18 Bulk Deformation Processes in Metalworking

Chapter Contents

The deformation processes described in this chapter accomplish significant shape change in metal parts whose initial form is bulk rather than sheet. The starting forms include cylindrical bars and billets, rectangular billets and slabs, and similar elementary geometries. The bulk deformation processes refine the starting shapes, sometimes improving mechanical properties, and always adding commercial value. Deformation processes work by stressing the metal sufficiently to cause it to plastically flow into the desired shape.

Bulk deformation processes are performed as cold, warm, and hot working operations. Cold and warm working are appropriate when the shape change is less severe, and there is a need to improve mechanical properties and achieve good finish on the part. Hot working is generally required when massive deformation of large work parts is involved.

The commercial and technological importance of bulk deformation processes derives from the following:

- When performed as hot working operations, they can achieve significant change in the shape of the work part.
- When performed as cold working operations, they can be used not only to shape the product, but also to increase its strength through strain hardening.
- These processes produce little or no waste as a by-product of the operation. Some bulk deformation operations are ***near net shape*** or ***net shape*** processes; they achieve final product geometry with little or no subsequent machining.

The bulk deformation processes covered in this chapter are (1) rolling, (2) forging, (3) extrusion, and (4) wire and bar drawing. The chapter also documents the variations and related operations of the four basic processes that have been developed over the years.

18.1 Rolling

Rolling is a deformation process in which the thickness of the work is reduced by compressive forces exerted by two opposing rolls. The rolls rotate as illustrated in Figure 18.1 to pull and simultaneously squeeze the work between them. The basic process shown in the figure is flat rolling, used to reduce the thickness of a rectangular cross section. A closely related process is shape rolling, in which a square cross section is formed into a shape such as an I-beam.

Most rolling processes are very capital intensive, requiring massive pieces of equipment, called rolling mills, to perform them. The high investment cost requires the mills to be used for production in large quantities of standard items such as sheets and plates. Most rolling is carried out by hot working, called ***hot rolling***, owing to the large amount of deformation required. Hot-rolled metal is generally free of residual stresses, and its properties are isotropic. Disadvantages of hot rolling are that the product cannot be held to close tolerances, and the surface has a characteristic oxide scale.

Steelmaking provides the most common application of rolling mill operations (Historical Note 18.1). The sequence of steps in a steel rolling mill illustrates the variety of products made. Similar steps occur in other basic metal industries. The work starts out as a cast steel ingot that has just solidified. While it is still hot, the ingot is placed in a furnace where it remains for many hours until it has reached a uniform temperature throughout, so that the metal will flow consistently during rolling. For steel, the desired temperature for rolling is around 1200°C (2200°F). The heating operation is called ***soaking***, and the furnaces in which it is carried out are called ***soaking pits***.

From soaking, the ingot is moved to the rolling mill, where it is rolled into one of three intermediate shapes called blooms, billets, or slabs. A ***bloom*** has a square cross section 150 mm × 150 mm (6 in × 6 in) or larger. A ***slab*** is rolled from an ingot or a bloom and has a rectangular cross section of width 250 mm (10 in) or more and thickness 40 mm (1.5 in) or more. A ***billet*** is rolled from a bloom and is square with dimensions 40 mm (1.5 in) on a side or larger. These intermediate shapes are subsequently rolled into final product shapes.

Blooms are rolled into structural shapes and rails for railroad tracks. Billets are rolled into bars and rods. These shapes are the raw materials for machining, wire drawing, forging, and other metalworking processes. Slabs are rolled into plates, sheets, and strips. Hot-rolled plates are used in shipbuilding, bridges, boilers, welded structures for various heavy machines, tubes and pipes, and many other products.

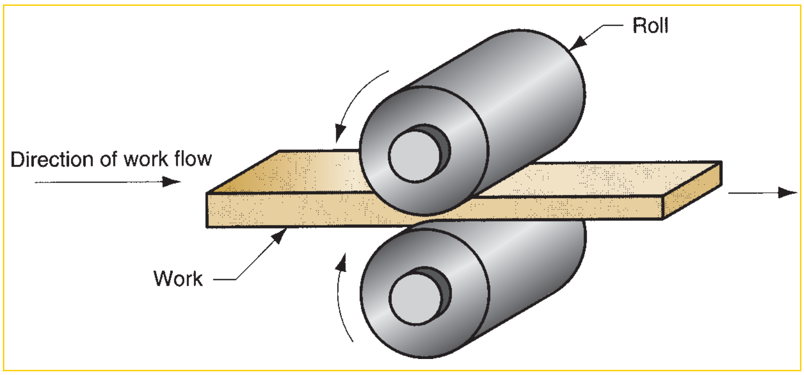


FIGURE 18.1 The rolling process (specifically, flat rolling).

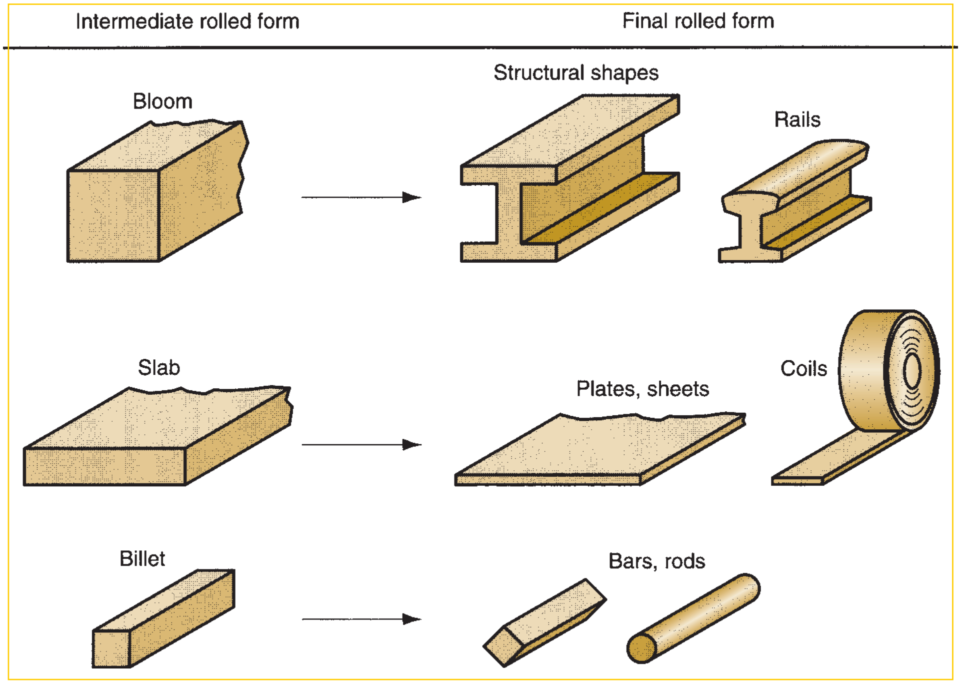


FIGURE 18.2 Some of the steel products made in a rolling mill.

Figure 18.2 shows some of these rolled steel products. Further flattening of hot-rolled plates and sheets is often accomplished by ***cold rolling***, in order to prepare them for subsequent sheet metal operations (Chapter 19). Cold rolling strengthens the metal and permits a tighter tolerance on thickness. In addition, the surface of the cold-rolled sheet is absent of scale and generally superior to the corresponding hot-rolled product. These characteristics make cold-rolled sheets, strips, and coils ideal for stampings, exterior panels, and other parts of products ranging from automobiles to appliances and office furniture.

Historical Note 18.1 *Rolling*

Rolling of gold and silver by manual methods dates from the fourteenth century. Leonardo da Vinci designed one of the first rolling mills in 1480, but it is doubtful that his design was ever built. By around 1600, cold rolling of lead and tin was accomplished on manually operated rolling mills. By around 1700, hot rolling of iron was being done in Belgium, England, France, Germany, and Sweden. These mills were used to roll iron bars into sheets. Prior to this time, the only rolls in steelmaking were slitting mills—pairs of opposing rolls with collars (cutting disks) used to slit iron and steel into narrow strips for making nails and similar products. Slitting mills were not intended to reduce thickness.

Modern rolling practice dates from 1783 when a patent was issued in England for using grooved rolls to produce iron bars. The Industrial Revolution created a tremendous demand for iron and steel, stimulating developments in rolling. The first mill for rolling railway rails was started in 1820 in England. The first I-beams were rolled in France in 1849. In addition, the size and capacity of flat rolling mills increased dramatically during this period.

Rolling is a process that requires a very large power source. Water wheels were used to power rolling mills until the eighteenth century. Steam engines increased the capacity of these rolling mills until soon after 1900 when electric motors replaced steam.

