continuous castings are converted to a wrought structure by hot working.

includes coarse and nonuniform grains; this structure usually is brittle and may be porous. Hot rolling converts the cast structure to a **wrought structure** (Fig. 13.6) with finer grains and enhanced ductility, both of which result from the breaking up of brittle grain boundaries and the closing up of internal defects (especially porosity). Typical temperature ranges for hot rolling are about 450°C (850°F) for aluminum alloys, up to 1250°C (2300°F) for alloy steels, and up to 1650°C (3000°F) for refractory alloys (see also Table 14.3).

The product of the first hot-rolling operation is called a **bloom**, a **slab**, or a **billet** (see Fig. 13.1). A bloom usually has a square cross section, at least 150 mm (6 in.) on the side; a slab usually is rectangular in cross section. Blooms are processed further by *shape rolling* into structural shapes such as I-beams and railroad rails (Section 13.5). Slabs are rolled into plates and sheets. Billets usually are square (with a cross-sectional area smaller than blooms) and later are rolled into various shapes, such as round rods and bars, using shaped rolls. Hot-rolled round rods (**wire rods**) are used as the starting material for rod- and wire-drawing operations (Chapter 15).

In the hot rolling of blooms, billets, and slabs, the surface of the material usually is **conditioned** (prepared for a subsequent operation) prior to rolling them. Conditioning is often done by means of a torch (*scarfing*) to remove heavy scale or by rough grinding to smoothen surfaces. Prior to cold rolling, the scale developed during hot rolling may be removed by *pickling* with acids (acid etching), by such mechanical means as blasting with water, or by grinding to remove other defects as well.

Cold rolling is carried out at room temperature and, compared with hot rolling, produces sheets and strips with a much better surface finish (because of lack of scale), better dimensional tolerances, and enhanced mechanical properties (because of strain hardening).

Pack rolling is a flat-rolling operation in which two or more layers of metal are rolled together, thus improving productivity. *Aluminum foil*, for example, is pack rolled in two layers, so only the top and bottom outer layers have been in contact with the rolls. Note that one side of aluminum foil is matte, while the other side is shiny. The foil-to-foil side has a matte and satiny finish, but the foil-to-roll side is shiny and bright because it has been in contact under high contact stresses with the polished rolls during rolling.

Rolled mild steel, when subsequently stretched during sheet-forming operations, undergoes *yield-point elongation* (Section 16.3)—a phenomenon that causes surface irregularities called *stretcher strains* or *Lüder's bands*. To correct this situation, the

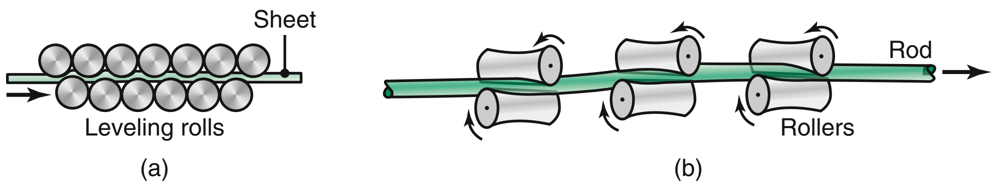


FIGURE 13.7 (a) A method of roller leveling to flatten rolled sheets. (b) Roller leveling to straighten drawn bars.

sheet metal is subjected to a final, light pass of 0.5 to 1.5% reduction known as **temper rolling** or **skin pass** shortly before stretching.

A rolled sheet may not be sufficiently flat as it leaves the roll gap, due to factors such as variations in the incoming material or in the processing parameters during rolling. To improve flatness, the rolled strip typically goes through a series of **leveling rolls**. Several roller arrangements are used, as shown in Fig. 13.7. The workpiece is flexed in opposite directions as it passes through the sets of rollers. Each roll usually is driven separately by an individual electric motor.

13.3.1 Defects in Rolled Plates and Sheets

Defects may be present on the surfaces of rolled plates and sheets, or there may be internal structural defects. Defects are undesirable not only because they compromise surface appearance, but also because they may adversely affect strength, formability, and other manufacturing characteristics. Several surface defects (such as scale, rust, scratches, gouges, pits, and cracks) have been identified in sheet metals. These defects may be caused by inclusions and impurities in the original cast material or by various other conditions related to material preparation and to the rolling operation.

Wavy edges on sheets (Fig. 13.8a) are the result of roll bending. The strip is thinner along its edges than at its center (see Fig. 13.4a); thus, the edges elongate more than the center. Consequently, the edges buckle because they are constrained by the central region from expanding freely in the longitudinal (rolling) direction. The **cracks** shown in Fig. 13.8b and c are usually the result of poor material ductility at the rolling temperature. Because the quality of the edges of the sheet may affect sheet-metal-forming operations, edge defects in rolled sheets often are removed by shearing and slitting operations (Section 16.2). **Alligatoring** (Fig. 13.8d) is a complex phenomenon and typically is caused by nonuniform bulk deformation of the billet during rolling or by the presence of defects in the original cast material.

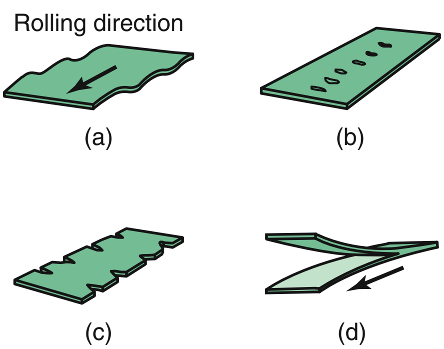


FIGURE 13.8 Schematic illustration of typical defects in flat rolling: (a) wavy edges; (b) zipper cracks in the center of the strip; (c) edge cracks; and (d) alligatoring.

13.3.2 Other Characteristics of Rolled Metals

Residual Stresses. Because of nonuniform deformation of the material in the roll gap, residual stresses can develop in rolled plates and sheets, especially during cold rolling. Small-diameter rolls or small thickness reductions per pass tend to plastically deform the metal more at its surfaces than in the bulk (Fig. 13.9a). This situation results in compressive residual stresses on the surfaces and tensile stresses in the bulk. Conversely, large-diameter rolls or high reductions per pass tend to deform the bulk more than the surfaces (Fig. 13.9b). This is due to the higher frictional constraint at the surfaces along the arc of contact—a situation that produces residual stress distributions that are the opposite of those with small-diameter rolls.

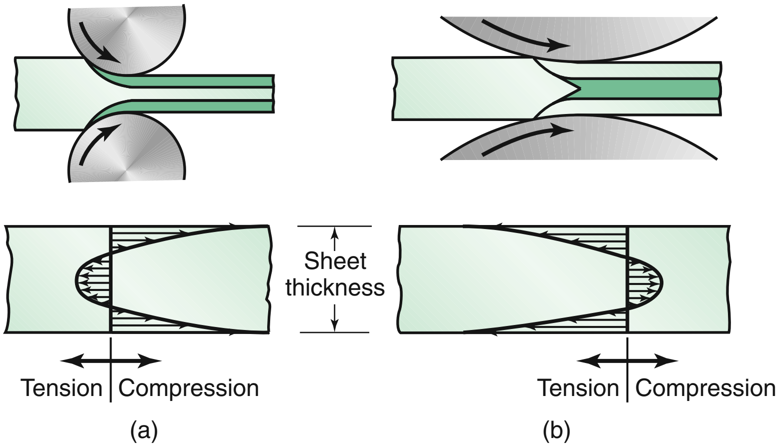


FIGURE 13.9 (a) Residual stresses developed in rolling with small-diameter rolls or at small reductions in thickness per pass. (b) Residual stresses developed in rolling with large-diameter rolls or at high reductions per pass. Note the reversal of the residual stress patterns.

Dimensional Tolerances. Thickness tolerances for cold-rolled sheets usually range from ±0.1 to 0.35 mm (±0.004 to 0.014 in.), depending on the thickness. Tolerances are much greater for hot-rolled plates, because of thermal effects. *Flatness tolerances* are usually within ±15 mm/m (±3/16 in./ft) for cold rolling and ±55 mm/m (5/8 in./ft) for hot rolling.

Surface Roughness. The ranges of surface roughness in cold and hot rolling are given in Fig. 23.13, which, for comparison, includes other manufacturing processes. Note that cold rolling can produce a very fine surface finish; hence, products made of cold-rolled sheets may not require additional finishing operations, depending on the application. Note also that hot rolling and sand casting produce the same range of surface roughness.

Gage Numbers. The thickness of a sheet usually is identified by a *gage number:* the smaller the number, the thicker the sheet. Several numbering systems are used in industry, depending on the type of sheet metal being classified. Rolled sheets of copper and of brass also are identified by thickness changes during rolling, such as ¼ hard, ½ hard, and so on.

13.4 Rolling Mills

Several types of *rolling mills* and equipment are available with diverse roll arrangements. Although the equipment for hot and cold rolling is essentially the same, there are important differences in the roll materials, process parameters, lubricants, and cooling systems. The design, construction, and operation of rolling mills (Fig. 13.10) require major investments. Highly automated mills produce close-tolerance, high-quality plates and sheets at high production rates and low cost per unit weight, particularly when integrated with continuous casting. Rolling speeds may range up to 40 m/s (130 ft/s). The width of rolled products may range up to 5 m (200 in.).

Two-high rolling mills (Fig. 13.3b) are used for hot rolling in initial breakdown passes (*primary roughing* or **cogging mills**) on cast ingots or in continuous casting,

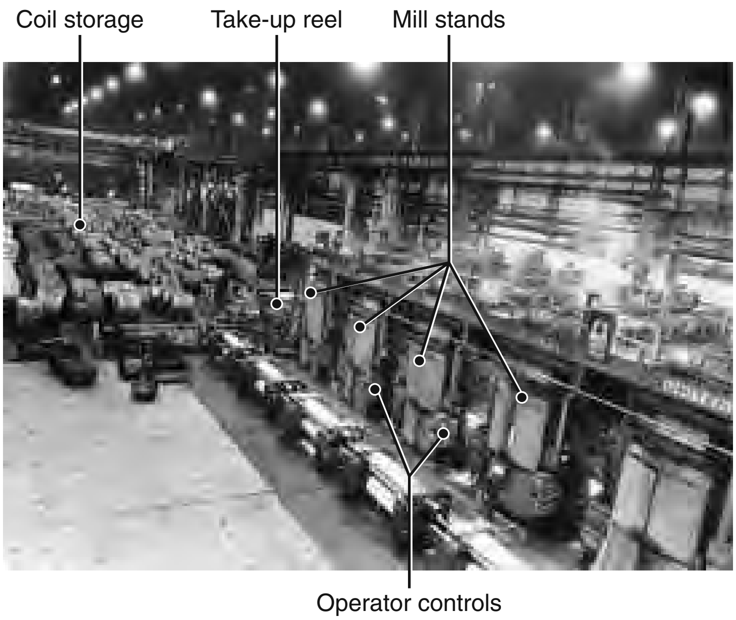


FIGURE 13.10 View of a rolling mill. *Source*: Courtesy of Ispat Inland.

with roll diameters ranging from 0.6 to 1.4 m (24 to 55 in.). In the **three-high mill** (*reversing mill*, Fig. 13.3c) the direction of material movement is reversed after each pass, using elevator mechanisms and various manipulators. The plate being rolled, which may weigh as much as 160 tons, is raised repeatedly to the upper roll gap, rolled, then lowered to the lower roll gap, rolled, and so on.

Four-high mills (Fig. 13.3a) and **cluster mills** (**Sendzimir** or **Z mill**, Fig. 13.3d) are based on the principle that small-diameter rolls lower roll forces (because of small roll-strip contact area) and power requirements and reduce spreading. Moreover, when worn or broken, small rolls can be replaced at lower cost than can large ones. On the other hand, small rolls deflect more under roll forces and have to be supported by other large-diameter rolls, as is done in four-high and cluster mills. Although the cost of a Sendzimir mill facility can be very high, it is particularly suitable for cold rolling thin sheets of high-strength metals. Common rolled widths in this mill are 0.66 m (26 in.), with a maximum of 1.5 m (60 in.).

In **tandem rolling**, the strip is rolled continuously through a number of **stands** to thinner gages with each pass (Fig 13.11). Each stand consists of a set of rolls with its own housing and controls; a group of stands is called a *train*. The control of the strip thickness and the speed at which the strip travels through each roll gap

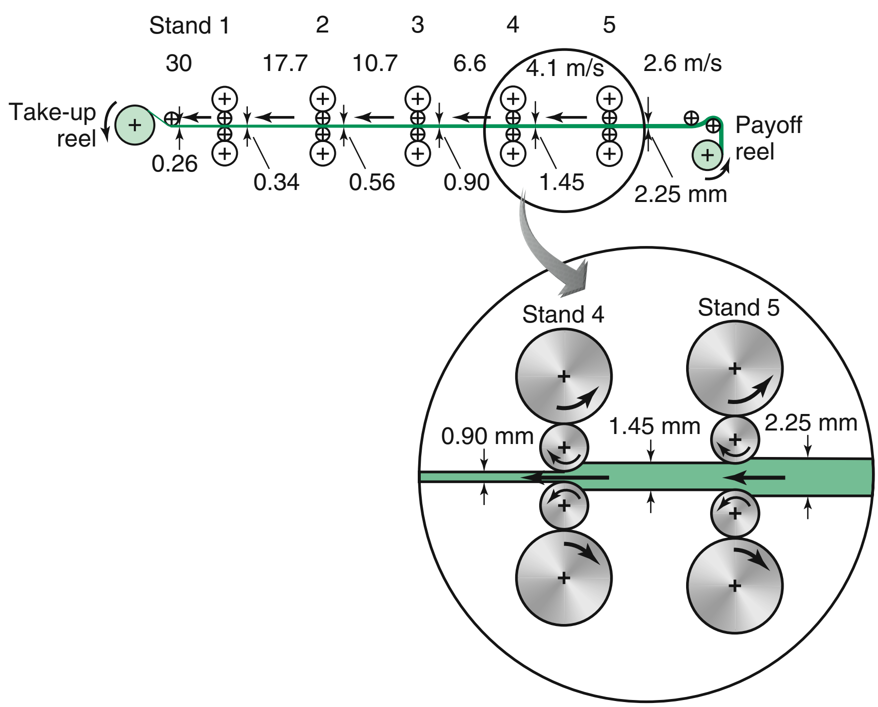


FIGURE 13.11 An example of a tandem-rolling operation.

is critical. Extensive electronic and computer controls are used in these operations, particularly in precision rolling.

Roll Materials. The basic requirements for roll materials are strength and resistance to wear. Common roll materials are cast iron, cast steel, and forged steel; tungsten carbide is also used for small-diameter rolls, such as the working roll in the cluster mill (Fig. 13.3d). Forged-steel rolls, although more costly than cast rolls, have higher strength, stiffness, and toughness than cast-iron rolls. Rolls for cold rolling are ground to a fine finish. For special applications, they also are polished. Rolls made for cold rolling should not be used for hot rolling, because they may crack from thermal cycling (*heat checking*) and *spalling* (cracking or flaking of surface layers). Recall also from earlier discussions that the elastic modulus of the roll influences roll deflection and flattening.

Note that the bottom surface of an aluminum beverage can, for example, has what appear to be longitudinal scratches on it. This is explained by the fact that the surface is a replica of the surface finish of the roll, which is produced by grinding (see Fig. 26.2a). In this way, the rolling direction of the original aluminum sheet also can be determined easily.

Lubricants. Hot rolling of ferrous alloys usually is carried out without lubricants, although graphite may be used. Water-based solutions are used to cool the rolls and to break up the scale on the rolled material. Nonferrous alloys are hot rolled with a variety of compounded oils, emulsions, and fatty acids. Cold rolling is carried out with water-soluble oils or low-viscosity lubricants, such as mineral oils, emulsions, paraffin, and fatty oils.

13.5 Various Rolling Processes and Mills

Several rolling processes and mills have been developed to produce a specific family of product shapes.

Shape Rolling. Straight and long structural shapes (such as channels, I-beams, railroad rails, and solid bars) are formed at elevated temperatures by *shape rolling* (*profile rolling*), in which the stock goes through a set of specially designed rolls (Fig. 13.12; see also Fig. 13.1). *Cold shape rolling* also can be done with the starting materials in the shape of wire with various cross sections. Because the material's cross section is reduced nonuniformly, the design of a series of rolls (**roll-pass design**) requires considerable experience in order to avoid external and internal defects, hold dimensional tolerances, and reduce roll wear.

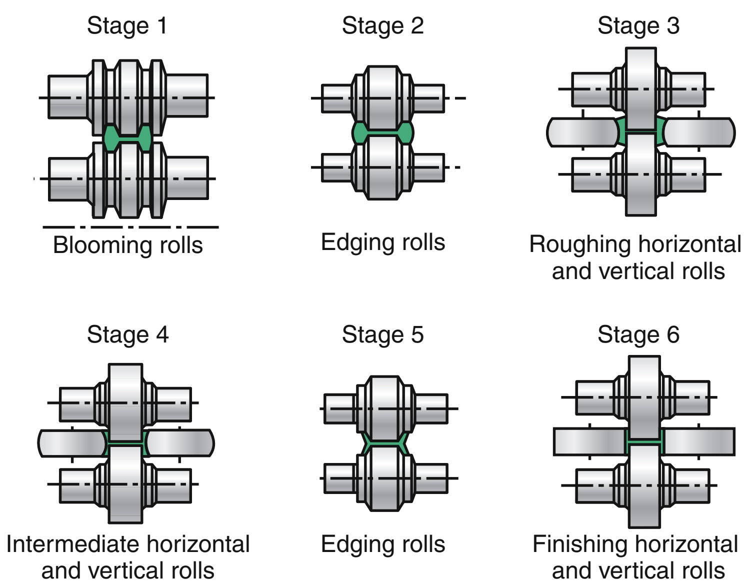


FIGURE 13.12 Steps in the shape rolling of an I-beam part. Various other structural sections, such as channels and rails, also are rolled by this kind of process.

Roll Forging. In this operation (also called *cross rolling*), the cross section of a round bar is shaped by passing it through a pair of rolls with profiled grooves (Fig. 13.13). Roll forging typically is used to produce tapered shafts and leaf springs, table knives, and

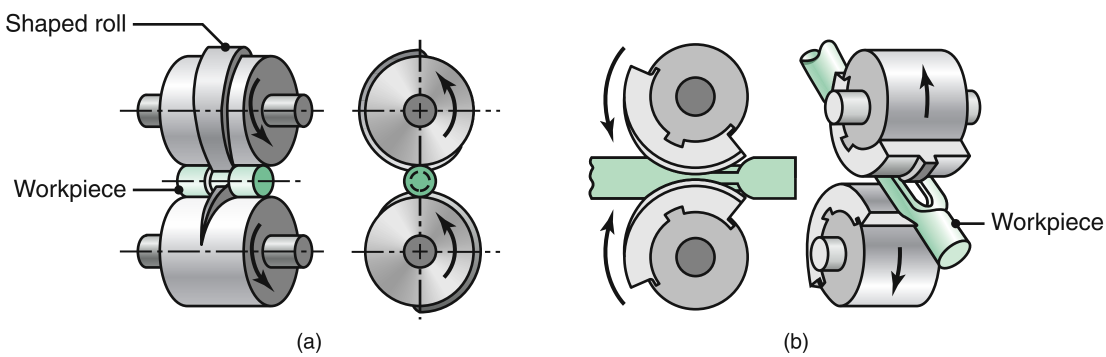


FIGURE 13.13 Two examples of the roll-forging operation, also known as *cross-rolling*. Tapered leaf springs and knives can be made by this process. *Source*: After J. Holub.

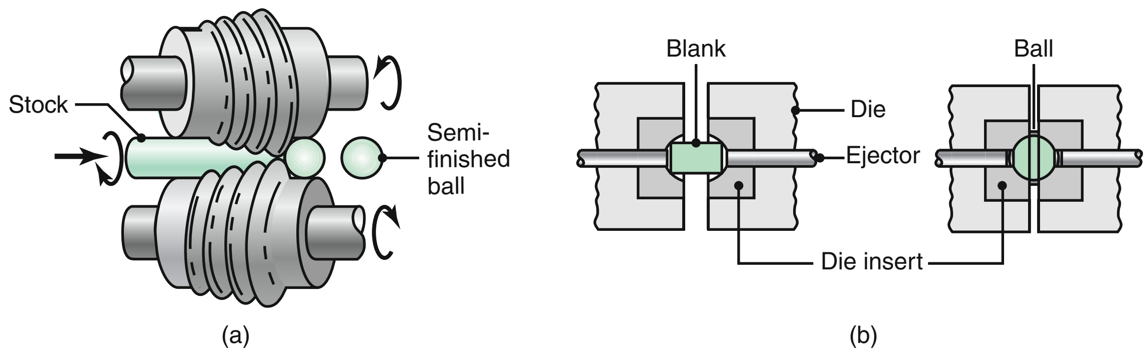


FIGURE 13.14 (a) Production of steel balls by the skew-rolling process. (b) Production of steel balls by upsetting a cylindrical blank. Note the formation of flash. The balls made by these processes subsequently are ground and polished for use in ball bearings.

hand tools; it also may be used as a preliminary forming operation, to be followed by other forging processes.

Skew Rolling. A process similar to roll forging is *skew rolling*, typically used for making ball bearings (Fig. 13.14a). Round wire or rod is fed into the roll gap, and roughly spherical blanks are formed continuously by the action of the rotating rolls. Another method of forming near-spherical blanks for ball bearings is to shear pieces from a round bar and then upset them in headers (see also Fig. 14.11) between two dies with hemispherical cavities (Fig. 13.14b). The balls subsequently are ground and polished in special machinery (see Fig. 26.15).

Ring Rolling. In *ring rolling*, a thick ring is expanded into a large-diameter thinner one. The ring is placed between two rolls, one of which is driven while the other is idle (Fig. 13.15a). Its thickness is reduced by bringing the rolls closer together as they rotate. Since the volume of the ring material remains constant during plastic deformation (volume constancy), the reduction in ring thickness results in an increase in its diameter. Depending on its size, the ring-shaped blank may be produced by such means as cutting from a plate, piercing, or cutting a thick-walled pipe. Various shapes can be ring rolled using shaped rolls (Fig. 13.15). Note that the thickness of rings also can be reduced by an open-die forging process, as illustrated in Fig. 14.4c; however, dimensional control and surface finish will not be as good as in ring rolling.