18.1.1 FLAT ROLLING AND ITS ANALYSIS

Flat rolling is illustrated in Figures 18.1 and 18.3. It involves the rolling of slabs, strips, sheets, and plates—work parts of rectangular cross section in which the width is greater than the thickness. In flat rolling, the work is squeezed between two rolls so that its thickness is reduced by an amount called the ***draft***:

$$d = t_o - t_f \tag{18.1}$$

where $d =$ draft, mm (in); $t_o =$ starting thickness, mm (in); and $t_f =$ final thickness, mm (in). Draft is sometimes expressed as a fraction of the starting stock thickness, called the ***reduction***:

$$r = \frac{d}{t_o} \tag{18.2}$$

where $r =$ reduction. When a series of rolling operations are used, reduction is taken as the sum of the drafts divided by the original thickness.

In addition to thickness reduction, rolling usually increases work width. This is called ***spreading***, and it tends to be most pronounced with low width-to-thickness ratios and low coefficients of friction. Conservation of matter is preserved, so the volume of metal exiting the rolls equals the volume entering:

$$t_o w_o L_o = t_f w_f L_f \tag{18.3}$$

where w_o and w_f are the before and after work widths, mm (in); and L_o and L_f are the before and after work lengths, mm (in). Similarly, before and after volume rates of material flow must be the same, so the before and after velocities can be related:

$$t_o w_o v_o = t_f w_f v_f \tag{18.4}$$

where v_o and v_f are the entering and exiting velocities of the work.

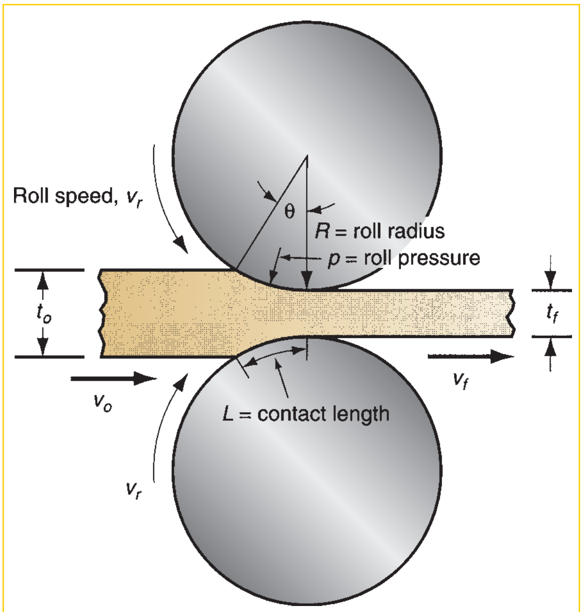


FIGURE 18.3 Side view of flat rolling, indicating before and after thicknesses, work velocities, angle of contact with rolls, and other features.

The rolls contact the work along an arc defined by the angle θ. Each roll has radius R, and its rotational speed gives it a surface velocity v_r. This velocity is greater than the entering speed of the work v_o and less than its exiting speed v_f. Since the metal flow is continuous, there is a gradual change in velocity of the work between the rolls. However, there is one point along the arc where work velocity equals roll velocity. This is called the ***no-slip point***, also known as the ***neutral point***. On either side of this point, slipping and friction occur between roll and work. The amount of slip between the rolls and the work can be measured by means of the ***forward slip***, a term used in rolling that is defined:

$$s = \frac{v_f - v_r}{v_r} \tag{18.5}$$

where $s =$ forward slip; $v_f =$ final (exiting) work velocity, m/s (ft/sec); and $v_r =$ roll speed, m/s (ft/sec).

The true strain experienced by the work in rolling is based on before and after stock thicknesses. In equation form,

$$\epsilon = \ln \frac{t_o}{t_f} \tag{18.6}$$

The true strain can be used to determine the average flow stress $\bar{Y}_f$ applied to the work material in flat rolling. Recall from the previous chapter, Equation (18.2), that

$$\bar{Y}_f = \frac{K\epsilon^n}{1 + n} \tag{18.7}$$

The average flow stress is used to compute estimates of force and power in rolling.

Friction in rolling occurs with a certain coefficient of friction, and the compression force of the rolls, multiplied by this coefficient of friction, results in a friction force between the rolls and the work. On the entrance side of the no-slip point, friction force is in one direction, and on the other side it is in the opposite direction. However, the two forces are not equal. The friction force on the entrance side is greater, so that the net force pulls the work through the rolls. If this were not the case, rolling would not be possible. There is a limit to the maximum possible draft that can be accomplished in flat rolling with a given coefficient of friction, defined by:

$$d_{max} = \mu^2 R \tag{18.8}$$

where $d_{max} =$ maximum draft, mm (in); $\mu =$ coefficient of friction; and $R =$ roll radius mm (in). The equation indicates that if friction were zero, draft would be zero, and it would be impossible to accomplish the rolling operation.

Coefficient of friction in rolling depends on lubrication, work material, and working temperature. In cold rolling, the value is around 0.1; in warm working, a typical value is around 0.2; and in hot rolling, μ is around 0.4 [16]. Hot rolling is often characterized by a condition called ***sticking***, in which the hot work surface adheres to the rolls over the contact arc. This condition often occurs in the rolling of steels and high-temperature alloys. When sticking occurs, the coefficient of friction can be as high as 0.7. The consequence of sticking is that the surface layers of the work are restricted to move at the same speed as the roll speed v_r; and below the surface, deformation is more severe in order to allow passage of the piece through the roll gap.

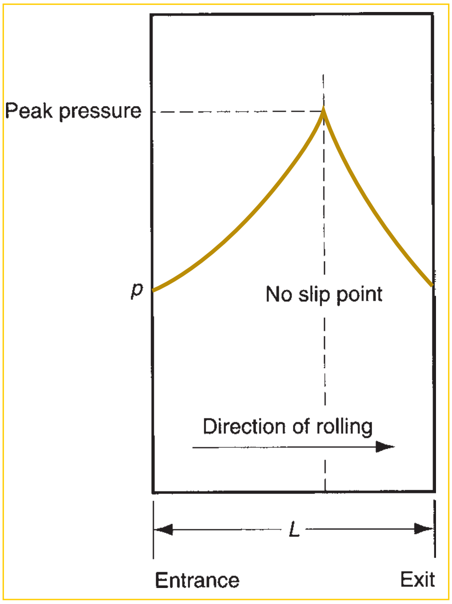


FIGURE 18.4 Typical variation in pressure along the contact length in flat rolling. The peak pressure is located at the neutral point. The area beneath the curve, representing the integration in Equation (18.9), is the roll force F.

Given a coefficient of friction sufficient to perform rolling, roll force F required to maintain separation between the two rolls can be computed by integrating the unit roll pressure (shown as p in Figure 18.3) over the roll-work contact area. This can be expressed:

$$F = w\int_0^L p\,dL \tag{18.9}$$

where $F =$ rolling force, N (lb); $w =$ the width of the work being rolled, mm (in); $p =$ roll pressure, MPa (lb/in^2); and $L =$ length of contact between rolls and work, mm (in). The integration requires two separate terms, one for either side of the neutral point. Variation in roll pressure along the contact length is significant. A sense of this variation can be obtained from the plot in Figure 18.4. Pressure reaches a maximum at the neutral point, and trails off on either side to the entrance and exit points. As friction increases, maximum pressure increases relative to entrance and exit values. As friction decreases, the neutral point shifts away from the entrance and toward the exit in order to maintain a net pull force in the direction of rolling. Otherwise, with low friction, the work would slip rather than pass between the rolls.

An approximation of the results obtained by Equation (18.9) can be calculated based on the average flow stress experienced by the work material in the roll gap. That is,

$$F = \bar{Y}_f wL \tag{18.10}$$

where $\bar{Y}_f =$ average flow stress from Equation (18.7), MPa (lb/in^2); and the product wL is the roll-work contact area, mm^2 (in^2). Contact length can be approximated by

$$L = \sqrt{R(t_o - t_f)} \tag{18.11}$$

The torque in rolling can be estimated by assuming that the roll force is centered on the work as it passes between the rolls, and that it acts with a moment arm of one-half the contact length L. Thus, torque for each roll is

$$T = 0.5\,FL \tag{18.12}$$

The power required to drive each roll is the product of torque and angular velocity. Angular velocity is $2\pi N$, where $N =$ rotational speed of the roll. Thus, the power for each roll is $2\pi NT$. Substituting Equation (18.12) for torque in this expression for power, and doubling the value to account for the fact that a rolling mill consists of two powered rolls, the following expression is obtained:

$$P = 2\pi NFL \tag{18.13}$$

where $P =$ power, J/s or W (in-lb/min); $N =$ rotational speed, 1/s (rev/min); $F =$ rolling force, N (lb); and $L =$ contact length, m (in).

Example 18.1
Flat rolling

A 300-mm-wide strip 25 mm thick is fed through a rolling mill with two powered rolls each of radius $= 250$ mm. The work thickness is to be reduced to 22 mm in one pass at a roll speed of 50 rev/min. The work material has a flow curve defined by $K = 275$ MPa and $n = 0.15$, and the coefficient of friction between the rolls and the work is assumed to be 0.12. Determine if the friction is sufficient to permit the rolling operation to be accomplished. If so, calculate the roll force, torque, and horsepower.

Solution: The draft attempted in this rolling operation is

$$d = 25 - 22 = 3 \text{ mm}$$

From Equation (18.8), the maximum possible draft for the given coefficient of friction is

$$d_{max} = (0.12)^2(250) = 3.6 \text{ mm}$$

Since the maximum allowable draft exceeds the attempted reduction, the rolling operation is feasible. To compute rolling force, contact length L and average flow stress $\bar{Y}_f$ are needed. The contact length is given by Equation (18.11):

$$L = \sqrt{250(25 - 22)} = 27.4 \text{ mm}$$

$\bar{Y}_f$ is determined from the true strain:

$$\epsilon = \ln\frac{25}{22} = 0.128$$

$$\bar{Y}_f = \frac{275(0.128)^{0.15}}{1.15} = 175.7 \text{ MPa}$$

Rolling force is determined from Equation (18.10):

$$F = 175.7(300)(27.4) = \mathbf{1{,}444{,}786\ N}$$

Torque required to drive each roll is given by Equation (18.12):

$$T = 0.5(1{,}444{,}786)(27.4)(10^{-3}) = \mathbf{19{,}786\ N\text{-}m}$$

and the power is obtained from Equation (18.13):

$$P = 2\pi(50)(1{,}444{,}786)(27.4)(10^{-3}) = 12{,}432{,}086\ \text{N-m/min} = 207{,}201\ \text{N-m/s(W)}$$

For comparison, convert this to horsepower, noting that one horsepower $=$ 745.7 W:

$$HP = \frac{207{,}201}{745.7} = \mathbf{278\ hp}$$

It can be seen from this example that large forces and power are required in rolling. Inspection of Equations (18.10) and (18.13) indicates that force and/or power to roll a strip of a given width and work material can be reduced by any of the following: (1) using hot rolling rather than cold rolling to reduce strength and strain hardening (K and n) of the work material; (2) reducing the draft in each pass; (3) using a smaller roll radius R to reduce force; and (4) using a lower rolling speed N to reduce power.

18.1.2 SHAPE ROLLING

In shape rolling, the work is deformed into a contoured cross section. Products made by shape rolling include construction shapes such as I-beams, L-beams, and U-channels; rails for railroad tracks; and round and square bars and rods (see Figure 18.2). The process is accomplished by passing the work through rolls that have the reverse of the desired shape.

Most of the principles that apply in flat rolling are also applicable to shape rolling. Shaping rolls are more complicated; and the work, usually starting as a square shape, requires a gradual transformation through several rolls in order to achieve the final cross section. Designing the sequence of intermediate shapes and corresponding rolls is called ***roll-pass design***. Its goal is to achieve uniform deformation throughout the cross section in each reduction. Otherwise, certain portions of the work are reduced more than others, causing greater elongation in these sections. The consequence of nonuniform reduction can be warping and cracking of the rolled product. Both horizontal and vertical rolls are utilized to achieve consistent reduction of the work material.

18.1.3 ROLLING MILLS

Various rolling mill configurations are available to deal with the variety of applications and technical problems in the rolling process. The basic rolling mill consists of two opposing rolls and is referred to as a ***two-high*** rolling mill, shown in Figure 18.5(a). The rolls in these mills have diameters in the range 0.6 to 1.4 m (2.0–4.5 ft). The

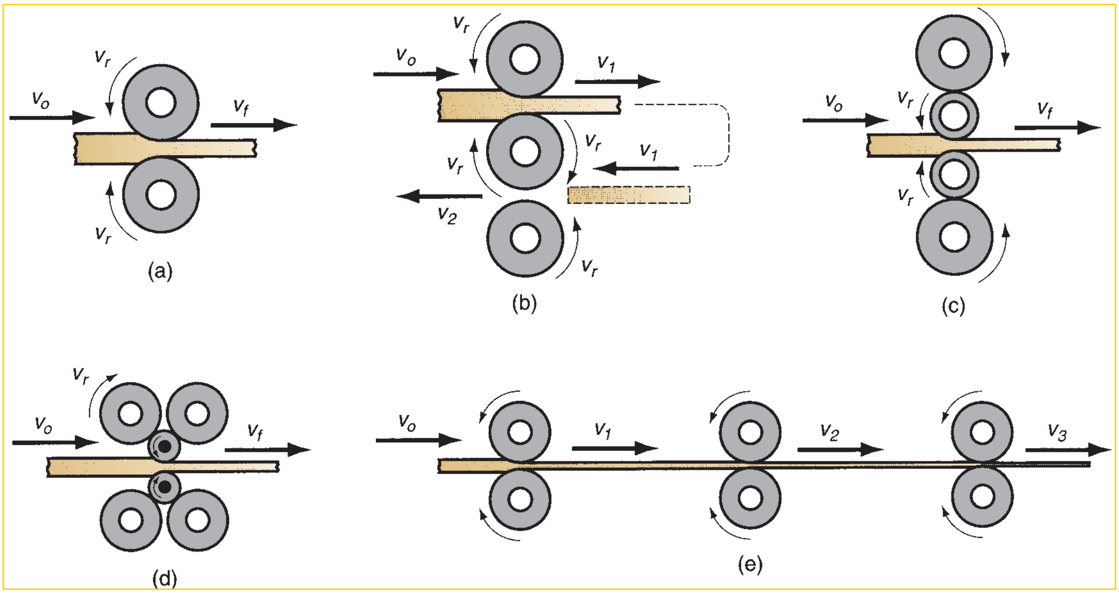


FIGURE 18.5 Various configurations of rolling mills: (a) 2-high, (b) 3-high, (c) 4-high, (d) cluster mill, and (e) tandem rolling mill.

two-high configuration can be either reversing or nonreversing. In the ***nonreversing mill***, the rolls always rotate in the same direction, and the work always passes through from the same side. The ***reversing mill*** allows the direction of roll rotation to be reversed, so that the work can be passed through in either direction. This permits a series of reductions to be made through the same set of rolls, simply by passing through the work from opposite directions multiple times. The disadvantage of the reversing configuration is the significant angular momentum possessed by large rotating rolls and the associated technical problems involved in reversing the direction.

Several alternative arrangements are illustrated in Figure 18.5. In the ***three-high*** configuration, Figure 18.5(b), there are three rolls in a vertical column, and the direction of rotation of each roll remains unchanged. To achieve a series of reductions, the work can be passed through from either side by raising or lowering the strip after each pass. The equipment in a three-high rolling mill becomes more complicated, because an elevator mechanism is needed to raise and lower the work.

As several of the previous equations indicate, advantages are gained in reducing roll diameter. Roll-work contact length is reduced with a lower roll radius, and this leads to lower forces, torque, and power. The ***four-high*** rolling mill uses two smaller-diameter rolls to contact the work and two backing rolls behind them, as in Figure 18.5(c). Owing to the high roll forces, these smaller rolls would deflect elastically between their end bearings as the work passes through unless the larger backing rolls were used to support them. Another roll configuration that allows smaller working rolls against the work is the ***cluster rolling mill***, shown in Figure 18.5(d).

To achieve higher throughput rates in standard products, a ***tandem rolling mill*** is often used. This configuration consists of a series of rolling stands, as represented in Figure 18.5(e). Although only three stands are shown in the sketch, a typical tandem rolling mill may have eight or ten stands, each making a reduction in thickness or a refinement in shape of the work passing through. With each rolling step, work velocity increases, and the problem of synchronizing the roll speeds at each stand is a significant one.

Modern tandem rolling mills are often supplied directly by continuous casting operations (Section 6.2.2). These setups achieve a high degree of integration among the processes required to transform starting raw materials into finished products. Advantages include elimination of soaking pits, reduction in floor space, and shorter manufacturing lead times. These technical advantages translate into economic benefits for a mill that can accomplish continuous casting and rolling.

8.2 Other Deformation Processes Related to Rolling

Several other bulk deformation processes use rolls to form the work part. The operations include thread rolling, ring rolling, gear rolling, and roll piercing.

Thread Rolling Thread rolling is used to form threads on cylindrical parts by rolling them between two dies. It is the most important commercial process for mass producing external threaded components (e.g., bolts and screws). The competing process is thread cutting (Section 21.7.1). Most thread rolling operations are performed by cold working in thread rolling machines. These machines are equipped with special dies that determine the size and form of the thread. The dies are of two types: (1) flat dies, which reciprocate relative to each other, as illustrated in Figure 18.6; and (2) round dies, which rotate relative to each other to accomplish the rolling action.