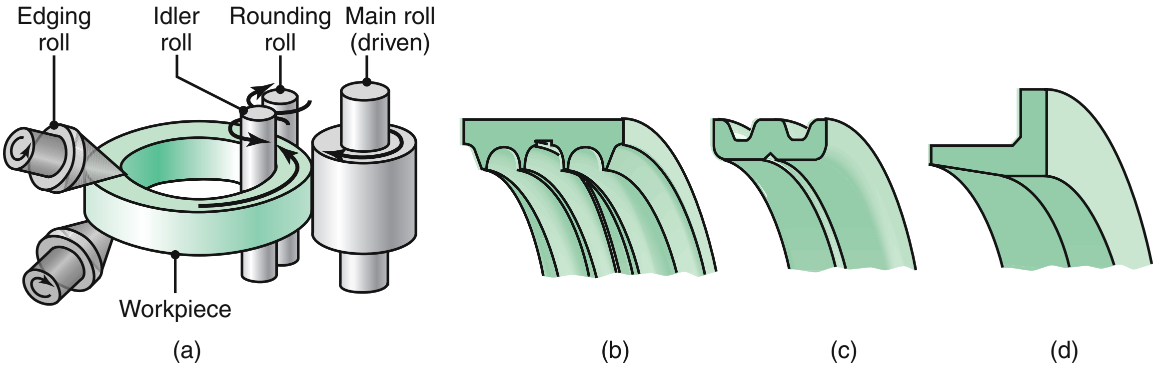


FIGURE 13.15 (a) Schematic illustration of a ring-rolling operation. Thickness reduction results in an increase in the part diameter. (b) through (d) Examples of cross sections that can be formed by ring rolling.

Typical applications of ring rolling are large rings for rockets and turbines, jet-engine cases, gearwheel rims, ball-bearing and roller-bearing races, flanges, and reinforcing rings for pipes. The process can be carried out at room temperature or at an elevated temperature, depending on the size (which can be up to 10 ft, or 3 m, in diameter), strength, and ductility of the workpiece material. Compared with other manufacturing processes capable of producing the same part, the advantages of ring rolling are short production times, material savings, close dimensional tolerances, and favorable grain flow in the product, thus enhancing its strength in the desired direction. The design of the profile rolls requires considerable experience. Analytical techniques are being developed to rely less on established practice and help minimize defects in rolled products.

Thread Rolling. *Thread rolling* is a cold-forming process by which straight or tapered threads are formed on round rods or wire. The threads are formed on the rod or wire with each stroke of a pair of flat reciprocating dies (Fig. 13.16a). In another method, threads are formed with *rotary dies* (Fig. 13.16c), at production rates as high as 80 pieces per second. Typical products are screws, bolts, and similar threaded parts. Depending on die design, the major diameter of a rolled thread may or may not be larger than a machined thread (Fig. 13.17a)—that is, the same as the blank diameter. The thread-rolling process is capable of generating other shapes as well, such as grooves and various gear forms, and it is used to produce almost all threaded fasteners at high production rates.

The thread-rolling process has the advantages of generating threads with good strength (due to cold working) and without any loss of material (scrap). The surface finish produced is very smooth, and the process induces compressive residual stresses on the workpiece surfaces, thus improving fatigue life. Thread rolling is superior to other methods of thread manufacture, because machining the threads cuts through the grain-flow lines of the material, whereas rolling the threads results in a grain-flow pattern that improves the strength of the thread (Fig. 13.17).

Spur and helical gears can be produced by cold-rolling processes similar to thread rolling (see also Section 24.7). The process may be carried out on solid cylindrical blanks or on precut gears. Cold rolling of gears has extensive applications in automatic transmissions and in power tools. **Internal thread rolling** can be carried out with a fluteless **forming tap**. This operation is similar to external thread rolling, and it produces accurate internal threads with good strength.

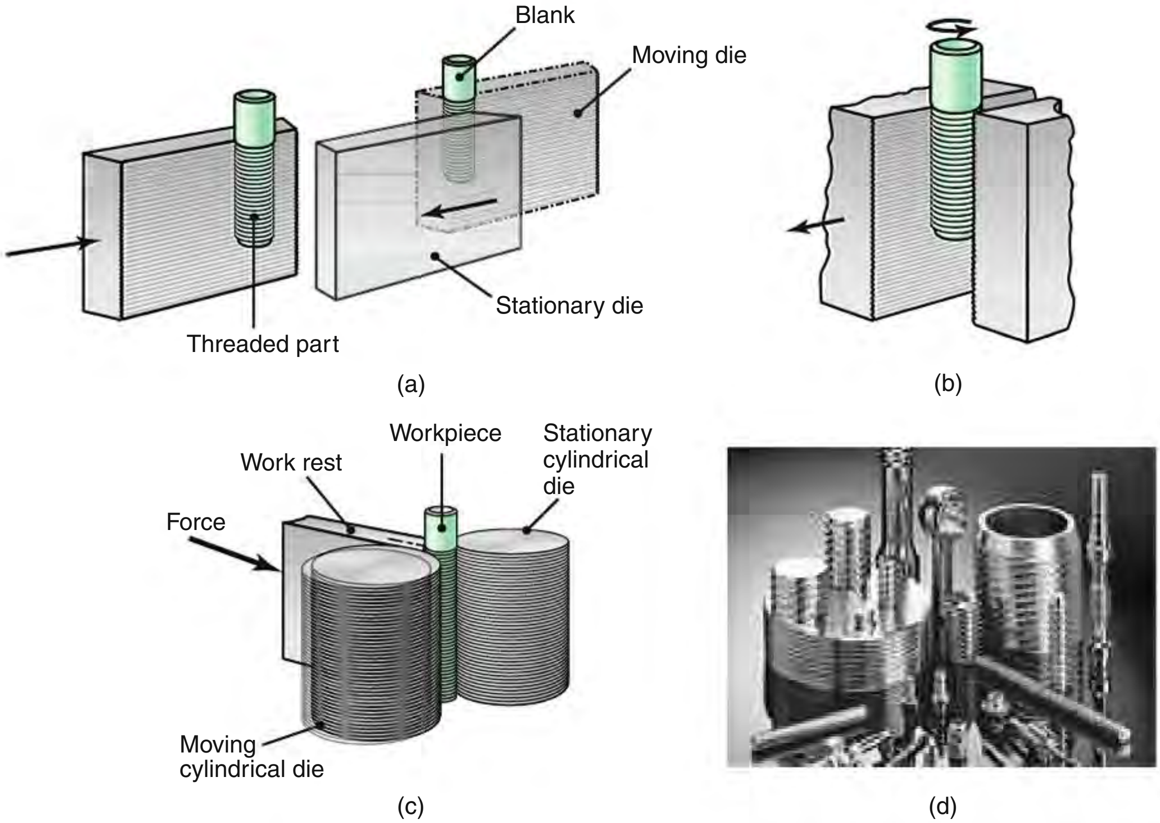


FIGURE 13.16 Thread-rolling processes: (a) and (b) reciprocating flat dies; (c) two-roller dies; (d) A collection of thread-rolled parts made economically at high production rates. *Source*: Courtesy of Tesker Manufacturing Corp.

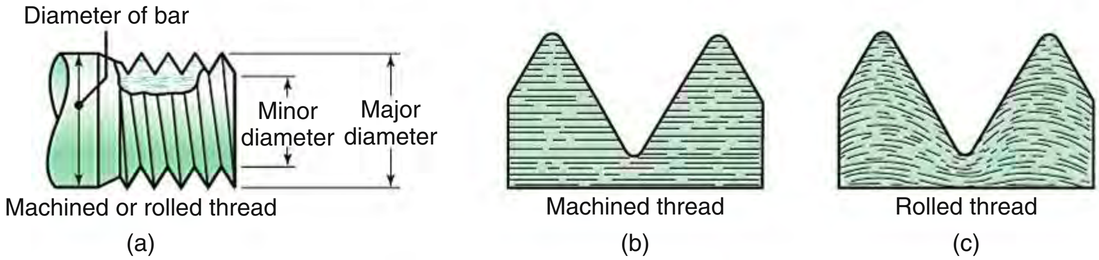


FIGURE 13.17 (a) Features of a machined or rolled thread. Grain flow in (b) machined and (c) rolled threads. Unlike machining, which cuts through the grains of the metal, the rolling of threads imparts improved strength because of cold working and favorable grain flow.

Lubrication is important in thread-rolling operations in order to obtain a good surface finish and surface integrity and to minimize defects. Lubrication affects the manner in which the material deforms during deformation, which is an important consideration because of the possibility of internal defects being developed (for example, see Fig. 14.16). Typically made of hardened steel, rolling dies are expensive because of their complex shape. They usually cannot be reground after they are worn. With proper die materials and preparation, however, die life may range up to millions of pieces.

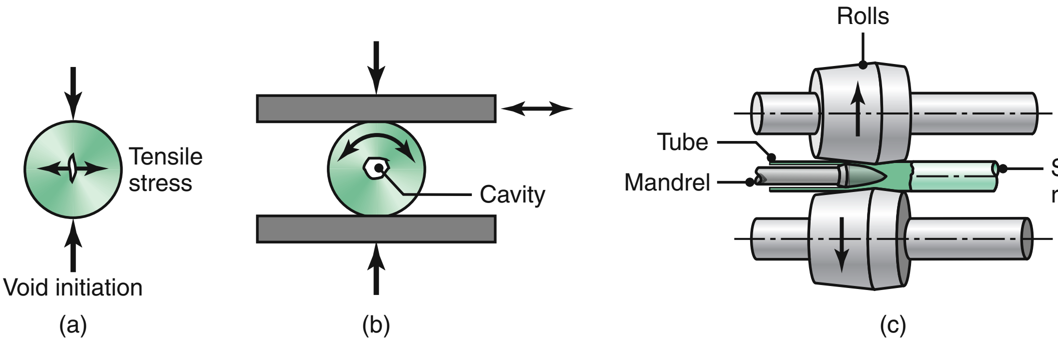


FIGURE 13.18 Cavity formation in a solid, round bar and its utilization in the rotary tube-piercing process for making seamless pipe and tubing. (See also Fig. 2.9.)

Rotary Tube Piercing. Also known as the **Mannesmann process**, this is a hot-working operation for making long, thick-walled *seamless pipe and tubing* (Fig. 13.18). Developed in the 1880s, this process is based on the principle that when a round bar is subjected to radial compressive forces, tensile stresses develop at the center of the bar (see Fig. 2.9). When it is subjected continuously to these cyclic compressive stresses (Fig. 13.18b), the bar begins to develop a small cavity at its center, which then begins to grow. (This phenomenon can be demonstrated with a short piece of round eraser by rolling it back and forth on a hard flat surface, as shown in Fig. 13.18b.)

Rotary tube piercing is carried out using an arrangement of rotating rolls (Fig. 13.18c). The axes of the rolls are *skewed* in order to pull the round bar through the rolls by the axial component of the rotary motion. An internal mandrel assists the operation by expanding the hole and sizing the inside diameter of the tube. The mandrel may be held in place by a long rod, or it may be a floating mandrel without a support. Because of the severe deformation that the bar undergoes, the material must be high in quality and free from defects (since internal defects may propagate rapidly and cause premature failure of the part during forming).

Tube Rolling. The diameter and thickness of pipes and tubing can be reduced by *tube rolling*, which utilizes shaped rolls (Fig. 13.19). Some of these operations can be carried out either with or without an internal mandrel. In the *pilger mill*, the tube and an internal mandrel undergo a reciprocating motion; the rolls are specially shaped and are rotated continuously. During the gap cycle on the roll, the tube is advanced and rotated, starting another cycle of tube reduction. As a result, the tube undergoes a reduction in both diameter and wall thickness. Steel tubing of 265 mm (10.5 in.) in diameter have been produced by this process. Other operations for tube manufacturing are described in Chapter 15.

13.5.1 Various Mills

Integrated Mills. These mills are large facilities that involve complete integration of the activities—from the production of hot metal in a blast furnace to the casting and rolling of finished products ready to be shipped to the customer.

Minimills. Competition in the steel industry has led to the development of *minimills*, in which scrap metal is (a) melted in electric-arc furnaces, (b) cast continuously, and (c) rolled directly into specific lines of products. Each minimill produces essentially one type of rolled product (rod, bar, or structural sections such as angle iron) from basically one type of metal or alloy. The scrap metal, which is obtained

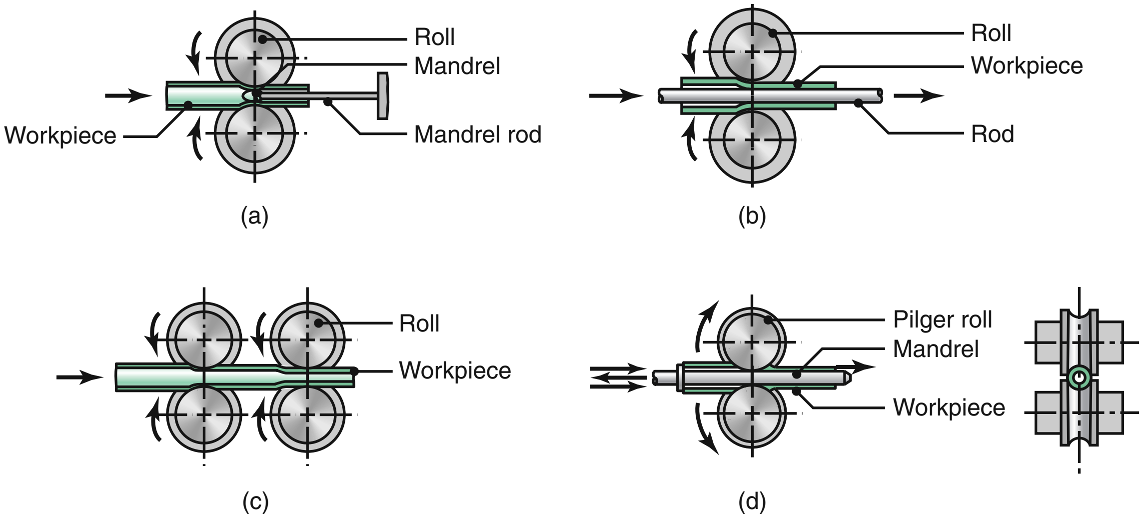


FIGURE 13.19 Schematic illustration of various tube-rolling processes: (a) with a fixed mandrel; (b) with a floating mandrel; (c) without a mandrel; and (d) pilger rolling over a mandrel and a pair of shaped rolls. Tube diameters and thicknesses also can be changed by other processes, such as drawing, extrusion, and spinning.

locally (to reduce transportation costs), is typically old machinery, cars, and farm equipment. Minimills have the economic advantages of low-investment optimal operations for each type of metal and product line and of low labor and energy costs. The products usually are aimed at markets in the mill's particular geographic area.

SUMMARY

- Rolling is the process of reducing the thickness or changing the cross section of a long strip by compressive forces applied through a set of rolls. In addition to flat rolling, shape rolling is used to make products with various cross sections. Products made by rolling include: (a) plate, sheet, foil, rod, seamless pipe, and tubing; (b) shape-rolled products, such as I-beams and structural shapes; and (c) bars of various cross section. Other rolling operations include ring rolling and thread rolling.
- Rolling may be carried out at room temperature (cold rolling) or at elevated temperatures (hot rolling). The process involves several material and process variables, including roll diameter (relative to material thickness), reduction per pass, speed, lubrication, and temperature. Spreading, bending, and flattening are important considerations for controlling the dimensional accuracy of the rolled stock.
- Rolling mills have a variety of roll configurations, such as two-high, three-high, four-high, cluster (Sendzimir), and tandem. Front and/or back tension may be applied to the material to reduce roll forces.
- Continuous casting and rolling of ferrous and of nonferrous metals into semifinished products have become a common practice because of their economic benefits.
- Integrated mills are large facilities involving the complete sequence of activities, from the production of hot metal in a blast furnace to the casting and the rolling of finished products ready to be shipped to the customer. On a much smaller scale, minimills utilize scrap metal that is melted in electric-arc furnaces, cast, and continuously rolled into specific lines of products.

Metal-Forging Processes and Equipment

CHAPTER 14

- This chapter describes the fundamentals of forging and related processes, including design and economic considerations.
- Open-die forging operations for producing simple shapes are discussed first, followed by impression-die and closed-die forging operations for producing more intricate shapes.
- Various forging operations, such as heading, piercing, coining, swaging, and cold extrusion, are then introduced.
- Factors involved in forging defects and die failures are explained.
- The economics of forging, as it relates to process selection, is also discussed.
- The chapter ends with a review of the design of forged parts, die design and manufacturing, and selection of die materials and lubricants in forging operations.

Typical parts made by forging and related processes: Shafts, gears, bolts, turbine blades, hand tools, dies, and components for machinery, transportation, and farm equipment.

Alternative processes: Casting, powder metallurgy, machining, and fabrication.

14.1 Introduction

Forging is a basic process in which the workpiece is shaped by compressive forces applied through various dies and tooling. One of the oldest and most important metalworking operations, dating back at least to 4000 B.C., forging first was used to make jewelry, coins, and various implements by hammering metal with tools made of stone. Forged parts now include large rotors for turbines; gears; bolts and rivets; cutlery (Fig. 14.1a); hand tools; numerous structural components for machinery, aircraft (Fig. 14.1b), and railroads; and a variety of other transportation equipment.

Unlike rolling operations described in Chapter 13 that generally produce continuous plates, sheets, strips, or various structural cross sections, forging operations produce *discrete parts*. Because the metal flow in a die and the material's grain structure can be controlled, forged parts have good strength and toughness, and are very reliable for highly stressed and critical applications (Fig. 14.2). Simple forging operations

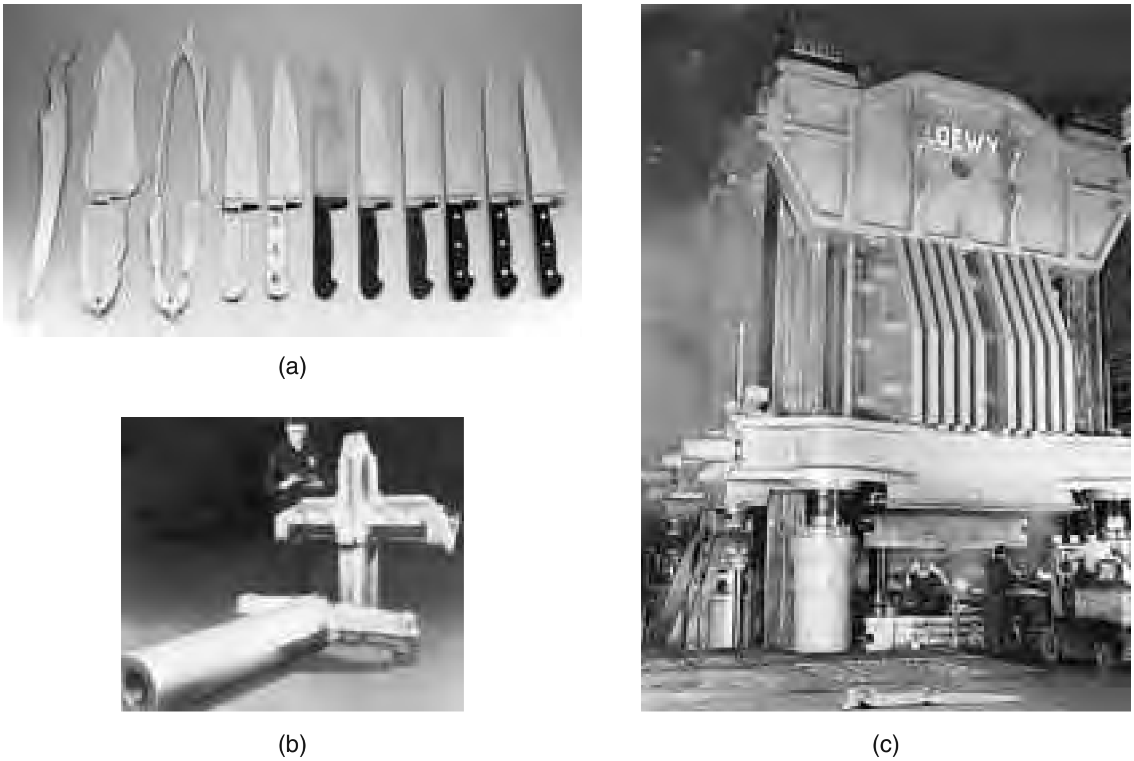


FIGURE 14.1 (a) Illustration of the steps involved in forging a knife. (b) Landing-gear components for the C5A and C5B transport aircraft, made by forging. (c) General view of a 445-MN (50,000-ton) hydraulic press. *Source*: (a) Courtesy of Mundial, LLC. (b) and (c) Courtesy of Wyman-Gordon Company.

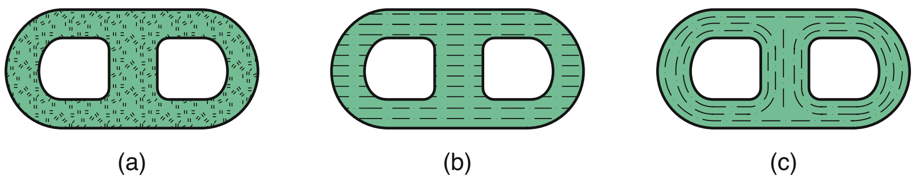


FIGURE 14.2 Schematic illustration of a part made by three different processes and showing grain flow. (a) Casting by the processes described in Chapter 11. (b) Machining from a blank, described in Part IV of this book, and (c) forging. Each process has its own advantages and limitations regarding external and internal characteristics, material properties, dimensional accuracy, surface finish, and the economics of production. *Source*: Courtesy of the Forging Industry Association.

can be performed with a heavy hammer and an anvil, as has been done traditionally by blacksmiths. However, most forgings require a set of dies and such equipment as a press or a powered forging hammer.

Forging may be carried out at room temperature (*cold forging*) or at elevated temperatures (*warm* or *hot forging*) depending on the homologous temperature; (see Section 1.8). Cold forging requires higher forces (because of the higher strength of the workpiece material), and the workpiece material must possess sufficient ductility at room temperature to undergo the necessary deformation without cracking. Cold-forged parts have a good surface finish and dimensional accuracy. Hot forging requires lower forces, but the dimensional accuracy and surface finish of the parts are not as good as in cold forging.

Forgings generally are subjected to additional finishing operations, such as heat treating to modify properties and machining to obtain accurate final dimensions and a good surface finish. These finishing operations can be minimized by *precision forging*, which is an important example of *net-shape* or *near-net-shape* forming processes. As we shall see throughout this book, components that can be forged successfully also may be manufactured economically by other methods, such as casting (Chapter 11), powder metallurgy (Chapter 17), or machining (Part IV). Each of these will produce a part having different characteristics, particularly with regard to strength, toughness, dimensional accuracy, surface finish, and the possibility of internal or external defects.

14.2 Open-die Forging

Open-die forging is the simplest forging operation (Table 14.1). Although most open-die forgings generally weigh 15 to 500 kg (30 to 1000 lb), forgings as heavy as 300 tons have been made. Part sizes may range from very small (the size of nails, pins, and bolts) to very large (up to 23 m (75 ft), long shafts for ship propellers). Open-die forging can be depicted by a solid workpiece placed between two flat dies and reduced in height by compressing it (Fig. 14.3a)—a process that is also called **upsetting** or **flat-die forging**. The die surfaces also may have shallow cavities or incorporate features to produce relatively simple forgings.

The deformation of a workpiece under *frictionless conditions* is shown in Fig. 14.3b. Because constancy of volume is maintained, any reduction in height increases the diameter of the forged part. Note that the workpiece is deformed *uniformly*. In actual operations, however, there is friction, and the part develops a *barrel* shape (Fig. 14.3c)—a deformation mode also known as *pancaking*.

Barreling is caused primarily by frictional forces that oppose the outward flow of the workpiece at the die interfaces and thus can be minimized by using an effective

TABLE 14.1

General Characteristics of Forging Processes

Process	Advantages	Limitations
Open die	Simple and inexpensive dies; wide range of part sizes; good strength characteristics; generally for small quantities	Limited to simple shapes; difficult to hold close tolerances; machining to final shape necessary; low production rate; relatively poor utilization of material; high degree of skill required
Closed die	Relatively good utilization of material; generally better properties than open-die forgings; good dimensional accuracy; high production rates; good reproducibility	High die cost, not economical for small quantities; machining often necessary
Blocker	Low die costs; high production rates	Machining to final shape necessary; parts with thick webs and large fillets
Conventional	Requires much less machining than blocker type; high production rates; good utilization of material	Higher die cost than blocker type
Precision	Close dimensional tolerances; very thin webs and flanges possible; machining generally not necessary; very good material utilization	High forging forces, intricate dies, and provision for removing forging from dies

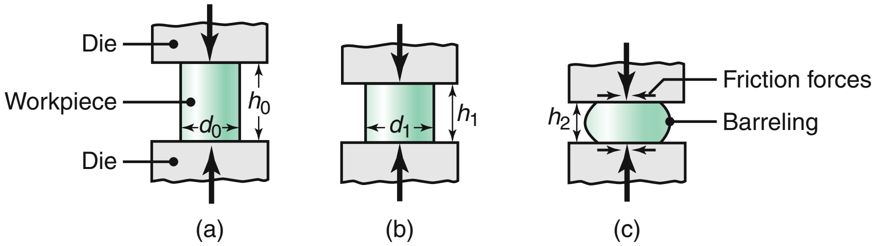


FIGURE 14.3 (a) Solid cylindrical billet upset between two flat dies. (b) Uniform deformation of the billet without friction. (c) Deformation with friction. Note barreling of the billet caused by friction forces at the billet–die interfaces.

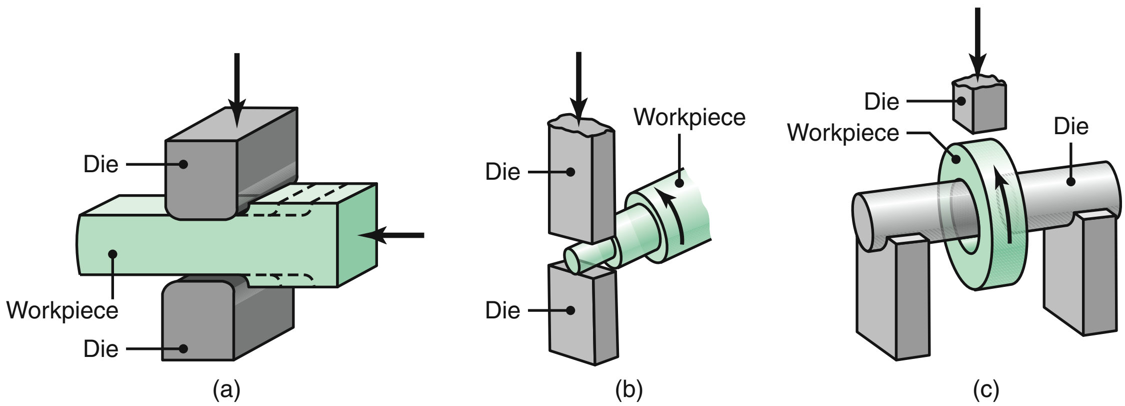


FIGURE 14.4 (a) Schematic illustration of a cogging operation on a rectangular bar. Blacksmiths use this process to reduce the thickness of bars by hammering the part on an anvil. Reduction in thickness is accompanied by barreling, as in Fig. 14.3c. (b) Reducing the diameter of a bar by open-die forging; note the movements of the dies and the workpiece. (c) The thickness of a ring being reduced by open-die forging.

lubricant. Barreling also can develop in upsetting hot workpieces between cold dies. The material at or near the die surfaces cools rapidly, while the rest of the workpiece remains relatively hot. Consequently, the material at the top and bottom of the workpiece has higher resistance to deformation than the material at the center. As a result, the central portion of the workpiece expands laterally to a greater extent than do the ends. Barreling from thermal effects can be reduced or eliminated by using heated dies. Thermal barriers, such as glass cloth, at the die–workpiece interfaces also can be used for this purpose.

Cogging (also called *drawing out*) is basically an open-die forging operation in which the thickness of a bar is reduced by successive forging steps (*bites*) at specific intervals (Fig. 14.4a). The thickness of bars and rings can be reduced by similar open-die forging techniques, as shown in Fig. 14.4b and c. Because the contact area between the die and the workpiece is small, a long section of a bar can be reduced in thickness without requiring large forces or heavy machinery. Blacksmiths perform such operations with a hammer and an anvil, using hot pieces of metal. Typical products are iron fences of various designs. Note that cogging can be a rough substitute for rolling operations. Cogging of larger workpieces usually is done using mechanized equipment and computer controls in which lateral and vertical movements are coordinated to produce the desired part.

Forging Force. The *forging force*, F, in an *open-die forging* operation on a solid cylindrical workpiece can be estimated from the formula

$$F = Y_f \pi r^2 \left(1 + \frac{2\,\mu r}{3h}\right), \tag{14.1}$$

where Y_f is the *flow stress* of the material (see Example 14.1), μ is the coefficient of friction between the workpiece and the die, and r and h are, respectively, the instantaneous radius and height of the workpiece. (Derivations of this formula and of others for various forging processes are given in references listed in the bibliography at the end of the chapter.)

EXAMPLE 14.1 Calculation of Forging Force in Upsetting

A solid cylindrical slug made of 304 stainless steel is 150 mm (6 in.) in diameter and 100 mm (4 in.) high. It is reduced in height by 50% at room temperature by open-die forging with flat dies. Assuming that the coefficient of friction is 0.2, calculate the forging force at the *end* of the stroke.

Solution: The forging force at the end of the stroke is calculated using Eq. (14.1), in which the dimensions pertain to the final dimensions of the forging. Thus, the final height is $h = 100/2 = 50$ mm, and the final radius, r, is determined from volume constancy by equating the volumes before and after deformation. Hence,

$$(\pi)(75)^2(100) = (\pi)(r)^2(50).$$

Therefore, $r = 106$ mm (4.17 in.).

The quantity Y_f in Eq. (14.1) is the flow stress of the material, which is the stress required to continue plastic deformation of the workpiece at a particular true strain. The absolute value of the true strain that the workpiece has undergone at the end of the stroke in this operation is

$$\varepsilon = \ln\left(\frac{100}{50}\right) = 0.69.$$

We can determine the flow stress by referring to Eq. (2.8) and noting from Table 2.3 that, for 304 stainless steel, $K = 1275$ MPa and $n = 0.45$. Thus, for a true strain of 0.69, the flow stress is calculated to be 1100 MPa. Another method is to refer to Fig. 2.6 and note that the flow stress for 304 stainless steel at a true strain of 0.69 is about 1000 MPa (140 ksi). The small difference between the two values is due to the fact that the data in Table 2.3 and Fig. 2.6 are from different sources. Taking the latter value, the forging force now can be calculated, noting that in this problem the units in Eq. (14.1) must be in N and m. Thus,

$$F = (1000)(10^6)(\pi)(0.106)^2(1) + \frac{(2)(0.2)(0.106)}{(3)(0.050)}$$

$$= 4.5 \times 10^7 \text{ N} = 45 \text{ MN} = 10^7 \text{ lb} = 5000 \text{ tons}.$$

14.3 Impression-die and Closed-die Forging

In *impression-die forging*, the workpiece takes the shape of the die cavity while being forged between two shaped dies (Fig. 14.5a through c). This process usually is carried out at elevated temperatures to lower the required forces and attain enhanced ductility in the workpiece. Note in Fig. 14.5c that, during deformation, some of the material flows outward and forms a **flash**. The flash has an important role in impression-die forging: The high pressure and the resulting high frictional resistance in the flash presents a severe constraint on any outward flow of the material in the die. Thus, based on the principle that in plastic deformation the material flows in the direction of least resistance (because it requires less energy), the material flows preferentially into the die cavity, ultimately filling it completely.

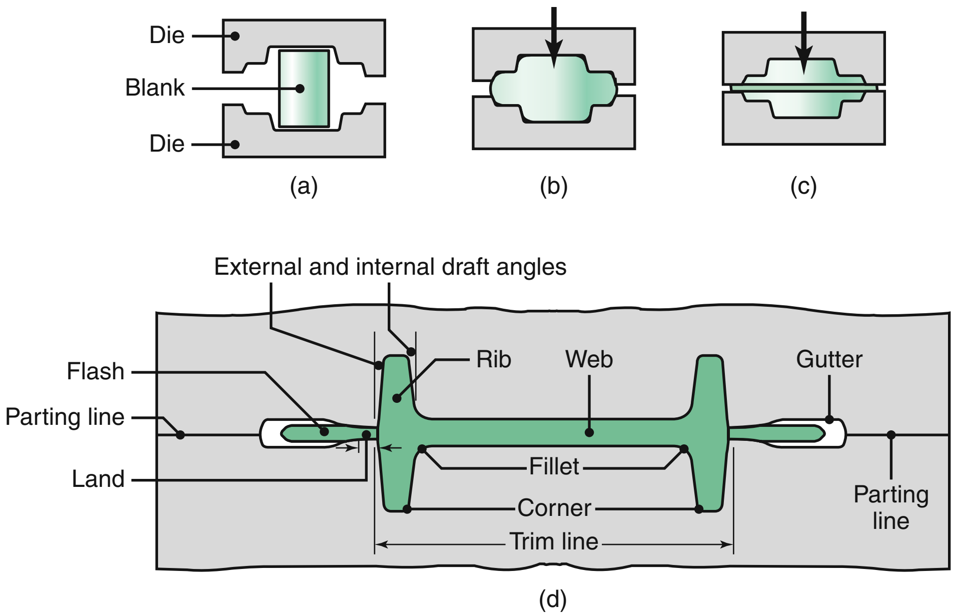


FIGURE 14.5 (a) through (c) Stages in impression-die forging of a solid round billet. Note the formation of flash, which is excess metal that is subsequently trimmed off. (d) Standard terminology for various features of a forging die.

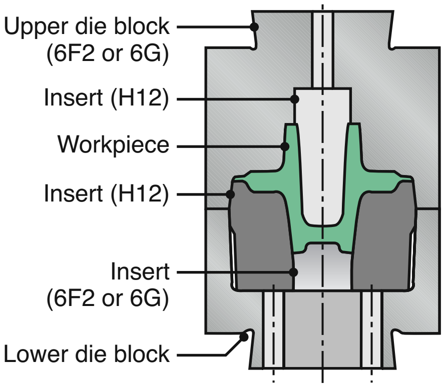


FIGURE 14.6 Die inserts used in forging an automotive axle housing. (See Section 5.7 for die materials.)

The standard terminology for a typical forging die is shown in Fig. 14.5d. Instead of being made as one piece, dies may be made of several pieces (segmented), including **die inserts** (Fig. 14.6) and particularly for complex shapes. The inserts can be replaced easily in the case of wear or failure in a particular section of the die and usually are made of stronger and harder materials.

The blank to be forged is prepared by (a) *cropping* from an extruded or drawn bar stock; (b) preforming from operations such as *powder metallurgy*; (c) *casting*; or (d) using a preformed blank from a prior forging operation. The blank is placed on the lower die, and as the upper die begins to descend, the blank's shape gradually changes—as is shown for the forging of a connecting rod in Fig. 14.7a.

Preforming operations (Figs. 14.7b and c) typically are used to distribute the material properly into various regions of the blank using simple shaped dies of various contours. In **fullering**, material is *distributed away* from an area. In **edging**, it is *gathered into* a localized area. The part then is formed into the rough shape (say, a connecting rod) by a process called **blocking**, using *blocker dies*. The final operation is the finishing of the forging in *impression dies* that give the forging its final shape. The flash is removed later by a trimming operation (Fig. 14.8).

Forging Force. The *forging force, F*, required to carry out an *impression-die forging* operation can be estimated from the formula

$$F = kY_fA, \tag{14.2}$$

where k is a multiplying factor obtained from Table 14.2, Y_f is the flow stress of the material at the forging temperature, and A is the projected area of the forging,

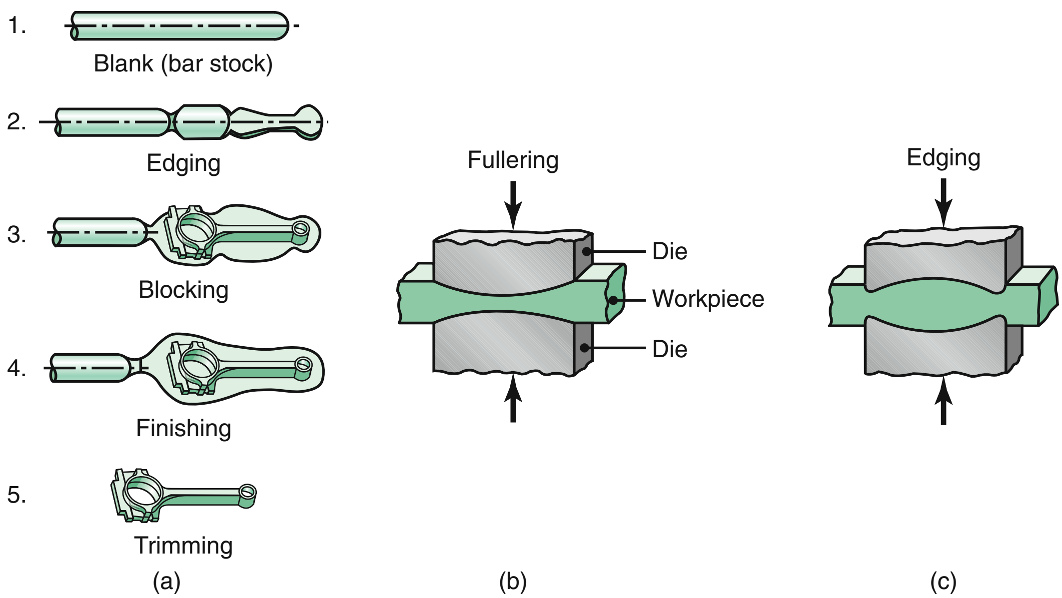


FIGURE 14.7 (a) Stages in forging a connecting rod for an internal combustion engine. Note the amount of flash required to ensure proper filling of the die cavities. (b) Fullering and (c) edging operations to distribute the material properly when preshaping the blank for forging.

including the flash. In hot-forging operations, the actual forging pressure for most metals typically ranges from 550 to 1000 MPa (80 to 140 ksi). As an example, assume that the flow stress of a material at the forging temperature is 100,000 psi, and a part (such as that shown in Fig. 14.7a) has a projected area (with flash) of 60 in^2. Taking a value of $k = 10$ from Table 14.2, the forging force would be $F = (10)(100{,}000)(60) = 60 = 60 \times 10^6$ lb $= 26.8$ tons.

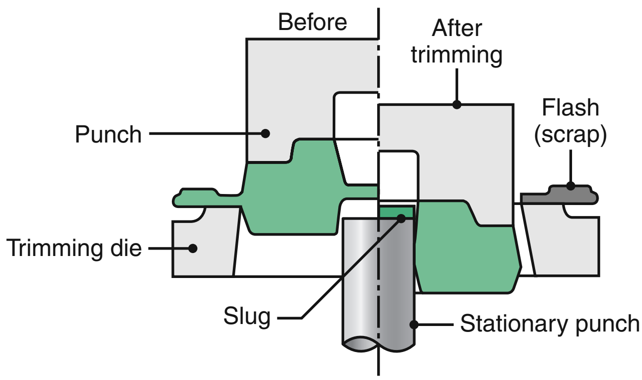


FIGURE 14.8 Trimming flash from a forged part. Note that the thin material at the center is removed by punching.

Closed-die Forging. The process shown in Fig. 14.5 also is referred to as *closed-die forging*. However, in true closed-die forging, flash does not form (hence the term *flashless forging*), and the workpiece completely fills the die cavity (see right side of Fig. 14.9b). Consequently, the forging pressure is very high, and accurate control of the blank volume and proper die design are essential to producing a forging with the desired dimensional tolerances. Undersized blanks prevent the complete filling of the die cavity; conversely, oversized blanks generate excessive pressures and may cause dies to fail prematurely or the machine to jam.

TABLE 14.2

Range of *k* Values for Eq. (14.2)

Shape	k
Simple shapes, without flash	3–5
Simple shapes, with flash	5–8
Complex shapes, with flash	8–12

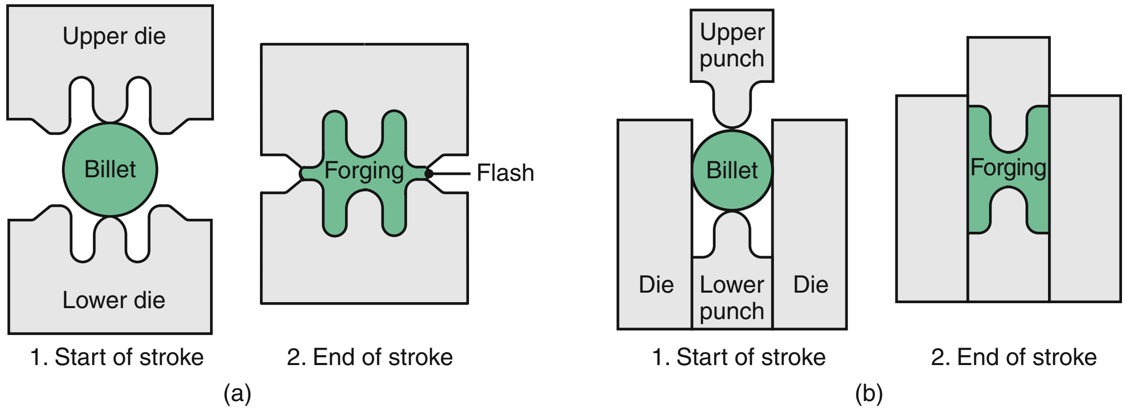


FIGURE 14.9 Comparison of (a) closed-die forging with flash and (b) precision or flashless forging of a round billet. *Source*: After H. Takemasu, V. Vazquez, B. Painter, and T. Altan.

Regardless, the term *closed-die forging* is often applied to impression die forging with flash generation, whereas *open-die forging* generally applies to operations with simple dies and tooling and with large deformations.

Precision Forging. In order to reduce the number of additional finishing operations required—hence the cost—the trend has been toward greater precision in forged products (net-shape forming). Typical precision-forged products are gears, connecting rods, and turbine blades. Precision forging requires (a) special and more complex dies, (b) precise control of the blank's volume and shape, and (c) accurate positioning of the blank in the die cavity. Also, because of the higher forces required to obtain fine details on the part, this process requires higher capacity equipment. Aluminum and magnesium alloys are particularly suitable for precision forging because of the relatively low forging loads and temperatures that they require; however, steels and titanium also can be precision forged.

Forging Practice and Product Quality. A forging operation typically involves the following sequence of steps:

1. Prepare a slug, billet, or preform by processes such as shearing (cropping), sawing, or cutting off. If necessary, clean surfaces by such means as shot blasting.
2. For hot forging, heat the workpiece in a suitable furnace and then, if necessary, descale it with a wire brush, water jet, steam, or by scraping. Some descaling also may occur during the initial stages of forging, when the scale (which is brittle) falls off during deformation.
3. For hot forging, preheat and lubricate the dies; for cold forging, lubricate the blank.
4. Forge the billet in appropriate dies and in the proper sequence. If necessary, remove any excess material (such as flash) by trimming, machining, or grinding.
5. Clean the forging, check its dimensions, and (if necessary) machine it to final dimensions and specified tolerances.
6. Perform additional operations, such as straightening and heat treating (for improved mechanical properties). Also, perform any finishing operations that may be required, such as machining and grinding.
7. Inspect the forging for any external and internal defects.

The quality, dimensional tolerances, and surface finish of a forging depend on how well these operations are performed and controlled. Generally, dimensional tolerances range between ±0.5 and ±1% of the dimensions of the forging. In good practice, tolerances for hot forging of steel are usually less than ±6 mm (0.25 in.); in precision forging, they can be as low as ±0.25 mm (0.01 in.). Other factors that contribute to dimensional inaccuracies are draft angles, radii, fillets, die wear, die closure (whether the dies have closed properly), and mismatching of the dies. The surface finish of the forging depends on blank preparation, die surface finish, die wear, and the effectiveness of the lubricant.

14.4 Various Forging Operations

Several other operations related to the basic forging process are carried out in order to impart the desired shape and features to forged products.

Coining. This is essentially a closed-die forging process that is typically used in the minting of coins, medallions, and jewelry (Fig. 14.10). The blank or slug is coined in a completely closed die cavity. In order to produce fine details (for example, the detail on newly minted coins), the pressures required can be as high as five or six times the strength of the material. On some parts, several coining operations may be required. Lubricants cannot be applied in coining, because they can become entrapped in the die cavities and (being incompressible) prevent the full reproduction of die-surface details and surface finish.