Production rates in thread rolling can be high, ranging up to eight parts per second for small bolts and screws. Not only are these rates significantly higher than thread cutting, but there are other advantages over machining as well: (1) better material utilization, (2) stronger threads due to work hardening, (3) smoother surface, and (4) better fatigue resistance due to compressive stresses introduced by rolling.

Ring Rolling Ring rolling is a deformation process in which a thick-walled ring of smaller diameter is rolled into a thin-walled ring of larger diameter. The before and after views of the process are illustrated in Figure 18.7. As the thick-walled ring is compressed, the deformed material elongates, causing the diameter of the ring to be enlarged. Ring rolling is usually performed as a hot-working process for large rings and as a cold-working process for smaller rings.

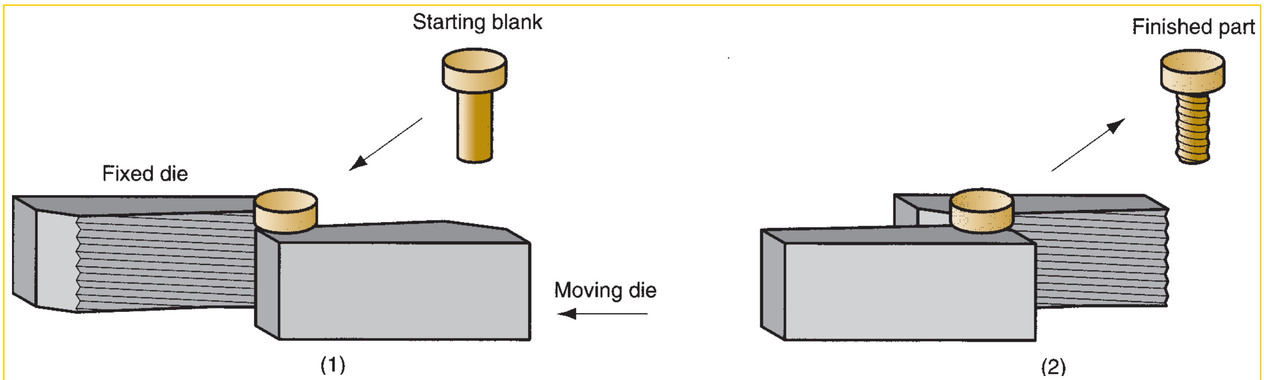


FIGURE 18.6 Thread rolling with flat dies: (1) start of cycle and (2) end of cycle.

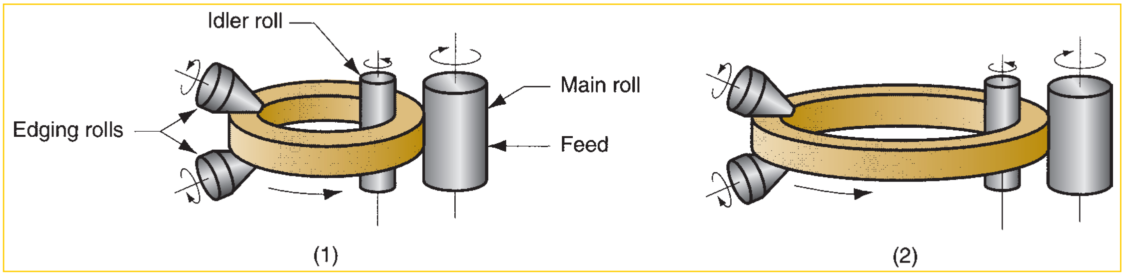


FIGURE 18.7 Ring rolling used to reduce the wall thickness and increase the diameter of a ring: (1) start and (2) completion of process.

Applications of ring rolling include ball and roller bearing races, steel tires for railroad wheels, and rings for pipes, pressure vessels, and rotating machinery. The ring walls are not limited to rectangular cross sections; the process permits rolling of more complex shapes. There are several advantages of ring rolling over alternative methods of making the same parts: raw material savings, ideal grain orientation for the application, and strengthening through cold working.

Gear Rolling Gear rolling is a cold working process to produce certain gears. The automotive industry is an important user of these products. The setup in gear rolling is similar to thread rolling, except that the deformed features of the cylindrical blank or disk are oriented parallel to its axis (or at an angle in the case of helical gears) rather than spiraled as in thread rolling. Alternative production methods for gears include several machining operations, discussed in Section 21.7.2. Advantages of gear rolling compared to machining are similar to those of thread rolling: higher production rates, better strength and fatigue resistance, and less material waste.

Roll Piercing Roll piercing is a specialized hot working process for making seamless thick-walled tubes. It utilizes two opposing rolls, and hence it is grouped with the rolling processes. The process is based on the principle that when a solid cylindrical part is compressed on its circumference, as in Figure 18.8(a), high tensile stresses are developed at its center. If compression is high enough, an internal crack is formed. In roll piercing, this principle is exploited by the setup shown in Figure 18.8(b).

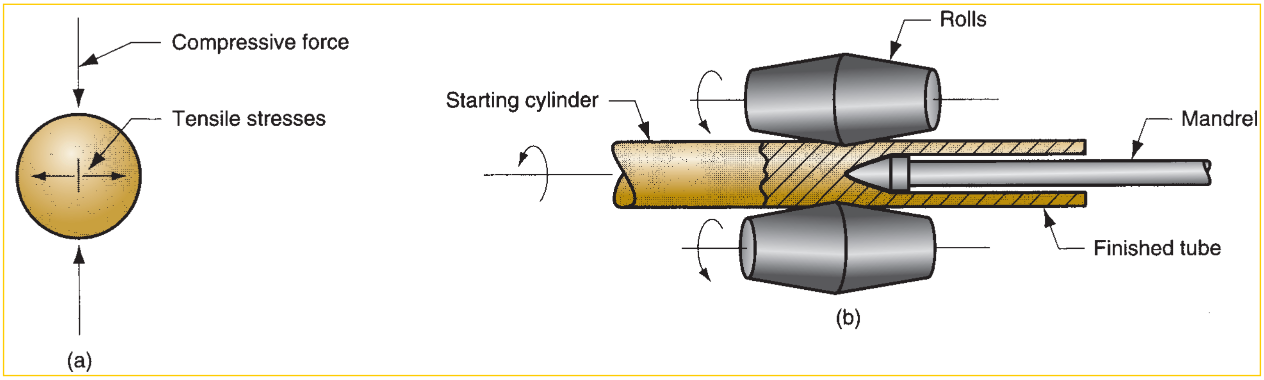


FIGURE 18.8 Roll piercing: (a) formation of internal stresses and cavity by compression of cylindrical part; and (b) setup of Mannesmann roll mill for producing seamless tubing.

Compressive stresses on a solid cylindrical billet are applied by two rolls, whose axes are oriented at slight angles (~ 6°) from the axis of the billet, so that their rotation tends to pull the billet through the rolls. A mandrel is used to control the size and finish of the hole created by the action. The terms ***rotary tube piercing*** and ***Mannesmann process*** are also used for this tube-making operation.

8.3 Forging

Forging is a deformation process in which the work is compressed between two dies, using either impact or gradual pressure to form the part. It is the oldest of the metal forming operations, dating back to perhaps 5000 B.C.E. (Historical Note 18.2). Today, forging is an important industrial process used to make a variety of high-strength components for automotive, aerospace, and other applications. These components include engine crankshafts and connecting rods, gears, aircraft structural components, and jet engine turbine parts. In addition, steel and other basic metals industries use forging to establish the basic form of large components that are subsequently machined to final shape and dimensions.

Historical Note 18.2 *Forging*

The forging process dates from the earliest written records of man, around 7000 years ago. There is evidence that forging was used in ancient Egypt, Greece, Persia, India, China, and Japan to make weapons, jewelry, and a variety of implements. Craftsmen in the art of forging during these times were held in high regard.

Engraved stone platens were used as impression dies in the hammering of gold and silver in ancient Crete around 1600 B.C.E. This evolved into the fabrication of coins by a similar process around 800 B.C.E. More complicated impression dies were used in Rome around 200 C.E. The blacksmith's trade remained relatively unchanged for many centuries until the drop hammer with guided ram was introduced near the end of the eighteenth century. This development brought forging practice into the Industrial Age.

Forging is carried out in many different ways. One way to classify the operations is by working temperature. Most forging operations are performed hot or warm, owing to the significant deformation demanded by the process and the need to reduce strength and increase ductility of the work metal. However, cold forging is also very common for certain products. The advantage of cold forging is the increased strength that results from strain hardening of the component.