Marking parts with letters and numbers also can be done rapidly through coining. In addition, the process is used with forgings and other products to improve surface finish and to impart the desired dimensional accuracy with little or no change in part size. Called **sizing**, this process requires high pressures.

Heading. Also called **upset forging**, *heading* is essentially an upsetting operation, usually performed on the end of a round rod or wire in order to increase the cross section. Typical products are nails, bolt heads, screws, rivets, and various other fasteners (Fig. 14.11a). Heading can be carried out cold, warm, or hot. An important

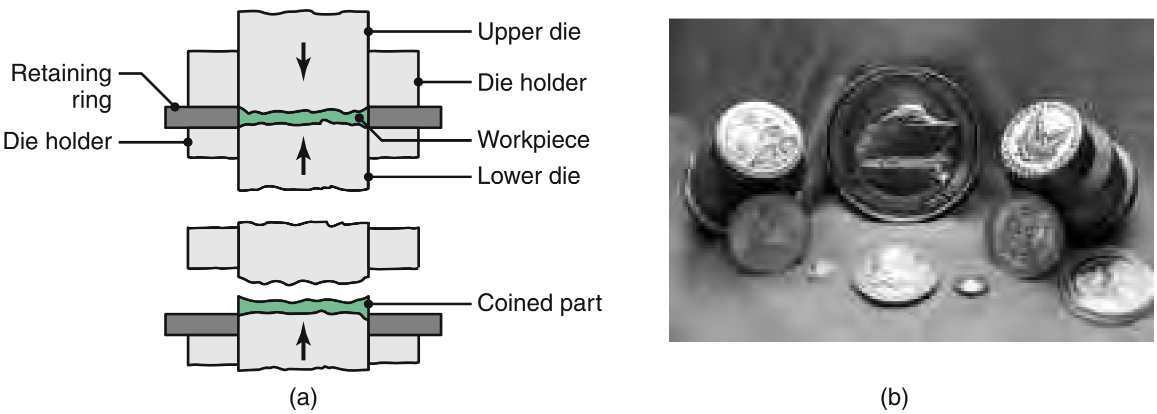


FIGURE 14.10 (a) Schematic illustration of the coining process. The earliest coins were made by open-die forging and lacked precision and sharp details. (b) An example of a modern coining operation, showing the coins and tooling. Note the detail and superior surface finish that can be achieved in this process. *Source*: Courtesy of C & W Steel Stamp Co., Inc.

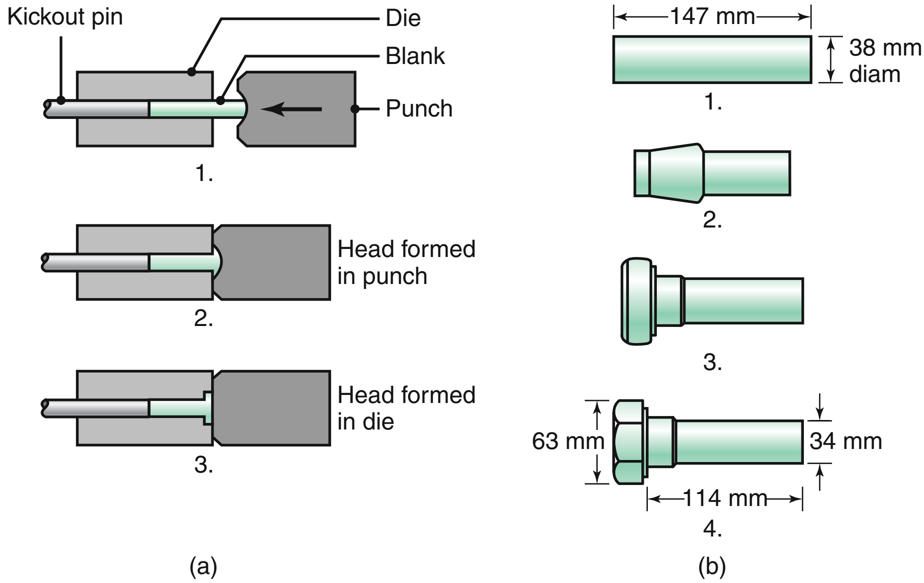


FIGURE 14.11 (a) Heading operation to form heads on fasteners, such as nails and rivets. (b) Sequence of operations used to produce a typical bolt head by heading.

FIGURE 14.12 A pierced round billet showing grain-flow pattern. (See also Fig. 14.2c). *Source*: Courtesy of Ladish Co., Inc.

consideration in heading is the tendency for the bar to buckle if its unsupported length-to-diameter ratio is too high. This ratio usually is limited to less than 3:1, but with appropriate dies, it can be higher. For example, higher ratios can be accommodated if the diameter of the die cavity is not more than 1.5 times the bar diameter.

Heading operations are performed on machines called **headers**, which usually are highly automated with production rates of hundreds of pieces per minute for small parts. Hot heading operations on larger parts typically are performed on *horizontal upsetters*. These machines tend to be noisy; a soundproof enclosure or the use of ear protectors is required. Heading operations can be combined with cold-extrusion processes to make various parts, as described in Section 15.4.

Piercing. This is a process of indenting (but not breaking through) the surface of a workpiece with a punch in order to produce a cavity or an impression (Fig. 14.12). The workpiece may be confined in a container (such as a die cavity) or may be unconstrained. The deformation of the workpiece will depend on how much it is constrained from flowing freely as the punch descends. A common example of piercing is the indentation of the hexagonal cavity in bolt heads. Piercing may be followed by punching to produce a hole in the part. (For a similar depiction of this situation, see the *slug* above the stationary punch in the central portion of Fig. 14.8.) Piercing also is performed to produce hollow regions in forgings using side-acting auxiliary equipment.

The *piercing force* depends on (a) the cross-sectional area and the tip geometry of the punch, (b) the strength of the material, and (c) the magnitude of friction at the sliding interfaces. The pressure may range from three to five times the strength of the material, which is approximately the same level of stress required to make an indentation in hardness testing (Section 2.6).

CASE STUDY 14.1 Manufacture of a Stepped Pin by Heading and Piercing Operations

Fig. 14.13a shows a stepped pin made from SAE 1008 steel and used as a part of a roller assembly to adjust the position of a car seat. The part is fairly complex and must be produced in a progressive manner in order to produce the required details and fill the die completely. The cold-forging steps used to produce this part are shown in Fig. 14.13b. First, a solid, cylindrical blank is extruded in two operations, followed by an upsetting operation. The upsetting operation uses a conical cross section in the die to produce the preform and is oriented such that material is concentrated at the top of the part in order to ensure proper die filling. After the impression-die forming, a piercing operation is performed to forms the bore. The part is made to net shape on a cold-forming machine at a rate of 240 parts per minute.

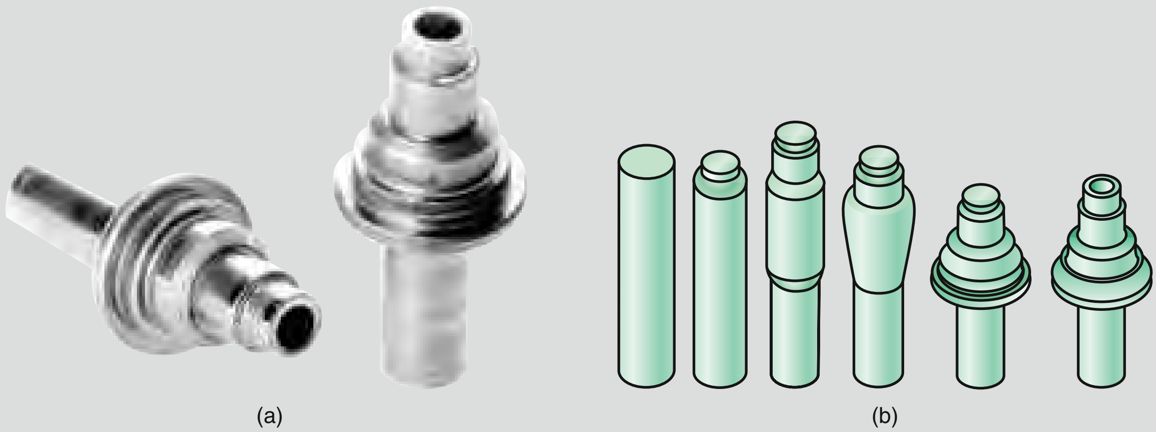


FIGURE 14.13 (a) The stepped pin used in Case Study 14.1. (b) Illustration of the manufacturing steps used to produce the stepped pin. *Source*: Courtesy of National Machinery, LLC.

Hubbing. This process consists of pressing a hardened punch with a particular tip geometry into the surface of a block of metal. The cavity produced is subsequently used as a die for forming operations, such as those employed in the making of tableware. The die cavity usually is shallow, but for deeper cavities, some material may be removed from the surface by machining prior to hubbing (see Fig. 24.2c and d). The *hubbing force* can be estimated from the equation

$$\text{Hubbing force} = 3(\text{UTS})(A), \tag{14.3}$$

where UTS is obtained from Table 2.2 and A is the projected area of the impression. For example, for high-strength steel with UTS = 1500 MPa and a part with a projected area of 400 mm^2, the hubbing force is $(3)(1500 \text{ N/mm}^2)(400 \text{ mm}^2) = 1.8 \text{ MN} = 179$ tons.

Orbital Forging. In this process, the upper die moves along an orbital path and forms the part *incrementally*. The operation is similar to the action of a mortar and pestle used for crushing herbs and seeds. Although not in common use, typical components that may be forged by this process are disk-shaped and conical parts, such as bevel gears and gear blanks. The forging force is relatively small, because at any particular instant, the die contact is concentrated onto a small area of the workpiece (see also *incremental forging* below). The operation is relatively quiet, and parts can be formed within 10 to 20 cycles of the orbiting die.

Incremental Forging. In this process, a tool forges a blank into a shape in several small steps. The operation is somewhat similar to cogging (see Fig. 14.4a), in which the die penetrates the blank to different depths along the surface. Because of the smaller area of contact with the die, the process requires much lower forces compared with conventional impression-die forging, and the tools are simpler and less costly.

Isothermal Forging. Also known as **hot-die forging**, this process heats the dies to the same temperature as that of the hot workpiece. Because the workpiece remains hot, its flow strength and high ductility are maintained during forging. Also, the forging load is low, and material flow within the die cavity is improved. Complex parts with good dimensional accuracy can be isothermally forged to near-net shape by one stroke in a hydraulic press. The dies for hot forging of high-temperature alloys usually are made of nickel or molybdenum alloys (because of their resistance to high temperature), but steel dies can be used for aluminum alloys. Isothermal forging is expensive and the production rate is low. However, it can be economical for specialized, intricate forgings made of materials such as aluminum, titanium, and superalloys, provided that the quantity required is sufficiently high to justify the die costs.

Rotary Swaging. In this process (also known as *radial forging, rotary forging*, or simply *swaging*), a solid rod or tube is subjected to radial impact forces by a set of reciprocating dies of the machine (Fig. 14.14a and b). The die movements are obtained by means of a set of rollers in a cage in an action similar to that of a roller bearing. The workpiece is stationary and the dies rotate (while moving radially in their slots), striking the workpiece at rates as high as 20 strokes per second. In *die-closing swaging machines*, die movements are obtained through the reciprocating motion of wedges (Fig. 14.14c). The dies can be opened wider than those in rotary swagers, thereby accommodating large-diameter or variable-diameter parts. In another type of machine, the dies do not rotate, but move radially in and out. Typical products made are screwdriver blades and soldering-iron tips.

Swaging also can be used to *assemble* fittings over cables and wire; in such cases, the tubular fitting is swaged directly onto the cable. The process is also used for operations such as *pointing* (tapering the tip of a cylindrical part) and *sizing* (finalizing the dimensions of a part).

Swaging generally is limited to a maximum workpiece diameter of about 150 mm (6 in.); parts as small as 0.5 mm (0.02 in.) have been swaged. Dimensional tolerances range from ±0.05 to ±0.5 mm (0.002 to 0.02 in.). The process is suitable for medium-to-high rates of production, with rates as high as 50 parts per minute possible, depending on part complexity. Swaging is a versatile process and is limited in length only by the length of the bar supporting the mandrel (if one is needed).

Tube Swaging. In this process, the internal diameter and/or the thickness of the tube is reduced with or without the use of *internal mandrels* (Figs. 14.15a and b). For small-diameter tubing, high-strength wire can be used as a mandrel. Mandrels also can be made with longitudinal grooves, to allow swaging of internally shaped tubes (Fig. 14.15c). For example, the rifling in gun barrels (internal spiral grooves to give gyroscopic effect to bullets) can be produced by swaging a tube over a mandrel with spiral grooves. Special machinery has been built to swage gun barrels and other parts with starting diameters as large as 350 mm (14 in.).

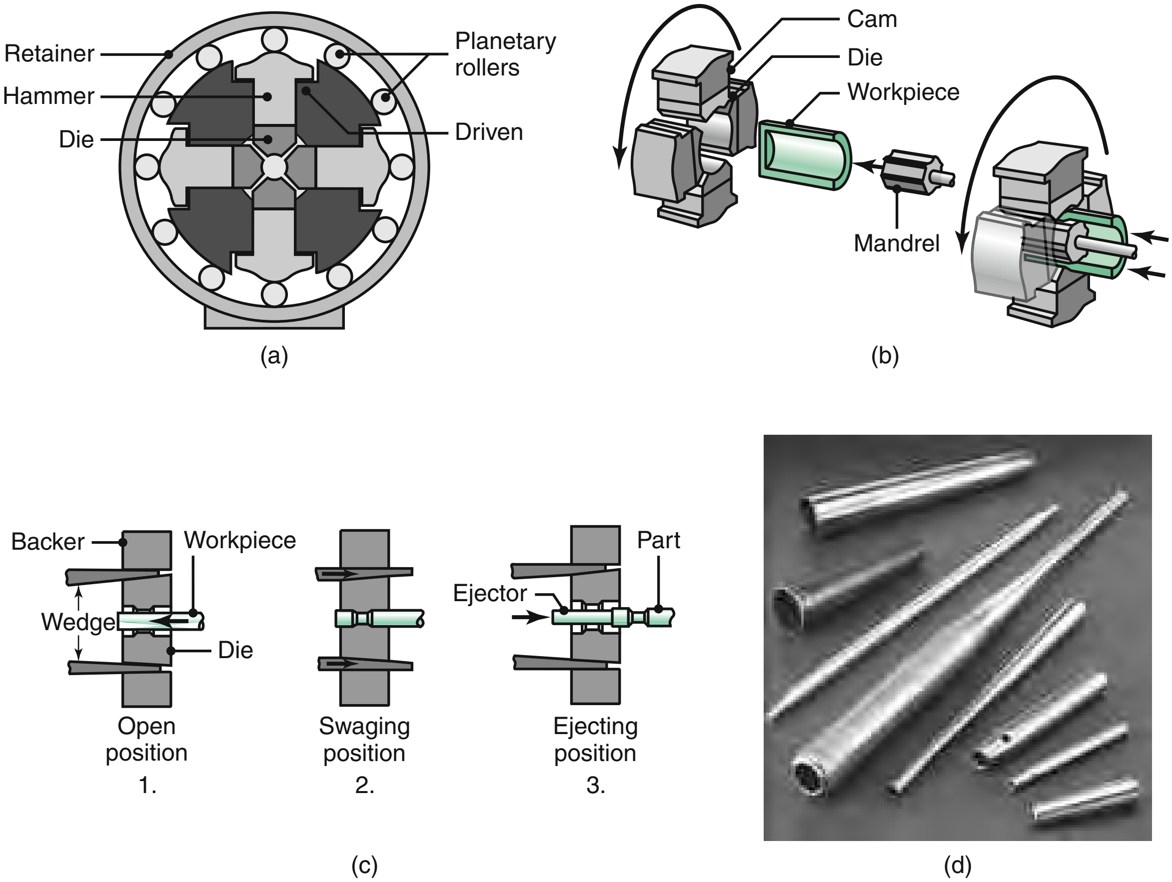


FIGURE 14.14 (a) Schematic illustration of the rotary-swaging process. (b) Forming internal profiles on a tubular workpiece by swaging. (c) A die-closing swaging machine, showing forming of a stepped shaft. (d) Typical parts made by swaging. *Source*: (d) Courtesy of J. Richard Industries.

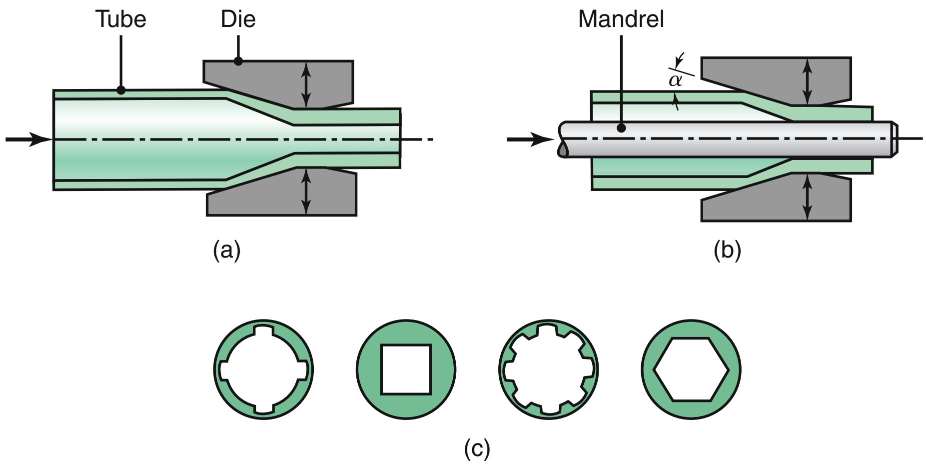


FIGURE 14.15 (a) Swaging of tubes without a mandrel; note the increase in wall thickness in the die gap. (b) Swaging with a mandrel; note that the final wall thickness of the tube depends on the mandrel diameter. (c) Examples of cross sections of tubes produced by swaging on shaped mandrels. Rifling (internal spiral grooves) in small gun barrels can be made by this process.

14.5 Forgeability of Metals; Forging Defects

Forgeability is generally defined as the capability of a material to undergo deformation without cracking. Various tests have been developed to quantify forgeability; however, because of their complex nature, only two simple tests have had general acceptance: upsetting and hot twist.

In the **upsetting test**, a solid, cylindrical specimen is upset between flat dies, and the reduction in height at which cracking on the barreled surfaces begins is noted (see also Fig. 2.20d). The greater the deformation prior to cracking, the greater the forgeability of the metal. The second method is the **hot-twist test**, in which a round specimen is twisted continuously in the same direction until it fails. This test is performed on a number of specimens and at different temperatures, and the number of complete turns that each specimen undergoes before failure at each temperature is plotted. The temperature at which the maximum number of turns occurs then becomes the forging temperature for maximum forgeability. The hot-twist test has been found to be useful particularly for steels.

The forgeability of various metals and alloys is given in Table 14.3 in decreasing order. Forgeability is based on considerations such as ductility and strength of the material, forging temperature required, frictional behavior, and the quality of the forgings produced. These ratings should be regarded only as general guidelines. Typical *hot-forging temperature* ranges for various metals and alloys are included in Table 14.3. Note that higher forging temperature does not necessarily indicate greater difficulty in forging that material. For *warm* forging, temperatures range from 200° to 300°C (400° to 600°F) for aluminum alloys and from 550° to 750°C (1000° to 1400°F) for steels.

Forging Defects. In addition to surface cracking, other defects can develop during forging as a result of the material flow pattern in the die, as described next in Section 14.6 regarding die design. For example, if there is an insufficient volume of material to fill the die cavity completely, the web may buckle during forging and develop laps (Fig. 14.16a). On the other hand, if the web is too thick, the excess material flows past the already formed portions of the forging and develops internal cracks (Fig. 14.16b).

TABLE 14.3

Forgeability of Metals, in Decreasing Order

Metal or alloy	Approximate range of hot-forging temperatures (°C)
Aluminum alloys	400–550
Magnesium alloys	250–350
Copper alloys	600–900
Carbon- and low-alloy steels	850–1150
Martensitic stainless steels	1100–1250
Austenitic stainless steels	1100–1250
Titanium alloys	700–950
Iron-based superalloys	1050–1180
Cobalt-based superalloys	1180–1250
Tantalum alloys	1050–1350
Molybdenum alloys	1150–1350
Nickel-based superalloys	1050–1200
Tungsten alloys	1200–1300

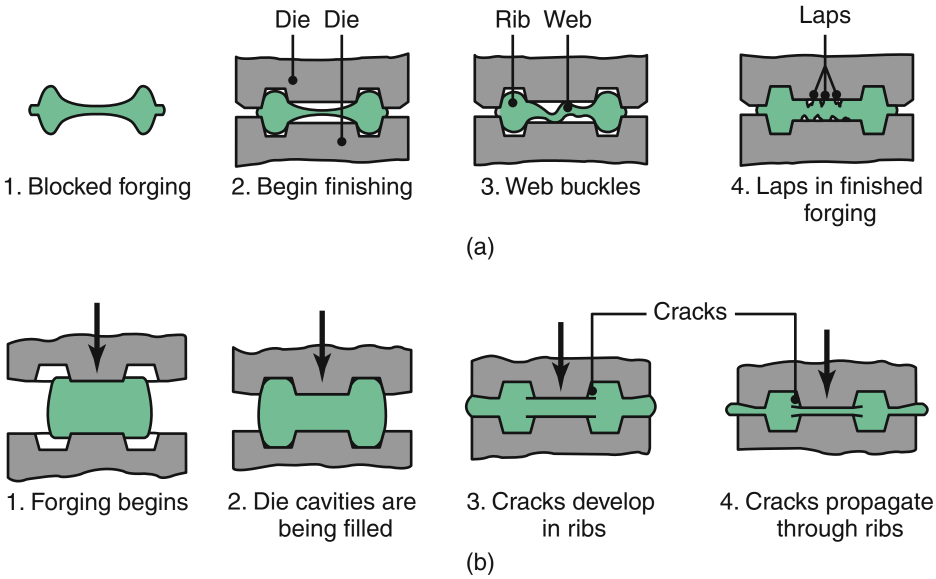


FIGURE 14.16 Examples of defects in forged parts. (a) Laps formed by web buckling during forging; web thickness should be increased to avoid this problem. (b) Internal defects caused by an oversized billet. Die cavities are filled prematurely, and the material at the center flows past the filled regions as the dies close.