Either impact or gradual pressure is used in forging. The distinction derives more from the type of equipment used than differences in process technology. A forging machine that applies an impact load is called a ***forging hammer***, while one that applies gradual pressure is called a ***forging press***.

Another difference among forging operations is the degree to which the flow of the work metal is constrained by the dies. By this classification, there are three types of forging operations, shown in Figure 18.9: (a) open-die forging, (b) impression-die forging, and (c) flashless forging. In ***open-die forging***, the work is compressed between two flat (or almost flat) dies, thus allowing the metal to flow without constraint in a lateral direction relative to the die surfaces. In ***impression-die forging***, the die surfaces contain a shape or impression that is imparted to the work during

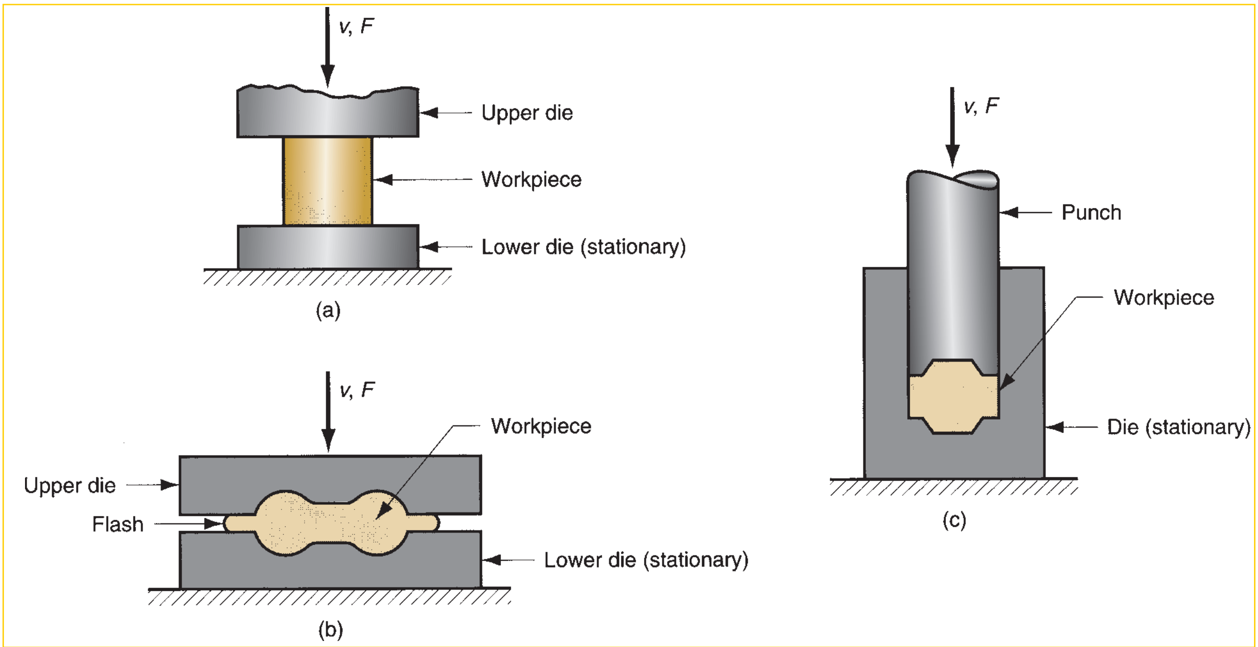


FIGURE 18.9 Three types of forging operation illustrated by cross-sectional sketches: (a) open-die forging, (b) impression-die forging, and (c) flashless forging.

compression, thus constraining metal flow to a significant degree. In this type of operation, a portion of the work metal flows beyond the die impression to form ***flash***, as shown in the figure. Flash is excess metal that must be trimmed off later. In ***flashless forging***, the work is completely constrained within the die and no excess flash is produced. The volume of the starting workpiece must be controlled very closely so that it matches the volume of the die cavity.

18.3.1 OPEN-DIE FORGING

The simplest case of open-die forging involves compression of a work part of cylindrical cross section between two flat dies, much in the manner of a compression test (Section 3.1.2). This forging operation, known as ***upsetting*** or ***upset forging***, reduces the height of the work and increases its diameter.

Analysis of Open-Die Forging If open-die forging is carried out under ideal conditions of no friction between work and die surfaces, then homogeneous deformation occurs, and the radial flow of the material is uniform throughout its height, as pictured in Figure 18.10. Under these ideal conditions, the true strain experienced by the work during the process can be determined by

$$\epsilon = \ln \frac{h_o}{h} \tag{18.14}$$

where $h_o =$ starting height of the work, mm (in); and $h =$ the height at some intermediate point in the process, mm (in). At the end of the compression stroke, $h =$ its final value h_f, and the true strain reaches its maximum value.

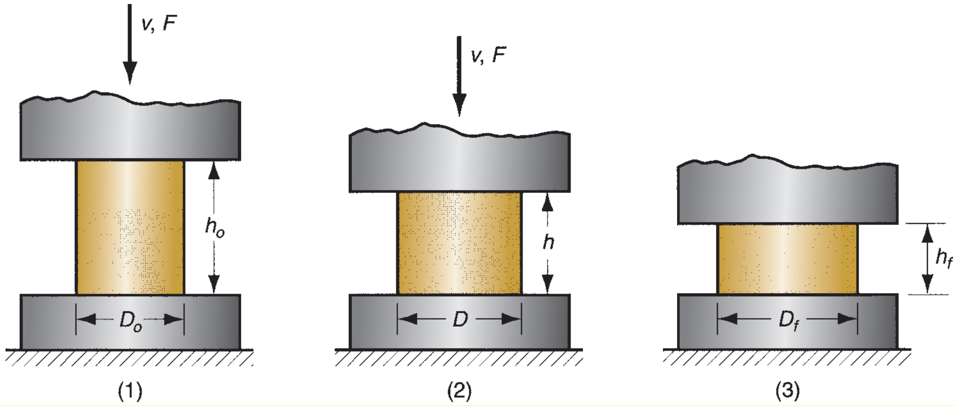


FIGURE 18.10 Homogeneous deformation of a cylindrical work part under ideal conditions in an open-die forging operation: (1) start of process with workpiece at its original length and diameter, (2) partial compression, and (3) final size.

Estimates of force to perform upsetting can be calculated. The force required to continue the compression at any given height h during the process can be obtained by multiplying the corresponding cross-sectional area by the flow stress:

$$F = Y_f A \tag{18.15}$$

where $F =$ force, lb (N); $A =$ cross-sectional area of the part, mm^2 (in^2); and $Y_f =$ flow stress corresponding to the strain given by Equation (18.14), MPa (lb/in^2). Area A continuously increases during the operation as height is reduced. Flow stress Y_f also increases as a result of work hardening, except when the metal is perfectly plastic (e.g., in hot working). In this case, the strain hardening exponent $n = 0$, and flow stress Y_f equals the metal's yield strength Y. Force reaches a maximum value at the end of the forging stroke, when both area and flow stress are at their highest values.

An actual upsetting operation does not occur quite as shown in Figure 18.10 because friction opposes the flow of work metal at the die surfaces. This creates the barreling effect shown in Figure 18.11. When performed on a hot work part with cold dies, the barreling effect is even more pronounced. This results from a higher coefficient of friction typical in hot working and heat transfer at and near the die surfaces, which cools the metal and increases its resistance to deformation. The hotter metal in the middle of the part flows more readily than the cooler metal at the ends. These effects are more significant as the diameter-to-height ratio of the work part increases, due to the greater contact area at the work-die interface.

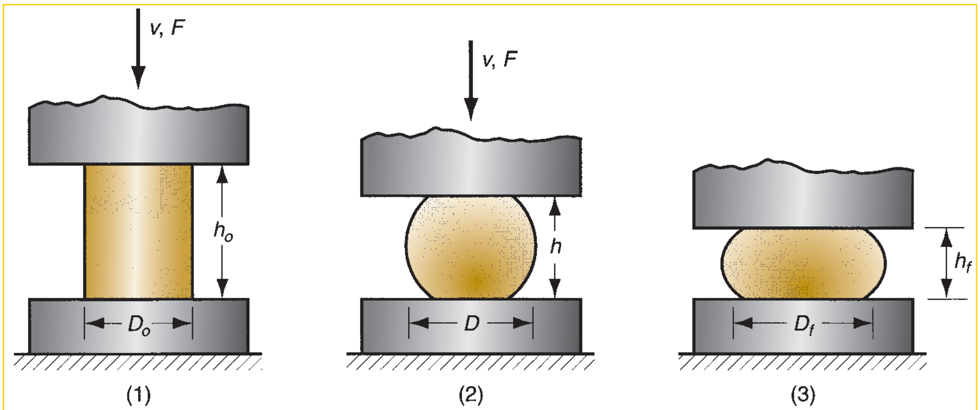


FIGURE 18.11 Actual deformation of a cylindrical work part in open-die forging, showing pronounced barreling: (1) start of process, (2) partial deformation, and (3) final shape.

All of these factors cause the actual upsetting force to be greater than what is predicted by Equation (18.15). As an approximation, a shape factor can be applied to Equation (18.15) to account for effects of the D/h ratio and friction:

$$F = K_f Y_f A \tag{18.16}$$

where F, Y_f, and A have the same definitions as in the previous equation; and K_f is the forging shape factor, defined as

$$K_f = 1 + \frac{0.4\,\mu D}{h} \tag{18.17}$$

where μ = coefficient of friction; D = work part diameter or other dimension representing contact length with die surface, mm (in); and h = work part height, mm (in).

Example 18.2 Open-die forging

A cylindrical workpiece is subjected to a cold upset forging operation. The starting piece is 75 mm in height and 50 mm in diameter. It is reduced in the operation to a height of 36 mm. The work material has a flow curve defined by $K = 350$ MPa and $n = 0.17$. Assume a coefficient of friction of 0.1. Determine the force as the process begins, at intermediate heights of 62 mm, 49 mm, and at the final height of 36 mm.

Solution: Workpiece volume $V = 75\pi(50^2/4) = 147{,}262$ mm^3. At the moment contact is made by the upper die, $h = 75$ mm and the force $F = 0$. At the start of yielding, h is slightly less than 75 mm; assume that strain = 0.002, at which the flow stress is

$$Y_f = K\epsilon^n = 350(0.002)^{0.17} = 121.7 \text{ MPa}$$

The diameter is still approximately $D = 50$ mm and area $A = \pi(50^2/4) = 1963.5$ mm^2. For these conditions, the adjustment factor K_f is computed as

$$K_f = 1 + \frac{0.4(0.1)(50)}{75} = 1.027$$

The forging force is

$$F = 1.027(121.7)(1963.5) = \mathbf{245{,}410\ N}$$

At $h = 62$ mm,

$$\epsilon = \ln\frac{75}{62} = \ln(1.21) = 0.1904$$

$$Y_f = 350(0.1904)^{.17} = 264.0 \text{ MPa}$$

Assuming constant volume, and neglecting barreling,

$$A = 147{,}262/62 = 2375.2 \text{ mm}^2 \text{ and } D = \sqrt{\frac{4(2375.2)}{\pi}} = 55.0 \text{ mm}$$

$$K_f = 1 + \frac{0.4(0.1)(55)}{62} = 1.035$$

$$F = 1.035(264)(2375.2) = \mathbf{649{,}303\ N}$$

Similarly, at $h = 49$ mm, $F = 955{,}642$ N; and at $h = 36$ mm, $F = \mathbf{1{,}467{,}422\ N}$. The load-stroke curve in Figure 18.12 was developed from the values in this example.

Open-Die Forging Practice Open-die hot forging is an important industrial process. Shapes generated by open-die operations are simple; examples include shafts, disks, and rings. In some applications, the dies have slightly contoured surfaces that help to shape the work. In addition, the work must often be manipulated (e.g., rotating in steps) to effect the desired shape change. Skill of the human operator is a factor in the success of these operations. An example of open-die forging in the steel industry is the shaping of a large square cast ingot into a round cross section. Open-die forging operations produce rough forms, and subsequent operations are required to refine the parts to final geometry and dimensions. An important contribution of open-die hot-forging is that it creates a favorable grain flow and metallurgical structure in the metal.

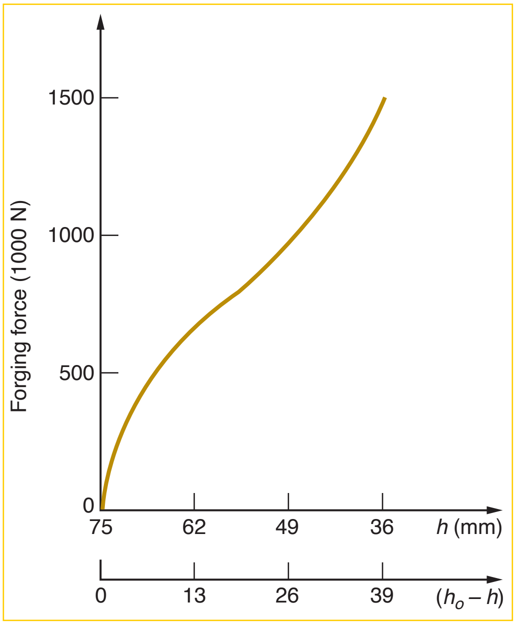


FIGURE 18.12 Upsetting force as a function of height h and height reduction $(h_o - h)$. This plot is sometimes called the load stroke curve.

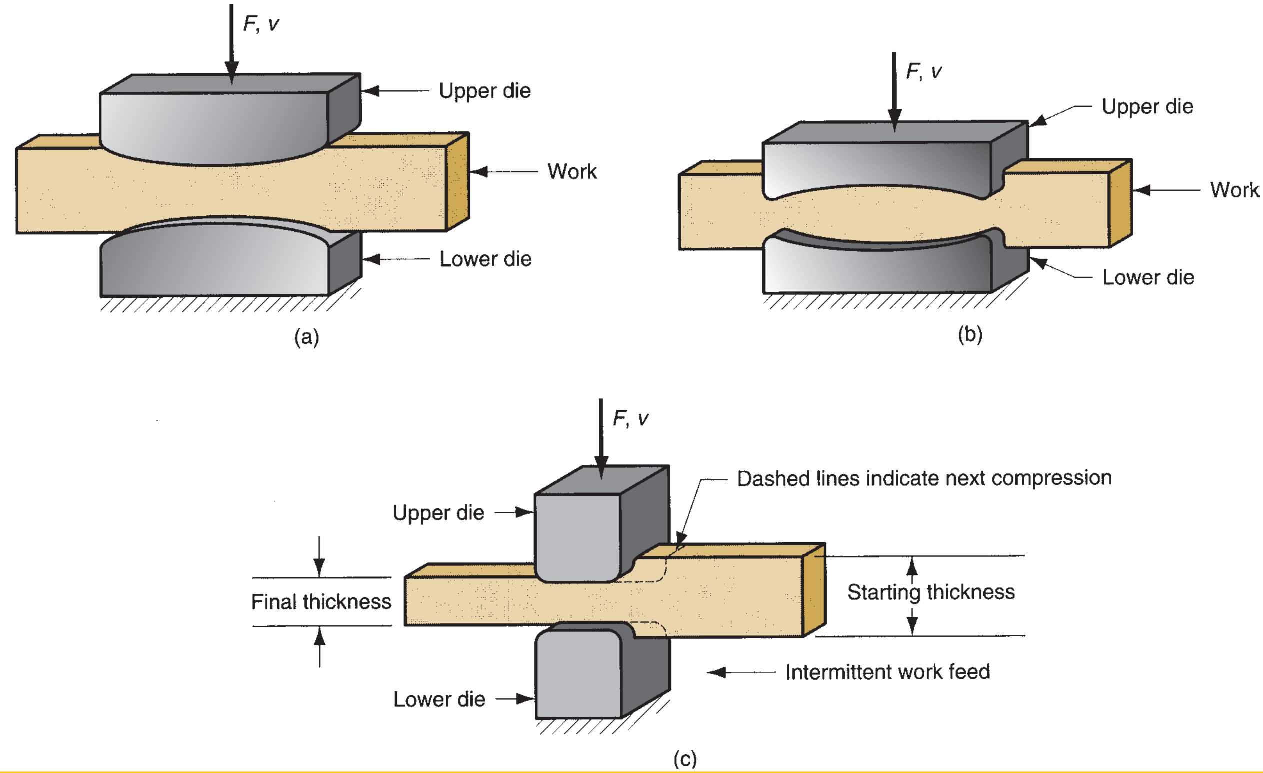


FIGURE 18.13 Several open-die forging operations: (a) fullering, (b) edging, and (c) cogging.

Operations classified as open-die forging or related operations include fullering, edging, and cogging, illustrated in Figure 18.13. ***Fullering*** is a forging operation performed to reduce the cross section and redistribute the metal in a work part in preparation for subsequent shape forging. It is accomplished by dies with convex surfaces. Fullering die cavities are often designed into multi-cavity impression dies, so that the starting bar can be rough formed before final shaping. ***Edging*** is similar to fullering, except that the dies have concave surfaces.

A ***cogging*** operation consists of a sequence of forging compressions along the length of a workpiece to reduce cross section and increase length. It is used in the steel industry to produce blooms and slabs from cast ingots. It is accomplished using open dies with flat or slightly contoured surfaces. The term ***incremental forging*** is sometimes used for this process.