The various radii in the forging-die cavity can significantly influence the formation of such defects. Internal defects also may develop from (a) nonuniform deformation of the material in the die cavity, (b) temperature gradients throughout the workpiece during forging, and (c) microstructural changes caused by phase transformations. The grain-flow pattern of the material in forging also is important. The flow lines may reach a surface perpendicularly, as shown in Fig. 14.12. In this condition, known as **end grains**, the grain boundaries become exposed directly to the environment and can be attacked by it, developing a rough surface and also acting as stress raisers.

Forging defects can cause fatigue failures, and they also may lead to such problems as corrosion and wear during the service life of the forged component. The importance of inspecting forgings prior to their placement in service, particularly in critical applications, such as aircraft, is obvious. Inspection techniques for manufactured parts are described in Chapter 36.

14.6 Die Design, Die Materials, and Lubrication

The design of forging dies requires considerable knowledge and experience regarding the shape and complexity of the workpiece, its ductility, its strength and sensitivity to deformation rate and temperature, and its frictional characteristics. Die distortion under high forging loads is also an important design consideration, particularly if close dimensional tolerances are required. The most important rule in die design is the fact that the part will flow in the direction of least resistance. Thus, the workpiece *intermediate shapes* should be planned so that they properly fill the die cavities. An example of the intermediate shapes for a connecting rod is given in Fig. 14.7a.

With continuing advances in developing reliable simulation of all types of metalworking operations, software is available to help predict material flow in forging-die cavities. The simulation incorporates various conditions, such as workpiece temperature and heat transfer, to tooling, frictional conditions at die–workpiece contact surfaces, and forging speed. Such software can be very helpful in die design and in eliminating future problems with defective forgings (see also Section 38.7).

Preshaping. In a properly preshaped workpiece, the material should not flow easily into the flash (otherwise die filling will be incomplete), the grain flow pattern should be favorable for the products' strength and reliability, and sliding at the workpiece–die interfaces should be minimized in order to reduce die wear. The selection of preshapes requires considerable experience and involves calculations of cross-sectional areas at each location in the forging. Computer modeling and simulation techniques are useful in such calculations.

Die Design Features. The terminology for forging dies is shown in Fig. 14.5d, and the significance of various features is described next. Some of these considerations are similar to those for casting (Section 12.2). For most forgings, the **parting line** is located at the largest cross section of the part. For simple symmetrical shapes, the parting line is normally a straight line at the center of the forging, but for more complex shapes, the line may not lie in a single plane. The dies are then designed in such a way that they lock during engagement, in order to avoid side thrust, balance forces, and maintain die alignment during forging.

After sufficiently constraining lateral flow to ensure proper die filling, the flash material is allowed to flow into a *gutter*, so that the extra flash does not increase the forging load excessively. A general guideline for flash thickness is 3% of the maximum thickness of the forging. The length of the *land* is usually two to five times the flash thickness.

Draft angles are necessary in almost all forging dies in order to facilitate removal of the part from the die. Upon cooling, the forging shrinks both radially and longitudinally, so internal draft angles (about 7° to 10°) are made larger than external ones (about 3° to 5°).

Selection of the proper radii for corners and fillets is important in ensuring smooth flow of the metal into the die cavity and improving die life. Small radii generally are undesirable because of their adverse effect on metal flow and their tendency to wear rapidly (as a result of stress concentration and thermal cycling). Small fillet radii also can cause fatigue cracking of the dies. As a general rule, these radii should be as large as can be permitted by the design of the forging. As with the patterns used in casting, *allowances* are provided in forging-die design when machining the forging is necessary to obtain final desired dimensions and surface finish. Machining allowance should be provided at flanges, at holes, and at mating surfaces.

Die Materials. Most forging operations (particularly for large parts) are carried out at elevated temperatures. General requirements for die materials therefore are

- Strength and toughness at elevated temperatures
- Hardenability and ability to harden uniformly
- Resistance to mechanical and thermal shock
- Wear resistance, particularly resistance to abrasive wear, because of the presence of scale in hot forging.

Common die materials are tool and die steels containing chromium, nickel, molybdenum, and vanadium (see Tables 5.7 and 5.8). Dies are made from die blocks, which themselves are forged from castings and then machined and finished to the desired shape and surface finish. Die-manufacturing methods are described in Section 14.7.

Lubrication. A wide variety of metalworking fluids can be used in forging, as described in Section 33.7. Lubricants greatly influence friction and wear. Consequently, they affect the forces required [see Eq. (14.1)], die life, and the manner in which the material flows into the die cavities. Lubricants can also act as a thermal barrier between the hot workpiece and the relatively cool dies—thus slowing the rate of cooling of the workpiece and improving metal flow. Another important role of the lubricant is to act as a *parting agent*, preventing the forging from sticking to the dies and helping release it from the die.

14.7 Die-manufacturing Methods and Die Failures

From the topics described thus far, it should be evident that dies, their quality, and die life are highly significant aspects of the total manufacturing operation, including the quality of the parts produced. This is particularly noteworthy in view of the fact that the vast majority of discrete parts that are produced in large quantities (such as gears, shafts, bolts, etc.), as well as castings of all types of products, are made in individual dies and molds. Dies also have an impact on the overall economics of manufacturing, because of their cost and the lead time needed to produce them, as some dies require months to manufacture. Equally important considerations are the maintenance of dies and their modifications as parts are first produced.

Several manufacturing methods, either singly or in combination, can be used to make dies for forging, as well as for other metalworking processes. These methods include casting, forging, machining, grinding, electrical and electrochemical methods—particularly electrical-discharge machining (EDM) and wire EDM—and the use of lasers for small dies. An important and continuing development is the production of tools and dies by **rapid tooling** using rapid protoyping techniques, described in Section 20.5.

The process of producing a die cavity in a **die block** is called **die sinking**. The process of *hubbing* (Section 14.4), either cold or hot, also may be used to make small dies with shallow cavities. Dies are usually heat treated for higher hardness and wear resistance (Chapter 33). If necessary, their surface profile and finish are improved further by finish grinding and polishing, either by hand or by programmable industrial robots.

The choice of a die-manufacturing method depends on its size and shape and the particular operation in which the die is to be used, such as casting, forging, extrusion, powder metallurgy, or plastics molding. As in all manufacturing operations, cost often dictates the process selected, because tool and die costs can be significant in manufacturing operations. Dies of various sizes and shapes can be **cast** from steels, cast irons, and nonferrous alloys. The processes used for preparing them may range from sand casting (for large dies weighing several tons) to shell molding (for casting small dies). Cast steels generally are preferred for large dies because of their strength and toughness, as well as the ease with which the steel composition, grain size, and other properties can be controlled and modified.

Most commonly, dies are *machined* from *forged die blocks* by processes such as high-speed milling, turning, grinding, and electrical discharge and electrochemical machining. Such an operation is shown in Fig. I.11b for making molds for eyeglass frames. For high-strength and wear-resistant die materials that are hard or are heat treated (and thus difficult to machine), processes such as hard machining (Section 25.6) and electrical and elctrochemical machining are a common practice. Typically, a die is machined by milling on computer-controlled machine tools with various software packages (see Fig. I.11) that have the capability (economically) of optimizing the cutting-tool path. Thus, the best surface finish can be obtained in the least possible machining time. Equally important is the setup for machining, because dies should be machined as much as possible in one setup without having to remove them from their fixtures and reorient them for subsequent machining operations.

After heat treating to achieve the desired mechanical properties, dies usually are subjected to *finishing operations* (Section 26.7), such as grinding, polishing, and chemical and electrical processes, to obtain the desired surface finish and dimensional accuracy. This also may include *laser surface treatments* and *coatings* (Chapter 34) to improve die life. Lasers are sometimes used for die repair and reconfiguration of the worn regions of dies (see also Fig. 33.11).

Die Costs. From the preceding discussion, it is evident that the cost of a die depends greatly on its size, shape complexity, application, and surface finish required, as well as the die material and manufacturing, heat treating, and finishing methods employed. Consequently, specific die costs cannot be categorized easily. Some qualitative ranges of tool and die costs are given throughout this book, such as in Table 12.6. Even small and relatively simple dies can cost hundreds of dollars to make, and the cost of a set of dies for automotive body panels can be as much as $2 million. On the other hand, because a large number of parts usually are made from one set of dies, the *die cost per piece made* is generally a small portion of a part's manufacturing cost (see also Section 40.9). The lead time required to produce dies also can have a significant impact on the overall manufacturing cost, particularly in a global and competitive marketplace.

Die Failures. Failure of dies in manufacturing operations generally results from one or more of the following causes:

- Improper die design
- Defective or improper selection of die material
- Improper manufacturing and improper heat-treatment and finishing operations
- Overheating and heat checking (i.e., cracking caused by temperature cycling)
- Excessive wear
- Overloading (i.e., excessive force on the die)
- Improper alignment of the die components with respect to their movements
- Misuse
- Improper handling of the die.

Although these factors typically apply to dies made of tool and die steels, many also apply to other die materials, such as carbides, ceramics, and diamond.

The proper design of dies is as important as the proper selection of die materials. In order to withstand the forces involved, a die must have sufficiently large cross sections and clearances (to prevent jamming). Abrupt changes in cross section, sharp corners, radii, fillets, and a coarse surface finish (including grinding marks and their orientation on die surfaces) act as stress raisers and thus can have detrimental effects on die life. For improved strength and to reduce the tendency for cracking, dies may be made in segments and assembled into a complete die with rings that prestress the dies. Proper handling, installation, assembly, and alignment of dies are essential. Overloading of tools and dies can cause premature failure.

A common cause of failure in cold-extrusion dies is that of the operator (or of a programmable robot) to fail to remove a formed part from the die before loading it with another blank.

14.8 Forging Machines

A variety of forging machines is available with a range of capacities (tonnage), speeds, and speed–stroke characteristics (Table 14.4).

Hydraulic Presses. These presses operate at constant speeds and are *load limited*, or load restricted. In other words, a press stops if the load required exceeds its capacity. Large amounts of energy can be transmitted to a workpiece by a constant load throughout a stroke—the speed of which can be controlled. Because forging in a hydraulic press takes longer than in the other types of forging machines described next, the workpiece may cool rapidly unless the dies are heated (see *isothermal forging*, Section 14.4). Compared with mechanical presses, hydraulic presses are slower and involve higher initial costs, but they require less maintenance.

A hydraulic press typically consists of a frame with two or four columns, pistons, cylinders (Fig. 14.17), rams, and hydraulic pumps driven by electric motors. The ram speed can be varied during the stroke. Press capacities range up to 125 MN (14,000 tons) for open-die forging and up to 450 MN (50,000 tons) in North America, 640 MN (72,000 tons) in France, and 730 MN (82,000 tons) in Russia for closed-die forging. The main landing-gear support beam for the Boeing 747 aircraft

TABLE 14.4

Typical Speed Ranges of Forging Equipment

Equipment	m/s
Hydraulic press	0.06–0.30
Mechanical press	0.06–1.5
Screw press	0.6–1.2
Gravity drop hammer	3.6–4.8
Power drop hammer	3.0–9.0
Counterblow hammer	4.5–9.0

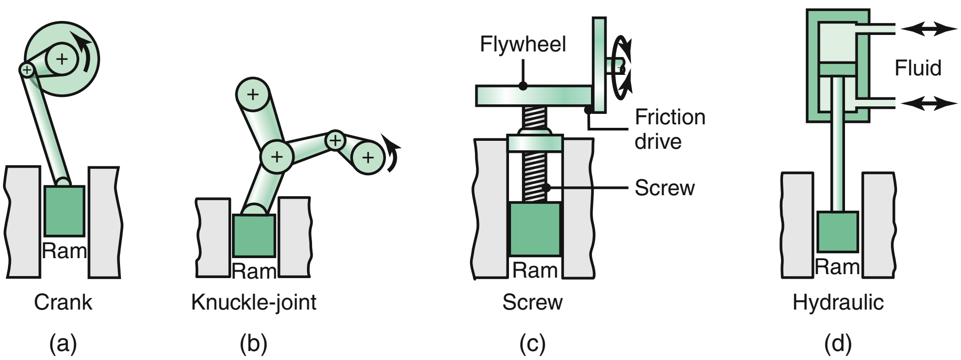


FIGURE 14.17 Schematic illustration of the principles of various forging machines. (a) Mechanical press with an eccentric drive; the eccentric shaft can be replaced by a crankshaft to give up-and-down motion to the ram. (b) Knuckle-joint press. (c) Screw press. (d) Hydraulic press.

is forged in a 450-MN (50,000-ton) hydraulic press, shown in Fig. 14.1c with the part in the forefront. This part is made of a titanium alloy and weighs approximately 1350 kg (3000 lb).

Mechanical Presses. These presses are basically of either the crank or the eccentric type (Fig. 14.17a). The speed varies from a maximum at the center of the stroke to zero at the bottom of the stroke; thus, mechanical presses are *stroke limited*. The energy in a mechanical press is generated by a large flywheel powered by an electric motor. A clutch engages the flywheel to an eccentric shaft. A connecting rod translates the rotary motion into a reciprocating linear motion. A *knuckle-joint* mechanical press is shown in Fig. 14.17b. Because of the linkage design, very high forces can be applied in this type of press (see also Fig. 11.20).

The force available in a mechanical press depends on the stroke position and becomes extremely high at the end of the stroke. Thus, proper setup is essential to avoid breaking the dies or equipment components. Mechanical presses have high production rates, are easier to automate, and require less operator skill than do other types of machines. Press capacities generally range from 2.7 to 107 MN (300 to 12,000 tons). Mechanical presses are preferred for forging parts with high precision.

Screw Presses. These presses (Fig. 14.17c) derive their energy from a flywheel; hence, they are *energy limited*. The forging load is transmitted through a large vertical screw, and the ram comes to a stop when the flywheel energy is dissipated. If the dies do not close at the end of the cycle, the operation is repeated until the forging is completed. Screw presses are used for various open-die and closed-die forging operations. They are suitable particularly for small production quantities, especially thin parts with high precision, such as turbine blades. Press capacities range from 1.4 to 280 MN (160 to 31,500 tons).

Hammers. Hammers derive their energy from the potential energy of the ram, which is converted into kinetic energy; hence, they are *energy limited*. Unlike hydraulic presses, hammers (as the name implies) operate at high speeds, and the resulting low forming time minimizes the cooling of a hot forging. Low cooling rates then allow the forging of complex shapes, particularly those with thin and deep recesses. To complete the forging, several successive blows usually are made in the same die. Hammers are available in a variety of designs and are the most versatile and the least expensive type of forging equipment.

Drop Hammers. In *power drop hammers*, the ram's downstroke is accelerated by steam, air, or hydraulic pressure at about 750 kPa (100 psi). Ram weights range from 225 to 22,500 kg (500 to 50,000 lb), with energy capacities reaching 1150 kJ (850,000 ft-lb). In the operation of *gravity drop hammers* (a process called **drop forging**), the energy is derived from the free-falling ram. The available energy of a drop hammer is the product of the ram's weight and the height of its drop. Ram weights range from 180 to 4500 kg (400 to 10,000 lb), with energy capacities ranging up to 120 kJ (90,000 ft-lb).

Counterblow Hammers. These hammers have two rams that simultaneously approach each other horizontally or vertically to forge the part. As in open-die forging operations, the part may be rotated between blows for proper shaping of the workpiece during forging. Counterblow hammers operate at high speeds and transmit less vibration to their bases. Capacities range up to 1200 kJ (900,000 ft-lb).

High-energy-rate Forging Machines. In these machines, the ram is accelerated rapidly by inert gas at high pressure and the part is forged in one blow at a very high speed. Although there are several types of these machines, various problems associated with their operation and maintenance, as well as die breakage and safety considerations, have greatly limited their use in industry.

14.9 Economics of Forging

Several factors are involved in the cost of forgings. Depending on the complexity of the forging, tool and die costs range from moderate to high. However, as in other manufacturing operations, these costs are spread out over the number of parts forged with that particular die set. Thus, even though the cost of workpiece material per piece made is constant, setup and tooling costs per piece decrease as the number of pieces forged increases (Fig. 14.18).

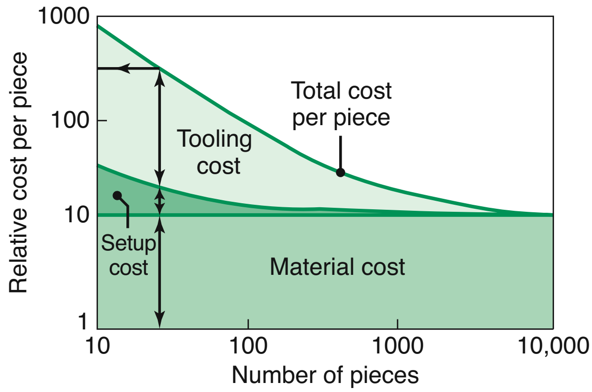


FIGURE 14.18 Typical cost per piece in forging; note how the setup and the tooling costs per piece decrease as the number of pieces forged increases if all pieces use the same die.

The ratio of the cost of the die material to the total cost of forging the part increases with the weight of forgings: The more expensive the material, the higher the cost of the material relative to the total cost. Because dies must be made and forging operations must be performed regardless of the size of the forging, the cost of dies and of the forging operation relative to material cost is high for small parts. By contrast, die material costs are relatively low.

The size of forgings also has some effect on cost. Sizes range from small forgings (such as utensils and small automotive components) to large ones (such as gears, crankshafts, and connecting rods for large engines). As forging size increases, the share of material cost in the total cost also increases, but at a lower rate. This occurs because (a) the incremental increase in die cost for larger dies is relatively small, (b) the machinery and operations involved are essentially the same regardless of forging size, and (c) the labor involved per piece made is not that much higher.

The total cost involved in a forging operation is not influenced to any major extent by the type of materials forged. Because they have been reduced significantly by automated and computer-controlled operations, labor costs in forging generally are moderate. Also, die design and manufacturing are now performed by computer-aided design and manufacturing techniques (Chapter 38), which result in major savings in time and effort.

The cost of forging a part compared to that of making it by various casting techniques, powder metallurgy, machining, or other methods is an important consideration in a competitive global marketplace. For example, all other factors being the same, and depending on the number of pieces required, manufacturing a certain part by, say, expendable-mold casting may well be more economical than producing it by forging for shorter production runs (Fig. 14.19). This casting method does not require expensive molds and tooling, whereas forging requires expensive dies. Some competitive aspects of manufacturing and process selection are discussed in greater detail in Chapter 40.

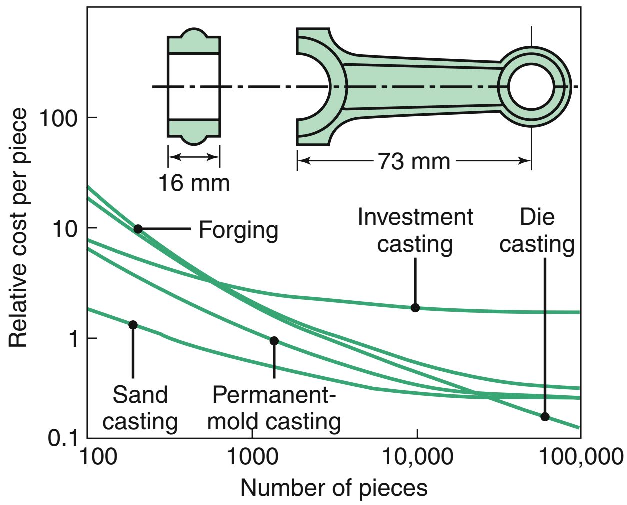


FIGURE 14.19 Relative unit costs of a small connecting rod made by various forging and casting processes. Note that, for large quantities, forging is more economical. Sand casting is the most economical process for fewer than about 20,000 pieces.

CASE STUDY 14.2 Suspension Components for the Lotus Elise Automobile

The automotive industry increasingly has been subjected to a demanding set of performance, cost, fuel efficiency, and environmental regulations. One of the main strategies in improving vehicle design with respect to all of these possibly conflicting constraints is to reduce vehicle weight while using advanced materials and manufacturing processes to preserve performance and safety. Previous design optimization has shown that weight savings of up to 34% can be realized on suspension system components—a significant savings, since suspensions make up approximately 12% of a car's mass. These weight savings could be achieved largely by developing optimum designs, utilizing advanced analytical tools, and using net-shape or near-net-shape steel forgings instead of cast-iron components. In addition, significant cost savings have been demonstrated in many parts when optimized steel forgings are used, as opposed to aluminum castings and extrusions.

The Lotus Elise is a high-performance sports car designed for superior ride and superior handling. The Lotus group investigated the use of steel forgings instead of extruded-aluminum suspension uprights in order to reduce cost and improve reliability and performance. Their development efforts consisted of two phases, shown in Fig. 14.20. The first phase involved the development of a forged-steel component that can be used on the existing Elise sports car; the second phase involved the production of a suspension upright for a new model.

A new design was developed using an iterative process with advanced software tools to reduce the number of components and to determine the optimum geometry. The material selected for the upright was an air-cooled forged steel, which gives uniform grain size and microstructure and uniform high strength without the need for heat treatment. These materials also have approximately 20% higher fatigue strengths than traditional carbon steels, such as AISI 1548-HT, which is used for similar applications.

The revised designs are summarized in Table 14.5. As can be seen, the optimized new forging

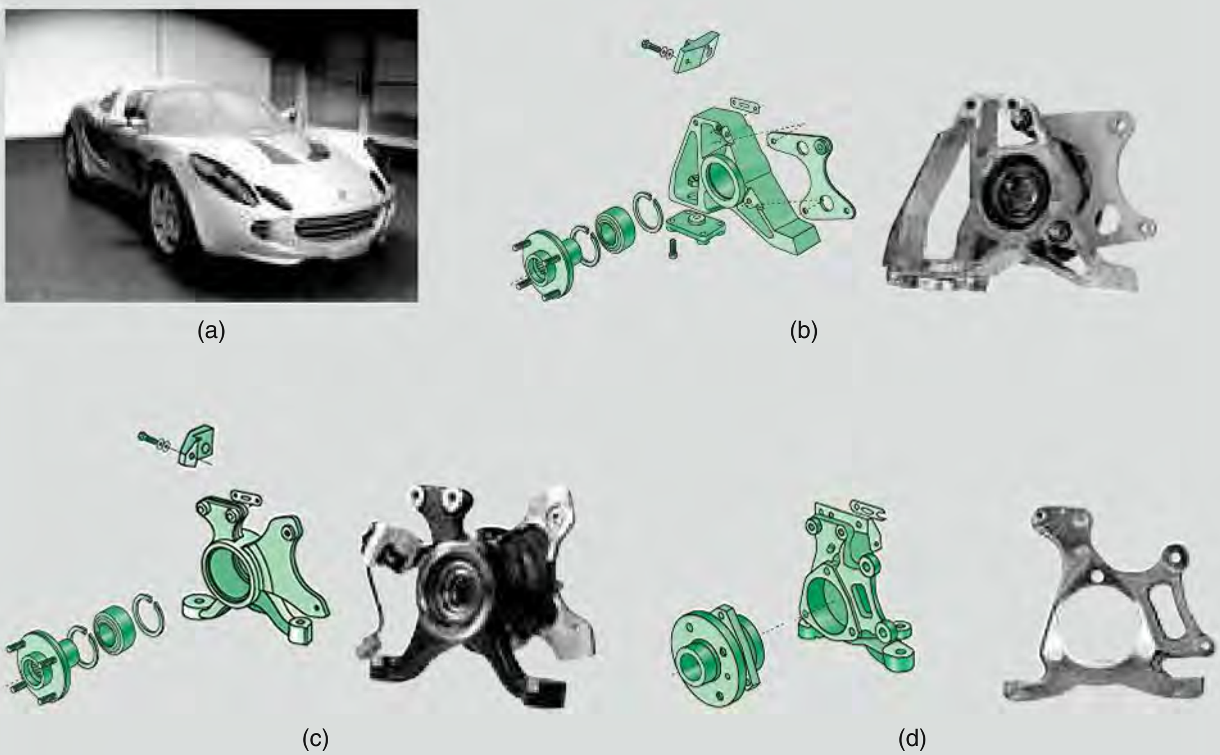


FIGURE 14.20 (a) The Lotus Elise Series 2 automobile. (b) illustration of the original design for the vertical suspension uprights, using an aluminum extrusion. (c) retrofit design, using a steel forging. (d) optimized steel forging design for new car models. *Source*: (a) Courtesy of Fox Valley Motorcars. (b) through (d) Courtesy of Lotus Engineering and the American Iron and Steel Institute.

TABLE 14.5

Comparison of Suspension Upright Designs for the Lotus Elise Automobile

Fig. 14.20 sketch	Material	Application	Mass (kg)	Cost ($)
(b)	Aluminum extrusion, steel bracket, steel bushing, housing	Original design	2.105	85
(c)	Forged steel	Phase I	2.685 (+28%)	27.7 (−67%)
(d)	Forged steel	Phase II	2.493 (+18%)	30.8 (−64%)

design (Fig. 14.20d) resulted in significant cost savings. Although it also resulted in a small weight increase when compared to the aluminum-extrusion design, the weight penalty is recognized as quite small, and the use of forged steel for such components is especially advantageous in fatigue-loading conditions constantly encountered by suspension components. The new design also had certain performance advantages in that the component stiffness is now higher, which registered as improved customer satisfaction and better "feel" during driving. Furthermore, the new design reduced the number of parts required, thus satisfying another fundamental principle in design.

Source: Courtesy of Lotus Engineering and the American Iron and Steel Institute.

SUMMARY

- Forging denotes a family of metalworking processes in which deformation of the workpiece is carried out by compressive forces applied through a set of dies. Forging is capable of producing a wide variety of structural parts with favorable characteristics, such as higher strength, improved toughness, dimensional accuracy, and reliability in service.
- The forging process can be carried out at room, warm, or high temperatures. Workpiece material behavior during deformation, friction, heat transfer, and material-flow characteristics in the die cavity are important considerations, as are the proper selection of die materials, lubricants, workpiece and die temperatures, forging speeds, and equipment.
- Various defects can develop if the forging process is not designed or controlled properly. Defects appear especially in workpiece quality, billet or preform shape, and die geometry. Computer-aided design and manufacturing techniques are now used extensively in die design and manufacturing, preform design, predicting material flow, and avoiding the possibility of internal and external defects during forging.
- A variety of forging machines is available, each with its own capabilities and characteristics. Forging operations are now highly automated and use industrial robots and computer controls.
- Swaging is a type of rotary forging in which a solid rod or a tube is reduced in diameter by the reciprocating radial movement of a set of two or four dies. The process is suitable for producing short or long lengths of bar or tubing with various internal or external profiles.
- Because die failure has a major economic impact, die design, material selection, and production method are of major importance. A variety of die materials and manufacturing methods is available, including advanced material-removal and finishing processes.

CHAPTER

15 Metal Extrusion and Drawing Processes and Equipment

- Extrusion and drawing involve, respectively, pushing or pulling a material through a die basically for the purpose of reducing or changing its cross-sectional area.
- This chapter examines the fundamentals of these processes and their applications.
- The chapter starts by discussing the basic types of extrusion processes, namely, direct, indirect, and hydrostatic extrusion, and explains how the extrusion force can be estimated from material and processing parameters.
- Hot and cold extrusion are then discussed; cold extrusion is often done in combination with forging to produce specific parts.
- Extrusion practices and die designs that avoid common defects are also presented.
- The drawing of rod, wire, and tubing is then examined in a similar manner, along with die design.
- The equipment characteristics for these processes are also described.

Typical parts made by extrusion and drawing: Long pieces having a wide variety of constant cross sections, rods, shafts, bars for machinery and automotive power-train applications, aluminum ladders, collapsible tubes, wire for numerous electrical and mechanical applications and musical instruments.

Alternative processes: Machining, powder metallurgy, shape rolling, roll forming, pultrusion, and continuous casting.

15.1 Introduction

Extrusion and drawing have numerous applications in the manufacture of continuous as well as discrete products from a wide variety of metals and alloys. Plastics also are extruded extensively, as described in Section 19.2. In **extrusion**, a cylindrical billet is forced through a die (Fig. 15.1) in a manner similar to squeezing toothpaste from a tube or extruding Play-Doh® in various cross sections in a toy press. A wide variety of solid or hollow cross sections may be produced by extrusion, which essentially are semifinished parts. A characteristic of extrusion (from the Latin *extrudere*, meaning "to force out") is that large deformations can take place without fracture (see Section 2.2.8), because the material is under high triaxial compression. Since the die geometry remains unchanged throughout the operation, extruded products typically have a constant cross section.

Typical products made by extrusion are railings for sliding doors, window frames, tubing having various cross sections, aluminum ladder frames, and numerous structural and architectural shapes. Extrusions can be cut into desired lengths, which then become discrete parts, such as brackets, gears, and coat hangers (Fig. 15.2). Commonly extruded materials are aluminum, copper, steel, magnesium, and lead; other metals and alloys also can be extruded, with various levels of difficulty.

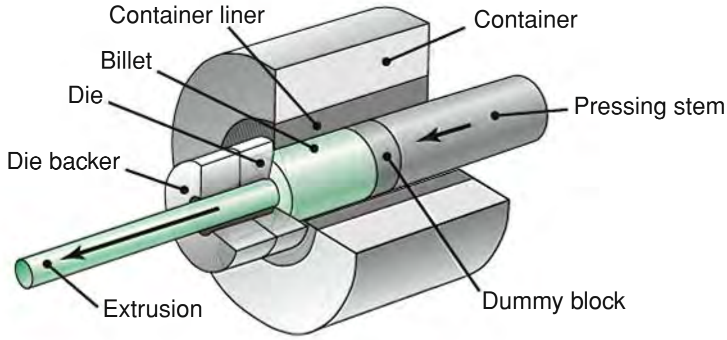


FIGURE 15.1 Schematic illustration of the direct-extrusion process.

Because a chamber is involved, each billet is extruded individually; thus, extrusion is a batch, or semicontinuous, process. Extrusion can be economical for large as well as short production runs. Tool costs generally are low, particularly for producing simple, solid cross sections.

Depending on the ductility of the material, extrusion is carried out at room or elevated temperatures. Extrusion at room temperature often is combined with forging operations, in which case it generally is known as **cold extrusion** (see also Section 14.4). It has numerous important applications, including fasteners and components for automobiles, bicycles, motorcycles, heavy machinery, and transportation equipment.

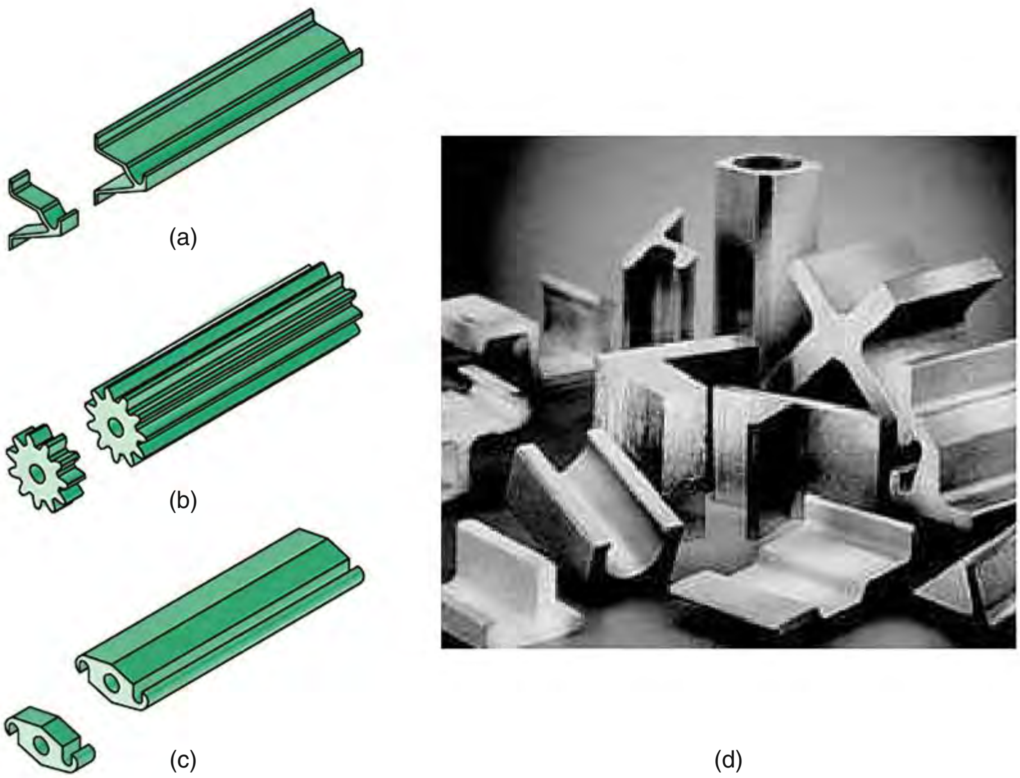


FIGURE 15.2 Extrusions and examples of products made by sectioning off extrusions. *Source*: Courtesy of Plymouth Extruded Shapes.

In **drawing**, an operation that was developed between 1000 and 1500 A.D., the cross section of solid rod, wire, or tubing is reduced or changed in shape by pulling it through a die. Drawn rods are used for shafts, spindles, and small pistons and as the raw material for fasteners (such as rivets, bolts, and screws). In addition to round rods, various profiles can be drawn. The term *drawing* also is used to refer to making cup-shaped parts by sheet-metal-forming operations, as described in Section 16.7.

The distinction between the terms **rod** and **wire** is somewhat arbitrary, with rod taken to be larger in cross section than wire. In industry, wire generally is defined as a rod that has been drawn through a die at least once, or its diameter is small enough so that it can be coiled. Wire drawing involves smaller diameters than rod drawing, with sizes down to 0.01 mm (0.0005 in.) for magnet wire and even smaller for use in very low current fuses.

15.2 The Extrusion Process

There are three basic types of extrusion. In the most common process (called **direct** or **forward extrusion**), a billet is placed in a *chamber* (container) and forced through a die opening by a hydraulically driven ram (pressing stem or punch), as shown in Fig. 15.1. The die opening may be round, or it may have various shapes, depending on the desired profile. The function of the dummy block shown in the figure is to protect the tip of the pressing stem (punch), particularly in hot extrusion. Other types of extrusion are indirect, hydrostatic, and impact extrusion.

In **indirect** extrusion (also called reverse, inverted, or backward extrusion), the die moves toward the unextruded billet (Fig. 15.3a). Indirect extrusion has the advantage of having no billet–container friction, since there is no relative motion. Thus, indirect extrusion is used on materials with very high friction, such as high-strength steels.

In **hydrostatic** extrusion (Fig. 15.3b), the billet is smaller in diameter than the chamber (which is filled with a fluid), and the pressure is transmitted to the fluid by a ram. The fluid pressure results in triaxial compressive stresses acting on the workpiece and thus improved formability; also, there is much less workpiece–container friction than in direct extrusion. A less common type of extrusion is *lateral* (or *side*) *extrusion* (Fig. 15.3c).

As can be seen in Fig. 15.4, the geometric variables in extrusion are the die angle, α, and the ratio of the cross-sectional area of the billet to that of the extruded product, A_o/A_f, called the **extrusion ratio**, R. Other variables are the temperature of the billet, the speed at which the ram travels, and the type of lubricant used.

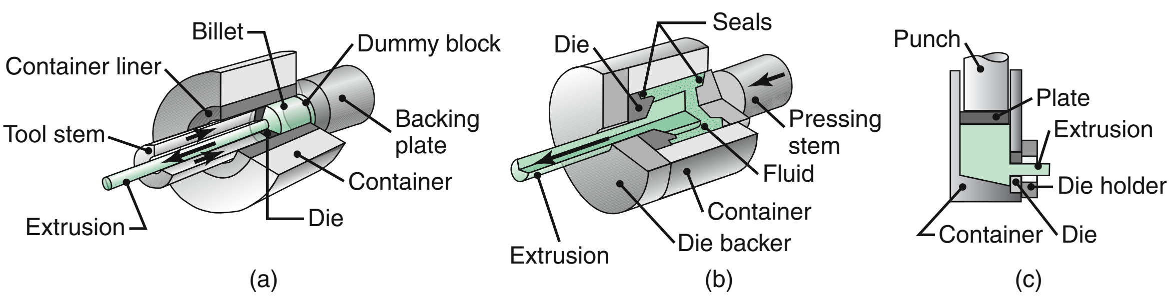


FIGURE 15.3 Types of extrusion: (a) indirect; (b) hydrostatic; (c) lateral.

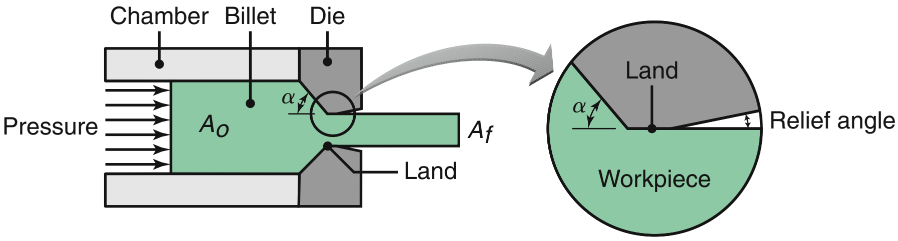


FIGURE 15.4 Process variables in direct extrusion. The die angle, reduction in cross section, extrusion speed, billet temperature, and lubrication all affect the extrusion pressure.

Extrusion Force. The force required for extrusion depends on (a) the strength of the billet material, (b) the extrusion ratio, (c) the friction between the billet and the chamber and die surfaces, and (d) process variables, such as the temperature of the billet and the speed of extrusion. The *extrusion force, F*, can be estimated from the formula

$$F = A_o k \ln\left(\frac{A_o}{A_f}\right), \tag{15.1}$$

where k is the **extrusion constant** (which is determined experimentally) and A_o and A_f are the billet and extruded product areas, respectively. The k value in Eq. (15.1) is thus a measure of the strength of the material being extruded and the frictional conditions. Figure 15.5 gives the k values of several metals for a range of extrusion temperatures.

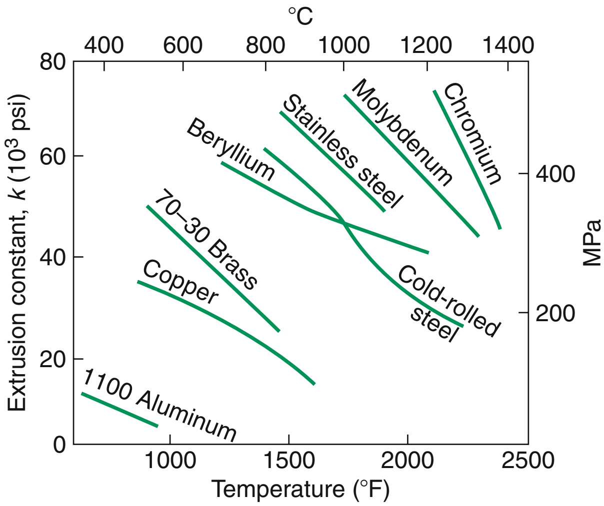


FIGURE 15.5 Extrusion constant k for various metals at different temperatures. *Source*: After P. Loewenstein.

EXAMPLE 15.1 Calculation of Force in Hot Extrusion

A round billet made of 70–30 brass is extruded at a temperature of 1250°F (675°C). The billet diameter is 5 in. (125 mm), and the diameter of the extrusion is 2 in. (50 mm). Calculate the extrusion force required.

Solution The extrusion force is calculated using Eq. (15.1), in which the extrusion constant, k, is obtained from Fig. 15.5. For 70–30 brass, k = 35,000 psi (250 MPa) at the given extrusion temperature. Thus,

$$F = \pi(2.5)^2(35{,}000)\ln\left[\frac{\pi(2.5)^2}{\pi(1.0)^2}\right] = 1.26 \times 10^6 \text{ lb}$$

$$= 630 \text{ tons} = 5.5 \text{ MN}.$$

(See Section 15.6 for capacities of extrusion presses.)

Metal Flow in Extrusion. The metal flow pattern in extrusion, as in other forming processes, is important because of its influence on the quality and the mechanical properties of the extruded product. The material flows longitudinally, much like incompressible fluid flows in a channel; thus, extruded products have an elongated grain structure (preferred orientation). Section 15.5 describes how improper metal flow during extrusion can produce various defects in the extruded product.

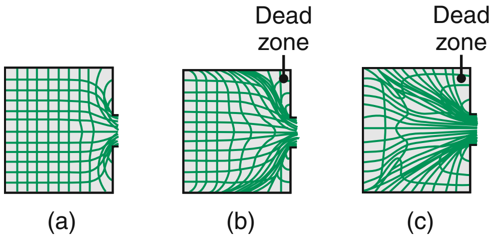


FIGURE 15.6 Types of metal flow in extruding with square dies. (a) Flow pattern obtained at low friction or in indirect extrusion. (b) Pattern obtained with high friction at the billet–chamber interfaces. (c) Pattern obtained at high friction or with cooling of the outer regions of the billet in the chamber. This type of pattern, observed in metals whose strength increases rapidly with decreasing temperature, leads to a defect known as pipe (or extrusion) defect.

A common technique for investigating the flow pattern is to cut the round billet in half lengthwise and then mark one face with a square grid pattern. The two halves may be brazed together, after which they are placed in the chamber together and are extruded. The two pieces are then taken apart (by melting the braze, if used, in a furnace) and studied. Figure 15.6 shows typical flow patterns obtained by this technique for the case of direct extrusion with *square dies* (a 90° die angle). The flow pattern is a function of several variables, including friction.

The conditions under which these different flow patterns occur are described in the caption of Fig. 15.6. Note the **dead-metal zones** in Fig. 15.6b and c, where the metal at the corners essentially is stationary. This situation is similar to the stagnation of fluid flow in channels that have sharp angles or turns.

Process Parameters. Because they have high ductility, wrought aluminum, copper, and magnesium and their alloys, as well as steels and stainless steels, are extruded with relative ease into numerous shapes. Other metals (such as titanium and refractory metals) also can be extruded, but only with some difficulty and considerable die wear.

In practice, extrusion ratios, R, usually range from about 10 to 100. They may be higher for special applications (400 for softer nonferrous metals) or lower for less ductile materials, although the ratio usually has to be at least 4 to deform the material plastically through the bulk of the workpiece. Extruded products usually are less than 7.5 m (25 ft) long because of the difficulty in handling greater lengths, but they can be as long as 30 m (100 ft). Ram speeds range up to 0.5 m/s (100 ft/min). Generally, lower speeds are preferred for aluminum, magnesium, and copper, higher speeds for steels, titanium, and refractory alloys. Dimensional tolerances in extrusion are usually in the range from ±0.25 to 2.5 mm (±0.01 to 0.1 in), and they increase with increasing cross section.

Most extruded products—particularly those with small cross sections—require straightening and twisting. This is accomplished typically by stretching and twisting the extruded product, usually in a hydraulic stretcher equipped with jaws. The presence of a die angle causes a small portion of the end of the billet to remain in the chamber after the operation has been completed. This portion (called scrap or the *butt end*) subsequently is removed by cutting off the extrusion at the die exit and removing the scrap from the chamber. Alternatively, another billet or a graphite block may be placed in the chamber to extrude the piece remaining from the previous extrusion.

In **coaxial extrusion**, or **cladding**, coaxial billets are extruded together—provided that the strength and ductility of the two metals are compatible. An example is copper clad with silver. *Stepped extrusions* are produced by extruding the billet partially in one die and then in one or more larger dies (see also *cold extrusion*, Section 15.4). Lateral extrusion (Fig. 15.3c) is used for the sheathing of wire and the coating of electric wire with plastic.

15.3 Hot Extrusion

For metals and alloys that do not have sufficient ductility at room temperature, or in order to reduce the forces required, extrusion is carried out at elevated temperatures (Table 15.1). As in all other hot-working operations, hot extrusion has special requirements because of the high operating temperatures. For example, die wear can

TABLE 15.1

Typical Extrusion Temperature Ranges for Various Metals and Alloys

	°C
Lead	200–250
Aluminum and its alloys	375–475
Copper and its alloys	650–975
Steels	875–1300
Refractory alloys	975–2200

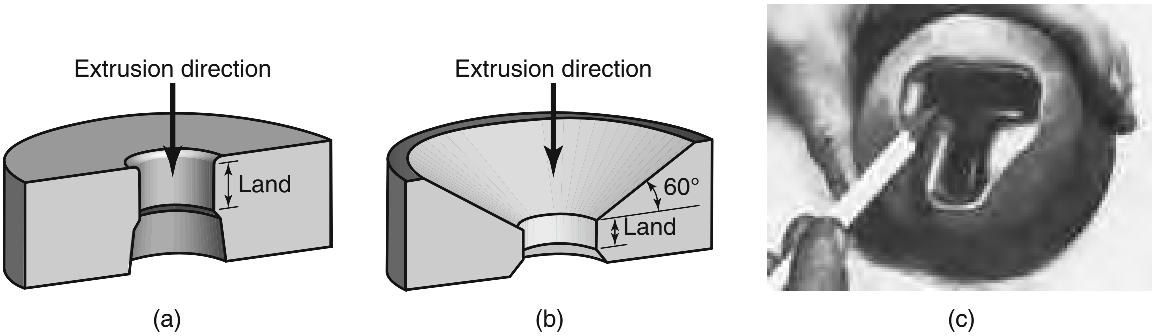


FIGURE 15.7 Typical extrusion–die configurations: (a) die for nonferrous metals; (b) die for ferrous metals; (c) die for a T-shaped extrusion made of hot-work die steel and used with molten glass as a lubricant. *Source*: (c) Courtesy of LTV Steel Company.

be excessive, and cooling of the surfaces of the hot billet (in the cooler chamber) and the die can result in highly nonuniform deformation (Fig. 15.6c). To reduce cooling of the billet and to prolong die life, extrusion dies may be preheated, as is done in hot-forging operations.