18.3.2 IMPRESSION-DIE FORGING

Impression-die forging, sometimes called ***closed-die forging***, is performed with dies that contain the inverse of the desired shape of the part. The process is illustrated in a three-step sequence in Figure 18.14. The raw workpiece is shown as a cylindrical part similar to that used in the previous open-die operation. As the die closes to its final position, flash is formed by metal that flows beyond the die cavity and into the small gap between the die plates. Although this flash must

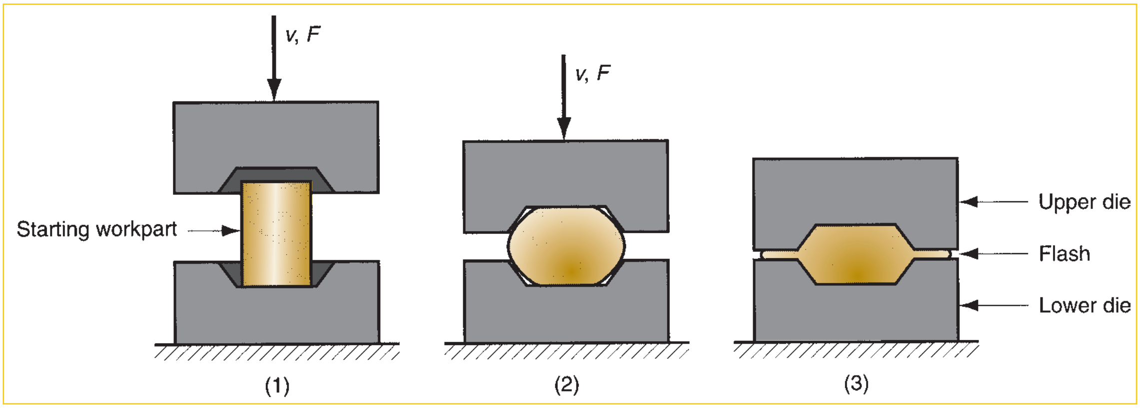


FIGURE 18.14 Sequence in impression-die forging: (1) just prior to initial contact with raw workpiece, (2) partial compression, and (3) final die closure, causing flash to form in gap between die plates.

be cut away from the part in a subsequent trimming operation, it actually serves an important function during impression-die forging. As the flash begins to form in the die gap, friction resists continued flow of metal into the gap, thus constraining the bulk of the work material to remain in the die cavity. In hot forging, metal flow is further restricted because the thin flash cools quickly against the die plates, thereby increasing its resistance to deformation. Restricting metal flow in the gap causes the compression pressures on the part to increase significantly, thus forcing the material to fill the sometimes intricate details of the die cavity to ensure a high-quality product.

Several forming steps are often required in impression die forging to transform the starting blank into the desired final geometry. Separate cavities in the die are needed for each step. The beginning steps are designed to redistribute the metal in the work part to achieve a uniform deformation and desired metallurgical structure in the subsequent steps. The final steps bring the part to its final geometry. In addition, when drop forging is used, several blows of the hammer may be required for each step. When impression-die drop forging is done manually, as it often is, considerable operator skill is required under adverse conditions to achieve consistent results.

Because of flash formation in impression die forging and the more complex part shapes made with these dies, forces in this process are significantly greater and more difficult to analyze than in open-die forging. Relatively simple formulas and design factors are often used to estimate forces in impression-die forging. The force formula is the same as previous Equation (18.16) for open-die forging, but its interpretation is slightly different:

$$F = K_f Y_f A \tag{18.18}$$

where F = maximum force in the operation, N (lb); A = projected area of the part including flash, mm^2 (in^2); Y_f = flow stress of the material, MPa (lb/in^2); and K_f = forging shape factor. In hot forging, the appropriate value of Y_f is the yield

TABLE • 18.1 Typical K_f values for various part shapes in impression-die and flashless forging.

Part Shape	K_f	Part Shape	K_f
Impression-die forging:		Flashless forging:	
Simple shapes with flash	6.0	Coining (top and bottom surfaces)	6.0
Complex shapes with flash	8.0	Complex shapes	8.0
Very complex shapes with flash	10.0		

strength of the metal at the elevated temperature. In other cases, selecting the proper value of flow stress is difficult because the strain varies throughout the workpiece for complex shapes. K_f in Equation (18.18) is a factor intended to account for increases in force required to forge part shapes of various complexities. Table 18.1 indicates the range of values of K_f for different part geometries. Obviously, the problem of specifying the proper K_f value for a given work part limits the accuracy of the force estimate.

Equation (18.18) applies to the maximum force during the operation, since this is the load that will determine the required capacity of the press or hammer used in the operation. The maximum force is reached at the end of the forging stroke, when the projected area is greatest and friction is maximum.

Impression-die forging is not capable of close tolerance work, and machining is often required to achieve the accuracies needed. The basic geometry of the part is obtained from the forging process, with machining performed on those portions of the part that require precision finishing (e.g., holes, threads, and surfaces that mate with other components). The advantages of forging, compared to machining the part completely, are higher production rates, conservation of metal, greater strength, and favorable grain orientation of the metal that results from forging. A comparison of the grain flow in forging and machining is illustrated in Figure 18.15.

Improvements in the technology of impression-die forging have resulted in the capability to produce forgings with thinner sections, more complex geometries, drastic reductions in draft requirements on the dies, closer tolerances, and the virtual elimination of machining allowances. Forging processes with these features are known as ***precision forging***. Common work metals used for precision forging include aluminum and titanium. A comparison of precision and conventional

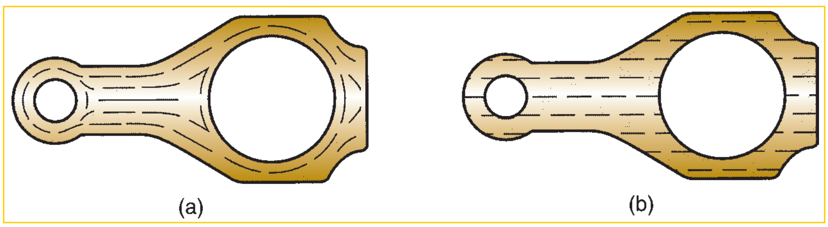


FIGURE 18.15 Comparison of metal grain flow in a part that is: (a) hot forged with finish machining, and (b) machined complete.

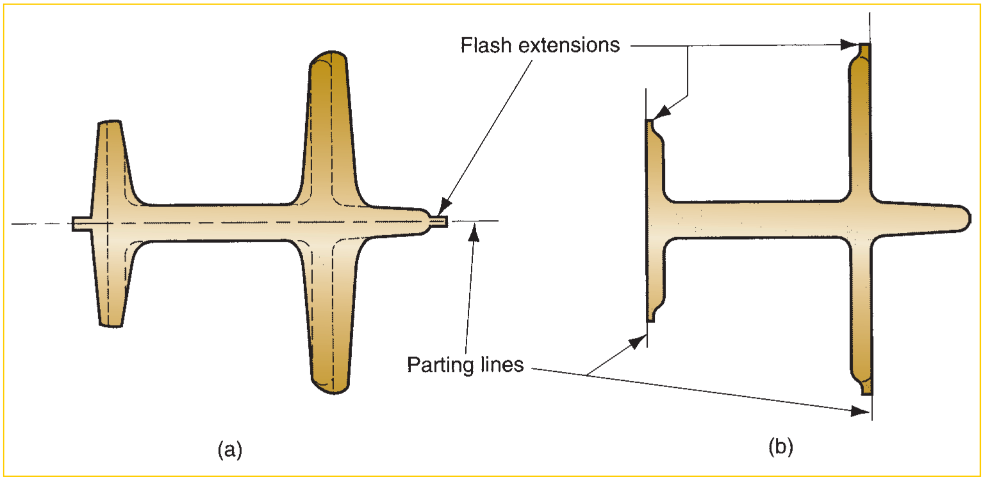


FIGURE 18.16 Cross sections of (a) conventional- and (b) precision forgings. Dashed lines in (a) indicate subsequent machining required to make the conventional forging equivalent in geometry to the precision forging. In both cases, flash extensions must be trimmed.

impression-die forging is presented in Figure 18.16. Note that precision forging in this example does not eliminate flash, although it reduces it. Some precision forging operations are accomplished without producing flash. Depending on whether machining is required to finish the part geometry, precision forgings are properly classified as ***near net shape*** or ***net shape*** processes.

18.3.3 FLASHLESS FORGING

As mentioned above, impression-die forging is sometimes called closed-die forging in industry terminology. However, there is a technical distinction between impression-die forging and true closed-die forging. The distinction is that in closed-die forging, the raw workpiece is completely contained within the die cavity during compression, and no flash is formed. The process sequence is illustrated in Figure 18.17. The term ***flashless forging*** is appropriate to identify this process.