Because the billet is hot, it develops an oxide film, unless it is heated in an inert-atmosphere furnace. Oxide films can be abrasive (see Section 33.2) and can affect the flow pattern of the material. Their presence also results in an extruded product that may be unacceptable when good surface finish is important. In order to avoid the formation of oxide films on the hot extruded product, the dummy block placed ahead of the ram (Fig. 15.1) is made a little smaller in diameter than the container. As a result, a thin shell (*skull*) consisting mainly of the outer oxidized layer of the billet is left in the container. The skull is removed later from the chamber.

Die Design. Die design requires considerable experience, as can be appreciated by reviewing Fig. 15.7. *Square dies* (*shear dies*) are used in extruding nonferrous metals, especially aluminum. Square dies develop dead-metal zones, which in turn form a "die angle" (see Fig. 15.6b and c) along which the material flows in the deformation zone. The dead-metal zones produce extrusions with bright finishes because of the burnishing that takes places as the material flows past the "die angle" surface.

Tubing is extruded from a solid or hollow billet (Fig. 15.8). Wall thickness is usually limited to 1 mm (0.040 in.) for aluminum, 3 mm (0.125 in.) for carbon steels, and 5 mm (0.20 in.) for stainless steels. When solid billets are used, the ram is fitted with a mandrel that pierces a hole into the billet. Billets with a previously pierced hole also may be extruded in this manner. Because of friction and the severity of deformation, thin-walled extrusions are more difficult to produce than those with thick walls.

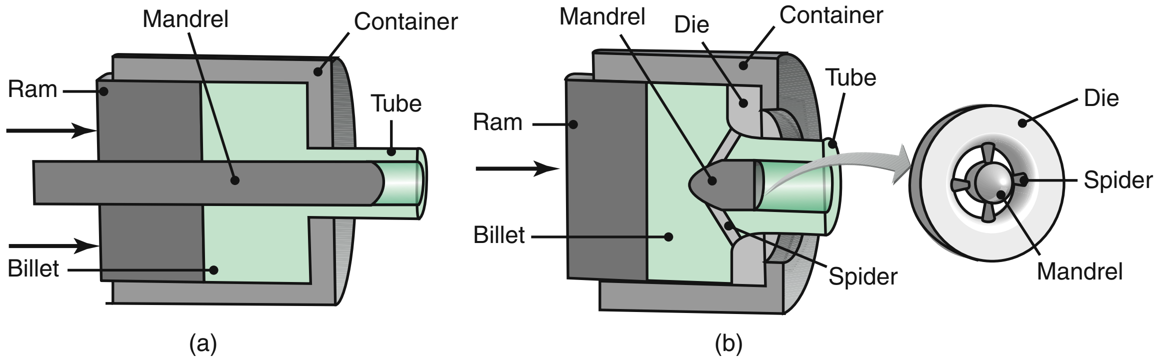


FIGURE 15.8 Extrusion of a seamless tube (a) using an internal mandrel that moves independently of the ram. (An alternative arrangement has the mandrel integral with the ram.) (b) using a spider die (see Fig. 15.9) to produce seamless tubing.

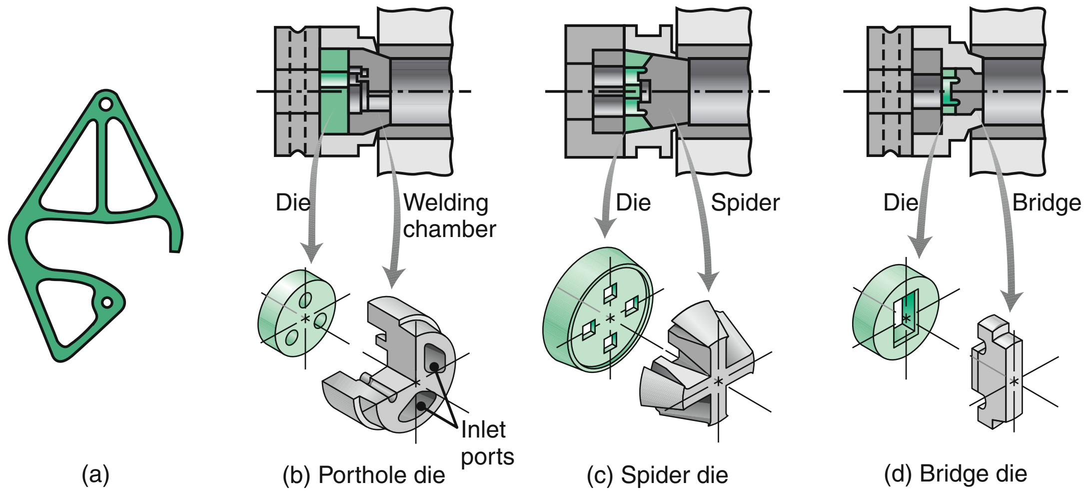


FIGURE 15.9 (a) An extruded 6063-T6 aluminum-ladder lock for aluminum extension ladders. This part is 8 mm (5/16 in.) thick and is sawed from the extrusion (see Fig. 15.2). (b) through (d) Components of various dies for extruding intricate hollow shapes. *Source*: (b) through (d) after K. Laue and H. Stenger.

Hollow cross sections (Fig. 15.9a) can be extruded by welding-chamber methods and using various dies known as a **porthole die, spider die**, and **bridge die** (Fig. 15.9b to d). During extrusion, the metal divides and flows around the supports for the internal mandrel into strands. (This condition is much like that of air flowing around a moving car and rejoining downstream or water flowing around large rocks in a river and rejoining.) The strands then become rewelded under the high pressure in the welding chamber before they exit through the die. The rewelded surfaces have good strength because they have not been exposed to the environment;

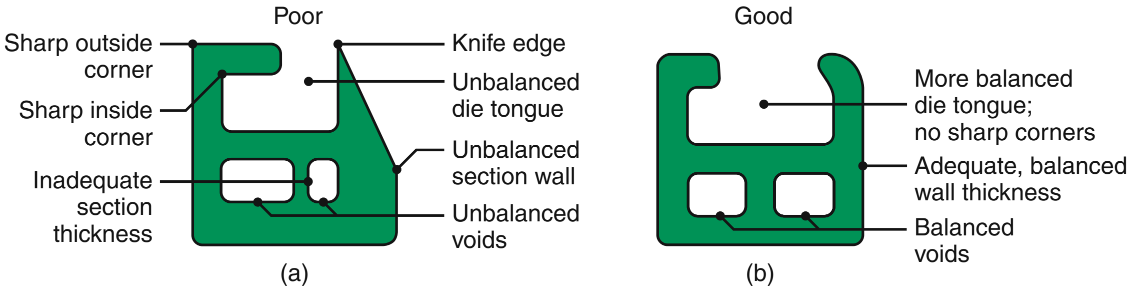


FIGURE 15.10 Poor and good examples of cross sections to be extruded. Note the importance of eliminating sharp corners and of keeping section thicknesses uniform. *Source*: J.G. Bralla (ed.), *Handbook of Product Design for Manufacturing*. McGraw-Hill Publishing Company, 1986. Used with permission.

otherwise they would develop oxides on the surfaces, thereby inhibiting good welding. However, the welding-chamber process is suitable only for aluminum and some of its alloys, because of their capacity for developing a strong weld under pressure (as is described in Section 31.2). Lubricants, of course, cannot be used, because they prevent rewelding of the metal in the die.

Some guidelines for proper die design in extrusion are illustrated in Fig. 15.10. Note the (a) importance of symmetry of cross section, (b) avoidance of sharp corners, and (c) avoidance of extreme changes in die dimensions within the cross section.

Die Materials. Die materials for hot extrusion usually are hot-worked die steels (Section 5.7). Coatings (such as partially stabilized zirconia) may be applied to the dies to extend their life. Partially stabilized zirconia dies (Section 8.2.2) also are used for hot extrusion of tubes and rods. However, they are not suitable for making dies for extruding complex shapes, because of the severe stress gradients developed in the die, which may lead to their premature failure.

Lubrication. Lubrication is important in hot extrusion because of its effects on (a) material flow during extrusion, (b) surface finish and integrity, (c) product quality, and (d) extrusion forces. *Glass* (Section 8.4) is an excellent lubricant for steels, stainless steels, and high-temperature metals and alloys. In a process developed in the 1940s and known as the **Séjournet process** (after J. Séjournet), a circular glass or fiberglass pad is placed in the chamber at the die entrance. The hot billet conducts heat to the pad, whereupon a thin layer of glass begins to melt and acts as a lubricant at the die interface as the extrusion progresses. Before the billet is placed in the chamber, its cylindrical surface is coated with a layer of powdered glass to develop a thin glass lubricant layer at the billet–chamber interface.

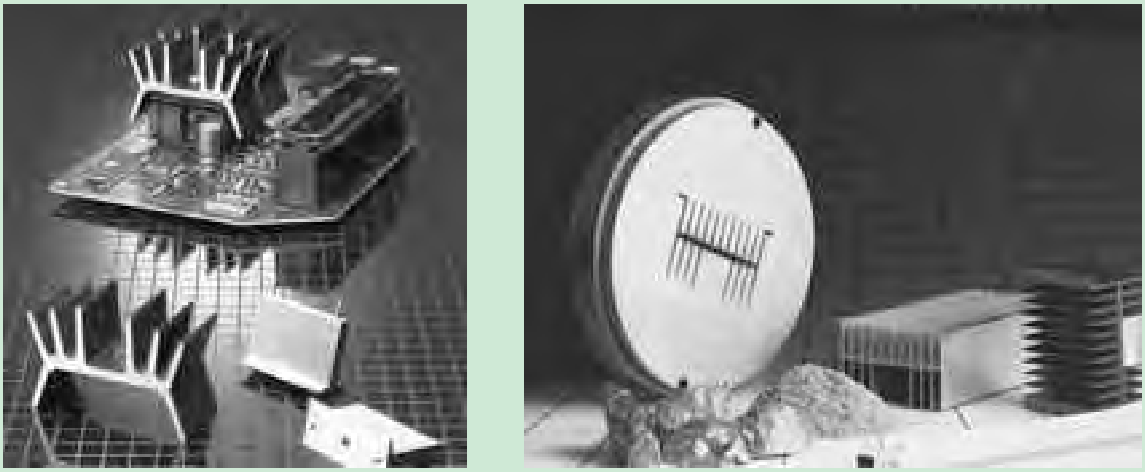
For metals that have a tendency to stick to the container and the die, the billet can be enclosed in a thin-walled container, or jacket, made of a softer and lower strength metal, such as copper or mild steel. This procedure is called **jacketing** or **canning**. In addition to acting as a low-friction interface, the jacket prevents contamination of the billet by the environment. Also, if the billet material is toxic or radioactive, the jacket prevents it from contaminating the environment. This technique also can be used for extruding reactive metal powders (Chapter 17).

EXAMPLE 15.2 Manufacture of Aluminum Heat Sinks

Aluminum is used widely to transfer heat for both cooling and heating applications because of its very high thermal conductivity. In fact, on a weight-to-cost basis, no other material conducts heat as economically as does aluminum.

Hot extrusion of aluminum is preferred for heat-sink applications, such as those in the electronics industry. Figure 15.11a shows an extruded heat sink used to remove heat from a transformer on a printed circuit board. Heat sinks usually are designed with a large number of fins that are intended to maximize the surface area and are evaluated from a thermodynamics standpoint using computer simulations. The fins are very difficult and expensive to machine, forge, or roll form. However, the tooling for hot extrusion can be produced through electrical-discharge machining (Section 27.5), so the process is favorable economically.

Figure 15.11b shows a die and a hot-extruded cross section suitable to serve as a heat sink. The shapes shown could be produced through a casting operation, but extrusion is preferred, since there is no internal porosity and the thermal conductivity is slightly higher.



(a) (b)

FIGURE 15.11 (a) Aluminum extrusion used as a heat sink for a printed circuit board, (b) Extrusion die and extruded heat sinks. *Source*: Courtesy of Aluminum Extruders Council.

15.4 Cold Extrusion

Developed in the 1940s, *cold extrusion* is a general term that often denotes a *combination* of operations, such as direct and indirect *extrusion and forging* (Fig. 15.12). Cold extrusion is used widely for components in automobiles, motorcycles, bicycles, and appliances and in transportation and farm equipment.

The cold-extrusion process uses slugs cut from cold-finished or hot-rolled bars, wire, or plates. Slugs that are less than about 40 mm (1.5 in.) in diameter are sheared (*cropped*), and if necessary, their ends are squared off by processes such as upsetting, machining, or grinding. Larger diameter slugs are machined from bars into specific lengths. Cold-extruded parts weighing as much as 45 kg (100 lb) and having lengths of up to 2 m (80 in.) can be made, although most parts weigh much less. Powder-metal slugs (preforms) also may be cold extruded.

The *force, F*, in cold extrusion may be estimated from the formula

$$F = 1.7A_o Y_{avg}\varepsilon, \tag{15.2}$$

where A_o is the cross-sectional area of the blank, Y_{avg} is the average flow stress of the metal, and ε is the true strain that the piece undergoes based on its original and final cross-sectional area; i.e., $\ln(A_o/A_f)$. For example, assume that a round slug 10 mm in diameter and made of a metal with $Y_{avg} = 50{,}000$ psi is reduced to a final diameter of 7 mm by cold extrusion. Then the force would be

$$F = 1.7(\pi)(10^2/4)(50{,}000)[\ln(10/7)^2] = 4.8 \times 10^6 \text{ lb} = 2140 \text{ tons}.$$

Cold extrusion has the following advantages over hot extrusion:

- Improved mechanical properties resulting from work hardening, provided that the heat generated by plastic deformation and friction does not recrystallize the extruded metal
- Good control of dimensional tolerances, reducing the need for subsequent machining or finishing operations
- Improved surface finish, due partly to the absence of an oxide film and provided that lubrication is effective
- Production rates and costs that are competitive with those of other methods of producing the same part, such as machining. Some machines are capable of producing more than 2000 parts per hour.

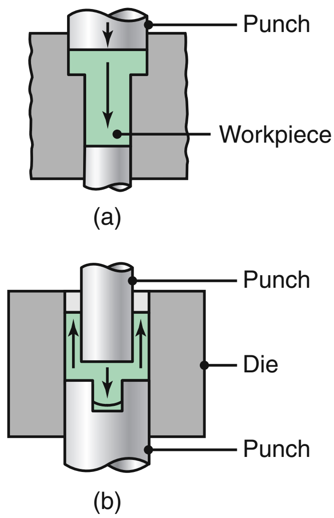


FIGURE 15.12 Two examples of cold extrusion. Thin arrows indicate the direction of metal flow during extrusion.

The magnitude of the stresses on the tooling in cold extrusion, however, is very high (especially with steel and specialty-alloy workpieces), being on the order of the hardness of the workpiece material. The punch hardness usually ranges between 60 and 65 HRC and the die hardness between 58 and 62 HRC. Punches are a critical component, as they must possess not only sufficient strength, but also sufficient toughness and resistance to wear and fatigue failure.

Lubrication is critical, especially with steels, because of the possibility of sticking (*seizure*) between the workpiece and the tooling (in the case of lubricant breakdown). The most effective means of lubrication is the application of a *phosphate-conversion coating* on the workpiece, followed by a coating of soap or wax, as described in Section 34.10.

Tooling design and the selection of appropriate tool and die materials are crucial to the success of cold extrusion. Also important are the selection and control of the workpiece material with regard to its quality, the accuracy of the slug dimensions, and its surface condition. Several specialty alloys have been developed (particularly for critical applications requiring high performance) that are suitable for a variety of cold-extrusion and cold-forming operations with good properties, dimensional tolerances, and at low cost.

EXAMPLE 15.3 Cold-extruded Part

A typical cold-extruded product, similar to the metal component of an automotive spark plug, is shown in Fig. 15.13. First, a slug is sheared off the end of a round rod (Fig. 15.13, left). It then is cold extruded (Fig. 15.13, middle) in an operation similar to those shown in Fig. 15.12 but with a blind hole. Then the material at the bottom of the blind hole is punched out, producing the small slug shown. Note the respective diameters of the slug and the hole at the bottom of the sectioned part.

Investigating material flow during the deformation of the slug helps avoid defects and leads to improvements in punch and die design. Furthermore, the part usually is sectioned in the midplane and then polished and etched to display the grain flow, as shown in Fig. 15.14 (see also Fig. 14.11).

FIGURE 15.13 Production steps for a cold-extruded spark plug. *Source*: Courtesy of National Machinery Company.

FIGURE 15.14 A cross section of the metal part in Fig. 15.13, showing the grain-flow pattern. *Source*: Courtesy of National Machinery Company.

15.4.1 Impact Extrusion

Impact extrusion is similar to indirect extrusion, and the process often is included in the cold-extrusion category. The punch descends rapidly on the blank (slug), which is extruded backwards (Fig. 15.15). Because of volume constancy, the thickness of the tubular extruded section is a function of the clearance between the punch and the die cavity.

Typical products made by this process are shown in Fig. 15.16a to c. Other examples of products made by impact extrusion are collapsible tubes (similar to those used for toothpaste), light fixtures, automotive parts, and small pressure vessels. Most nonferrous metals can be impact extruded in vertical presses and at production rates as high as two parts per second.

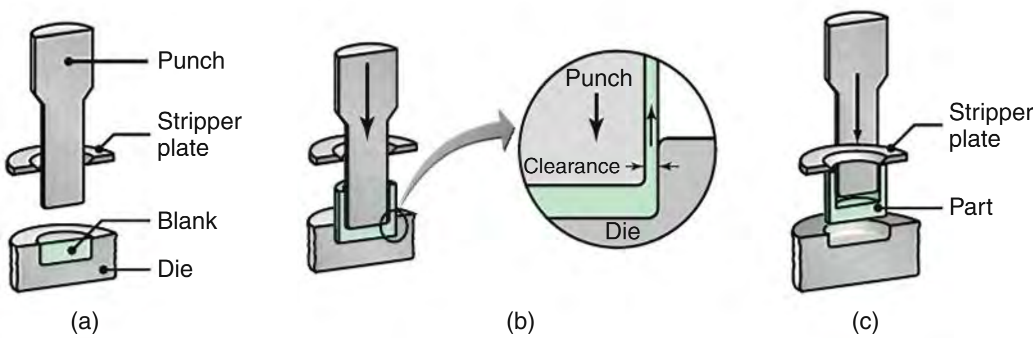


FIGURE 15.15 Schematic illustration of the impact-extrusion process. The extruded parts are stripped by the use of a stripper plate, because they tend to stick to the punch.

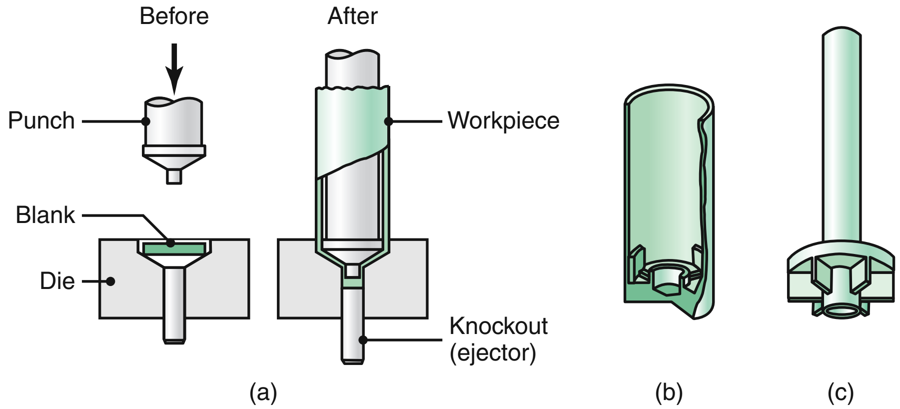


FIGURE 15.16 (a) Impact extrusion of a collapsible tube by the *Hooker process*. (b) and (c) Two examples of products made by impact extrusion. These parts also may be made by casting, forging, or machining. The choice of process depends on the materials involved, part dimensions and wall thickness, and the properties desired. Economic considerations also are important in final process selection.

The maximum diameter of the parts made is about 150 mm (6 in.). The impact-extrusion process can produce thin-walled tubular sections having thickness-to-diameter ratios as small as 0.005. Consequently, the symmetry of the part and the concentricity of the punch and the blank are important.

15.4.2 Hydrostatic Extrusion

In *hydrostatic extrusion*, the pressure required in the chamber is supplied via a piston through an incompressible fluid medium surrounding the billet (Fig. 15.3b). Pressures are typically on the order of 1400 MPa (200 ksi). The high pressure in the chamber transmits some of the fluid to the die surfaces, where it significantly reduces friction. Hydrostatic extrusion usually is carried out at room temperature, typically using vegetable oils as the fluid (particularly castor oil, because it is a good lubricant and its viscosity is not influenced significantly by pressure).

Brittle materials can be extruded successfully by this method, because the hydrostatic pressure (along with low friction and the use of small die angles and high extrusion ratios) increases the ductility of the material. Long wires also have been extruded from an aluminum billet at room temperature and at an extrusion ratio of 14,000, which means that a 1-m billet becomes a 14-km-long wire. In spite of the success obtained, hydrostatic extrusion has had limited industrial applications, mainly because of the somewhat complex nature of the tooling, the experience needed with high pressures and the design of specialized equipment, and the long cycle times required—all of which make the process uneconomical for most materials and applications.

15.5 Extrusion Defects

Depending on workpiece material condition and process variables, extruded products can develop several types of defects that can affect significantly their strength and product quality. Some defects are visible to the naked eye, while others can be detected only by the techniques described in Section 36.10. There are three principal *extrusion defects:* surface cracking, pipe, and internal cracking.

Surface Cracking. If extrusion temperature, friction, or speed is too high, surface temperatures can rise significantly, which may cause surface cracking and tearing (*fir-tree cracking* or *speed cracking*). These cracks are intergranular (i.e., along the grain boundaries; see Fig. 2.27) and usually are caused by **hot shortness** (Section 1.5.2). These defects occur especially in aluminum, magnesium, and zinc alloys, although they may also occur in high-temperature alloys. This situation can be avoided by lowering the billet temperature and the extrusion speed.

Surface cracking also may occur at lower temperatures, where it has been attributed to periodic sticking of the extruded product along the die land. Because of the similarity in appearance to the surface of a bamboo stem, it is known as a **bamboo defect**. When the product being extruded temporarily sticks to the *die land* (see Fig. 15.7), the extrusion pressure increases rapidly. Shortly thereafter, the product moves forward again, and the pressure is released. The cycle is repeated continually, producing periodic circumferential cracks on the surface.

Pipe. The type of metal-flow pattern in extrusion shown in Fig. 15.6c tends to draw surface oxides and impurities toward the center of the billet—much like a funnel. This defect is known as *pipe defect*, *tailpipe*, or *fishtailing*. As much as one-third of the length of the extruded product may contain this type of defect and thus has to be cut off as scrap. Piping can be minimized by modifying the flow pattern to be more uniform, such as by controlling friction and minimizing temperature gradients. Another method is to machine the billet's surface prior to extrusion, so that scale and surface impurities are removed. These impurities also can be removed by the chemical etching of the surface oxides prior to extrusion.

Internal Cracking. The center of the extruded product can develop cracks, called *center cracking, center-burst, arrowhead fracture,* or *chevron cracking* (Fig. 15.17a). These cracks are attributed to a state of hydrostatic tensile stress at the centerline in the deformation zone in the die (Fig. 15.17b), a situation similar to the necked region in a tensile-test specimen (see Fig. 2.23). These cracks also have been observed in tube extrusion and in tube spinning (see Fig. 16.46b and c); they appear on the inside

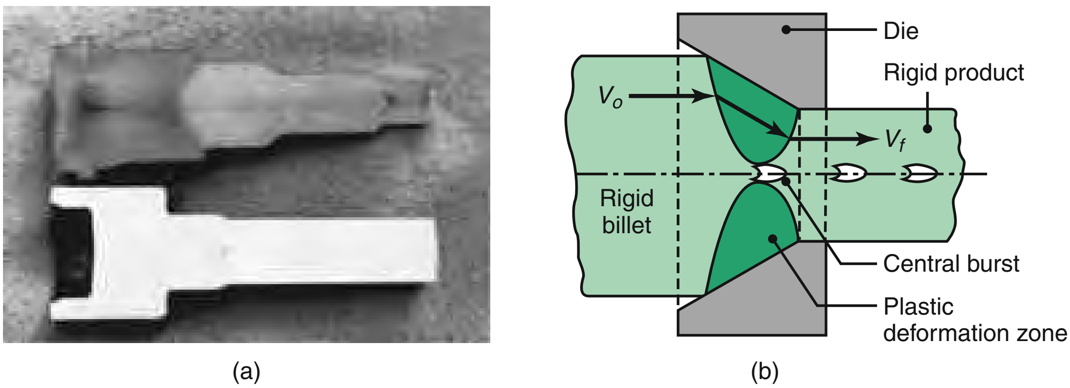


FIGURE 15.17 (a) Chevron cracking (central burst) in extruded round steel bars. Unless the products are inspected, such internal defects may remain undetected and later cause failure of the part in service. This defect can also develop in the drawing of rod, of wire, and of tubes. (b) Schematic illustration of rigid and plastic zones in extrusion. The tendency toward chevron cracking increases if the two plastic zones do not meet. Note that the plastic zone can be made larger either by decreasing the die angle, by increasing the reduction in cross section, or both. *Source*: After B. Avitzur.

surfaces of tubes. The tendency for center cracking (a) increases with increasing die angle, (b) increases with increasing amount of impurities, and (c) decreases with increasing extrusion ratio and friction.

15.6 Extrusion Equipment

The basic equipment for extrusion is a *horizontal hydraulic press* (Fig. 15.18; see also Fig. 14.17d). These presses are suitable for extrusion because the stroke and speed of the operation can be controlled, depending on the particular application. They are capable of applying a constant force over a long stroke. Consequently, long billets can be used, correspondingly larger extrusions produced per setup, and the production rate thus increased. Hydraulic presses with a ram-force capacity as high as 120 MN (14,000 tons) have been built, particularly for hot extrusion of large-diameter billets.

Vertical hydraulic presses typically are used for cold extrusion. They generally have less capacity than those used for hot extrusion, but they take up less floor space. In addition to such presses, *crank-joint* and *knuckle-joint* mechanical presses are used for cold extrusion and for impact extrusion to mass-produce small components. Multistage operations, where the cross-sectional area is reduced in a number of individual operations, are carried out on specially designed presses.

FIGURE 15.18 General view of a 9-MN (1000-ton) hydraulic-extrusion press. *Source*: Courtesy of Jones & Laughlin Steel Corporation.

15.7 The Drawing Process

In *drawing*, the cross section of a long rod or wire is reduced or changed by pulling (hence the term drawing) it through a die called a *draw die* (Fig. 15.19). Thus, the difference between drawing and extrusion is that in extrusion the material is pushed through a die, whereas in drawing it is pulled through it. Rod and wire products cover a very wide range of applications, including shafts for power transmission, machine and structural components, blanks for bolts and rivets, electrical wiring, cables, tension-loaded structural members, welding electrodes, springs, paper clips, spokes for bicycle wheels, and stringed musical instruments.

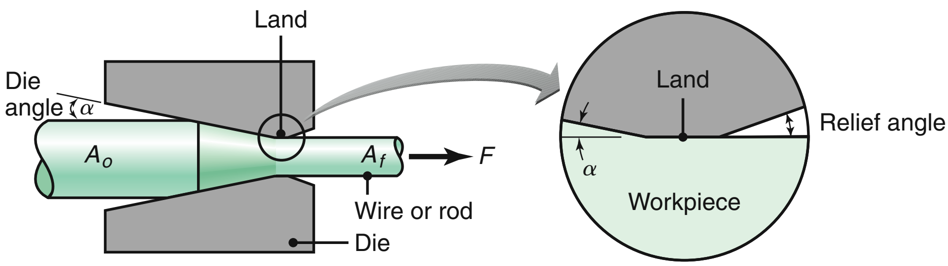


FIGURE 15.19 Process variables in wire drawing. The die angle, the reduction in cross-sectional area per pass, the speed of drawing, the temperature, and the lubrication all affect the drawing force, F.

The major processing variables in drawing are similar to those in extrusion—that is, reduction in cross-sectional area, die angle, friction along the die–workpiece interface, and drawing speed. The die angle influences the drawing force and the quality of the drawn product.

Drawing Force. The expression for the *drawing force, F*, under *ideal and frictionless* conditions is similar to that for extrusion and is given by the equation

$$F = Y_{avg} A_f \ln\left(\frac{A_o}{A_f}\right), \tag{15.3}$$

where Y_{avg} is the average true stress of the material in the die gap. Because more work has to be done to overcome friction, the force increases with increasing friction. Furthermore, because of the nonuniform deformation that occurs within the die zone, additional energy (known as the *redundant work of deformation*) is required. Although various equations have been developed to estimate the force (described in greater detail in advanced texts), a useful formula that includes friction and the redundant work is

$$F = Y_{avg} A_f \left[\left(1 + \frac{\mu}{\alpha}\right)\ln\left(\frac{A_o}{A_f}\right) + \frac{2}{3}\alpha\right], \tag{15.4}$$

where α is the die angle in radians.

As can be seen from these equations, the drawing force increases as reduction increases. However, there has to be a limit to the magnitude of the force, because when the tensile stress reaches the yield stress of the metal being drawn, the workpiece will simply yield and, eventually, break. It can be shown that, ideally and without friction, the maximum reduction in cross-sectional area per pass is 63%. Thus, a 10-mm-diameter rod can be reduced (at most) to a diameter of 6.1 mm in one pass without failure.

It can be shown that, for a certain reduction in diameter and a certain frictional condition, there is an *optimum die angle* at which the drawing force is a minimum. Often, however, the die force is not the major product quality concern, and the actual die angle may deviate from this value.

Drawing of Other Shapes. Various solid cross sections can be produced by drawing through dies with different profiles. Proper die design and the proper selection of

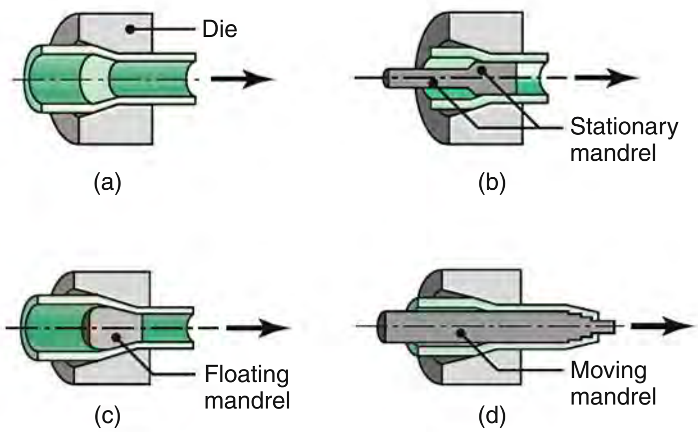


FIGURE 15.20 Examples of tube-drawing operations, with and without an internal mandrel. Note that a variety of diameters and wall thicknesses can be produced from the same initial tube stock (which has been made by other processes).

reduction sequence per pass require considerable experience to ensure proper material flow in the die, reduce internal or external defects, and improve surface quality.

The wall thickness, diameter, or shape of tubes that have been produced by extrusion or by other processes described in this book can be reduced further by *tube-drawing* processes (Fig. 15.20). Tubes as large as 0.3 m (12 in.) in diameter can be drawn by these techniques. Mandrels of various profiles are available for tube-drawing operations.

Wedge-shaped dies are used for the drawing of flat strips and are used only in specific applications. However, the principle behind this process is the fundamental deformation mechanism in **ironing**, used extensively in making aluminum beverage cans, as shown in Fig. 16.30.

15.8 Drawing Practice

As in all metalworking processes, successful drawing requires careful selection of process parameters. In drawing, reductions in the cross-sectional area per pass range up to about 45%. Usually, the smaller the initial cross section, the smaller the reduction per pass. Fine wires usually are drawn at 15 to 25% reduction per pass and larger sizes at 20 to 45%. Reductions of higher than 45% may result in lubricant breakdown, leading to surface-finish deterioration. Although most drawing is done at room temperature, drawing large solid or hollow sections can be done at elevated temperatures in order to reduce forces.

A light reduction (**sizing pass**) also may be taken on rods to improve their surface finish and dimensional accuracy. However, because they basically deform only the surface layers, light reductions usually produce highly nonuniform deformation of the material and its microstructure. Consequently, the properties of the material will vary with location within the cross section.

Note in Fig. 15.19 that a rod or wire has to have its tip reduced in cross section in order to be fed through the die opening and be pulled. This typically is done by *swaging* the tip of the rod or wire in a manner similar to that shown in Fig. 14.15a and b; this operation is called *pointing*. Drawing speeds depend on the material and on the reduction in cross-sectional area. They may range from 1 to 2.5 m/s (200 to 500 ft/min) for heavy sections to as much as 50 m/s (165 ft/s) for very fine wire, such as that used for electromagnets. Because the product does not have sufficient time to dissipate the heat generated, temperatures can rise substantially at high drawing speeds and can have detrimental effects on product quality.

Drawn copper and brass wires are designated by their *temper* (such as 1/4 hard, 1/2 hard, etc.) because of work hardening. Intermediate annealing between passes may be necessary to maintain sufficient ductility of the material during cold drawing. High-carbon steel wires for springs and for musical instruments are made by heat treating (**patenting**) the drawn wire; the microstructure obtained is fine pearlite (see Fig. 4.11). These wires have ultimate tensile strengths as high as 5 GPa (700 ksi) and a tensile reduction of area of about 20%.

Bundle Drawing. Although very fine wire can be produced by drawing, the cost can be high. One method employed to increase productivity is to draw many wires (a hundred or more) simultaneously as a *bundle*. The wires are separated from one another by a suitable metallic material with similar properties, but lower chemical resistance (so that it subsequently can be leached out from the drawn-wire surfaces).

Bundle drawing produces wires that are somewhat polygonal, rather than round, in cross section. In addition to producing continuous lengths, techniques have

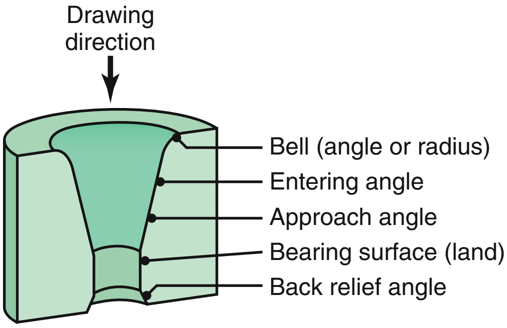


FIGURE 15.21 Terminology pertaining to a typical die used for drawing a round rod or wire.

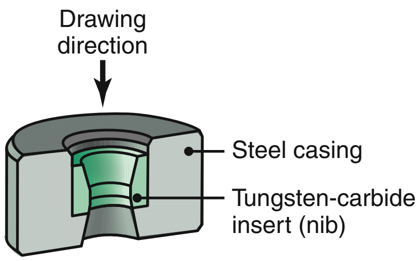


FIGURE 15.22 Tungsten-carbide die insert in a steel casing. Diamond dies used in drawing thin wire are encased in a similar manner.

been developed to produce fine wire that is broken or chopped into various sizes and shapes. These wires are then used in applications such as electrically conductive plastics, heat-resistant and electrically conductive textiles, filter media, radar camouflage, and medical implants. The wires produced can be as small as 4 μm (0.00016 in.) in diameter and can be made from such materials as stainless steels, titanium, and high-temperature alloys.

Die Design. The characteristic features of a typical die for drawing are shown in Fig. 15.21. Die angles usually range from 6° to 15°. Note, however, that there are two angles (entering and approach) in a typical die. The purpose of the bearing surface (*land*) is to set the final diameter of the product (*sizing*) and to maintain this diameter even with wear on the die–workpiece interface.

A set of dies is required for **profile drawing**, which involves various stages of deformation to produce the final profile. The dies may be made in one piece or (depending on the complexity of the cross-sectional profile) with several segments held together in a retaining ring. Computer-aided design techniques are being implemented to design dies for smooth material flow, as well as to minimize defects. A set of idling cylindrical or shaped rolls also may be used in drawing rods or bars of various shapes. Such an arrangement (called a *Turk's head*) is more versatile than that in ordinary draw dies, because the rolls can be adjusted to different positions and angles for specific profiles.

Die Materials. Die materials for drawing (Table 5.8) typically are tool steels and carbides. For hot drawing, cast-steel dies are used because of their high resistance to wear at elevated temperatures. Diamond dies are used for drawing fine wire with diameters ranging from 2 μm to 1.5 mm (0.0001 to 0.06 in.). They may be made from a single-crystal diamond or in polycrystalline form with diamond particles in a metal matrix (*compacts*). Because of their very low tensile strength and toughness, carbide and diamond dies typically are used as **inserts** or **nibs**, which are supported in a steel casing (Fig. 15.22).

Lubrication. Proper lubrication is essential in drawing in order to improve die life and product surface finish and to reduce drawing forces and temperature. Lubrication is critical, particularly in tube drawing, because of the difficulty of maintaining a sufficiently thick lubricant film at the mandrel–tube interface. In the drawing of rods, a common method of lubrication uses phosphate coatings.

The following are the basic methods of lubrication used in wire drawing (see also Section 33.7):

- **Wet drawing**, in which the dies and the rod are immersed completely in the lubricant
- **Dry drawing**, in which the surface of the rod to be drawn is coated with a lubricant by passing it through a box filled with the lubricant (*stuffing box*)
- **Metal coating**, in which the rod or wire is coated with a soft metal, such as copper or tin, that acts as a solid lubricant
- **Ultrasonic vibration** of the dies and mandrels; in this process, vibrations reduce forces, improve surface finish and die life, and allow larger reductions per pass without failure.

15.9 Drawing Defects and Residual Stresses

Typical defects in a drawn rod or wire are similar to those observed in extrusion—especially *center cracking* (see Fig. 15.17). Another major type of defect in drawing is **seams**, which are longitudinal scratches or folds in the material. Seams may open up during subsequent forming operations (such as upsetting, heading, thread rolling, or bending of the rod or wire), and they can cause serious quality-control problems. Various other surface defects (such as scratches and die marks) also can result from improper selection of the process parameters, poor lubrication, or poor die condition.

Because they undergo nonuniform deformation during drawing, cold-drawn products usually have *residual stresses*. For light reductions, such as only a few percent, the longitudinal-surface residual stresses are compressive (while the bulk is in tension) and fatigue life is thus improved. Conversely, heavier reductions induce tensile surface stresses (while the bulk is in compression). Residual stresses can be significant in causing stress-corrosion cracking of the part over time. Moreover, they cause the component to *warp* if a layer of material subsequently is removed (see Fig. 2.30), such as by slitting, machining, or grinding.

Rods and tubes that are not sufficiently straight (or are supplied as coil) can be straightened by passing them through an arrangement of rolls placed at different axes—a process similar to roller leveling (see Fig. 13.7b).

15.10 Drawing Equipment

Although it is available in several designs, the equipment for drawing is basically of two types: the draw bench and the bull block.

A **draw bench** contains a single die, and its design is similar to that of a long, horizontal tension-testing machine (Fig. 15.23). The pulling force is supplied by a chain drive or is activated hydraulically. Draw benches are used for a single-length drawing of straight rods and tubes with diameters larger than 20 mm (0.75 in.) and lengths up to 30 m (100 ft.). Machine capacities reach 1.3 MN (300 klb) of pulling force with a speed range of 6 to 60 m/min (20 to 200 ft/min).

Very long rods and wire (many kilometers) and wire of smaller cross sections, usually less than 13 mm (0.5 in.), are drawn by a rotating **drum** (**bull block** or **capstan**, Fig. 15.24). The tension in this setup provides the force required for drawing the wire, usually through multiple dies (*tandem drawing*).

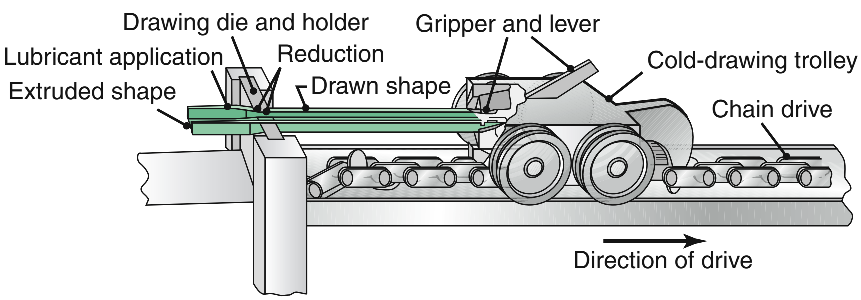


FIGURE 15.23 Cold drawing of an extruded channel on a draw bench to reduce its cross section. Individual lengths of straight rods or of cross sections are drawn by this method.

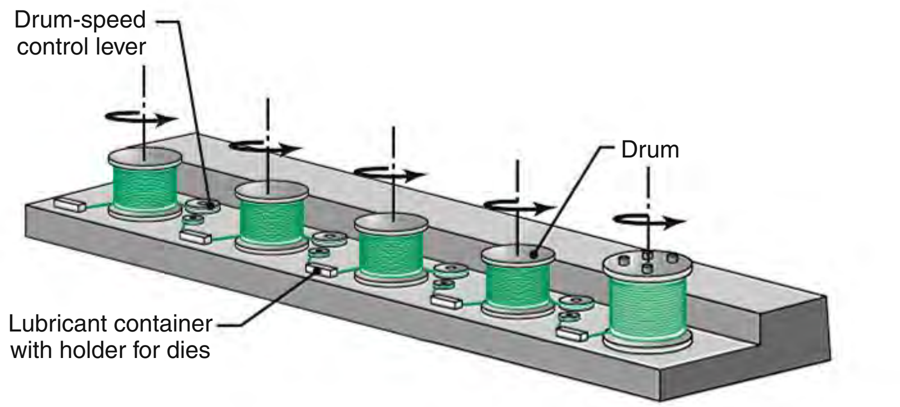


FIGURE 15.24 An illustration of multistage wire drawing typically used to produce copper wire for electrical wiring. *Source*: After H. Auerswald.

SUMMARY

- Extrusion is the process of pushing a billet through a die to reduce its cross section or to produce various solid or hollow cross sections. This process generally is carried out at elevated temperatures in order to reduce the extrusion force and improve the ductility of the material.
- Important factors in extrusion are die design, extrusion ratio, billet temperature, lubrication, and extrusion speed. Although the term "cold extrusion" applies to extrusion at room temperature, it is also the name for a combination of extrusion and forging operations. Cold extrusion is capable of economically producing discrete parts in various shapes with good mechanical properties and dimensional tolerances.
- Rod, wire, and tube drawing basically involve the process of pulling the material through a die or a set of dies in tandem. The cross sections of most drawn products are round, but other shapes also can be drawn. Drawing tubular products to reduce either their diameter or their thickness usually requires internal mandrels.
- Die design, reduction in cross-sectional area per pass, and selection of die materials and lubricants are all important parameters in making drawn products of high quality with a good surface finish. External as well as internal defects (chevron cracking) can develop both in extrusion and in drawing. Their minimization or avoidance depends principally on the die angle, the reduction per pass, and the quality of the workpiece material.

KEY TERMS

Bamboo defect
Bridge die
Bull block
Bundle drawing
Canning
Capstan
Center cracking
Chevron cracking
Cold extrusion
Conversion coating
Dead-metal zone
Draw bench
Drawing
Extrusion
Extrusion constant
Extrusion defects
Extrusion ratio
Fir-tree cracking
Hydrostatic extrusion
Impact extrusion
Ironing
Jacketing
Patenting
Pipe defect
Porthole die
Rod
Seam
Séjournet process
Shear die
Sizing pass
Speed cracking
Spider die
Turk's head
Wire