Flashless forging imposes requirements on process control that are more demanding than impression-die forging. Most important is that the work volume must equal

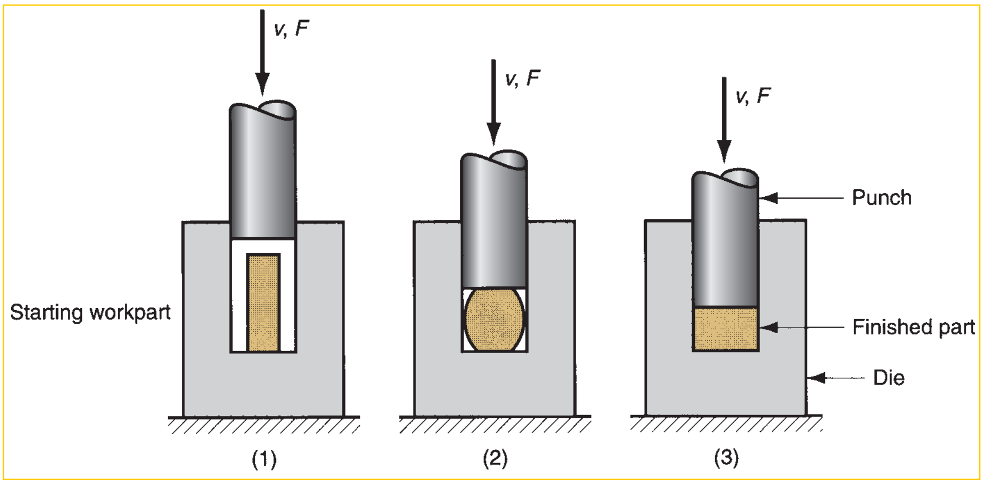


FIGURE 18.17 Flashless forging: (1) just before initial contact with workpiece, (2) partial compression, and (3) final punch and die closure. Symbols v and F indicate motion (v = velocity) and applied force, respectively.

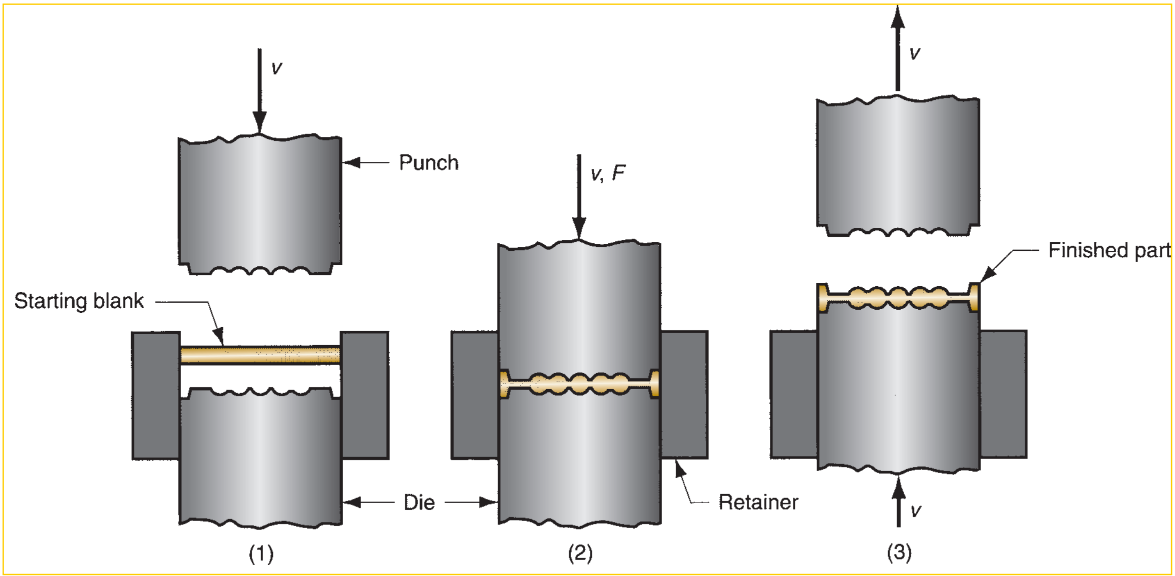


FIGURE 18.18 Coining operation: (1) start of cycle, (2) compression stroke, and (3) ejection of finished part.

the space in the die cavity within a very close tolerance. If the starting blank is too large, excessive pressures may cause damage to the die or press. If the blank is too small, the cavity will not be filled. Because of the special demands made by flashless forging, the process lends itself best to part geometries that are usually simple and symmetrical, and to work materials such as aluminum and magnesium and their alloys. Flashless forging is often classified as a ***precision forging*** process [5].

Forces in flashless forging reach values comparable to those in impression die forging. Estimates of these forces can be computed using the same methods as for impression die forging: Equation (18.18) and Table 18.1.

Coining is a special application of closed-die forging in which fine details in the die are impressed into the top and bottom surfaces of the work part. There is little flow of metal in coining, yet the pressures required to reproduce the surface details in the die cavity are high, as indicated by the value of K_f in Table 18.1. A common application of coining is, of course, in the minting of coins, shown in Figure 18.18. The process is also used to provide good surface finish and dimensional accuracy on work parts made by other operations.

18.3.4 FORGING HAMMERS, PRESSES, AND DIES

Equipment used in forging consists of forging machines, classified as hammers or presses, and forging dies, which are the special tooling used in these machines. In addition, auxiliary equipment is needed, such as furnaces to heat the work, mechanical devices to load and unload the work, and trimming stations to cut away the flash in impression-die forging.

Forging Hammers Forging hammers operate by applying an impact loading against the work. The term ***drop hammer*** is often used for these machines, owing to the means

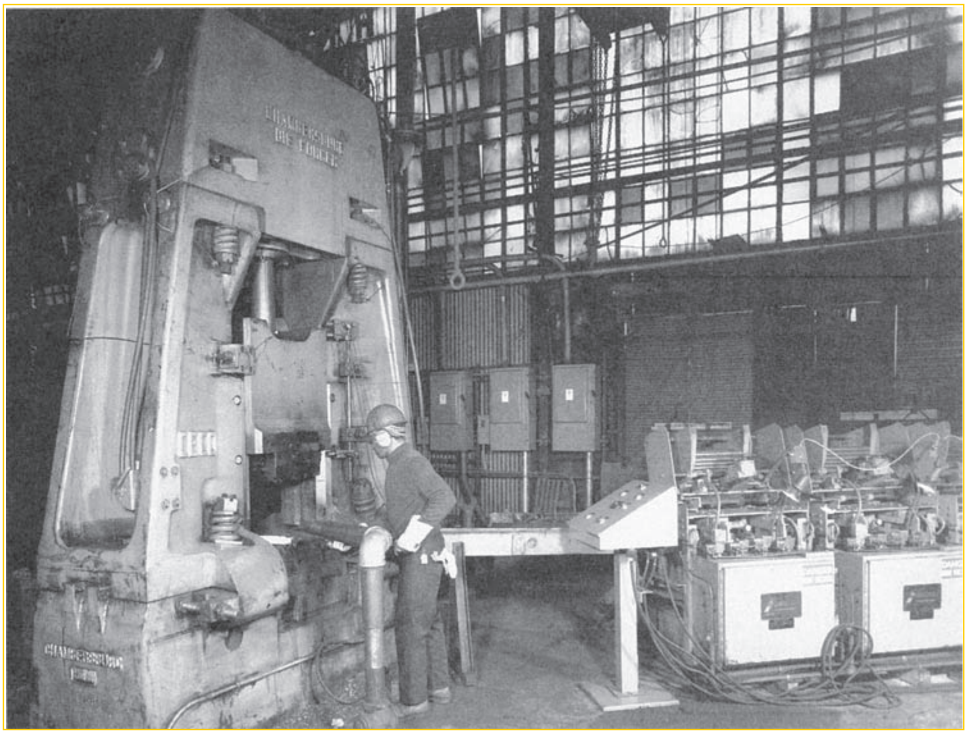


FIGURE 18.19 Drop forging hammer, fed by conveyor and heating units at the right of the scene. (Photo courtesy of Ajax-Ceco.)

of delivering the impact energy; see Figures 18.19 and 18.20. Drop hammers are most frequently used for impression-die forging. The upper portion of the forging die is attached to the ram, and the lower portion is attached to the anvil. In the operation, the work is placed on the lower die, and the ram is lifted and then dropped. When the upper die strikes the work, the impact energy causes the part to assume the form of the die cavity. Several blows of the hammer are often required to achieve the desired change in shape. Drop hammers can be classified as gravity drop hammers and power drop hammers. ***Gravity drop hammers*** achieve their energy by the falling weight of

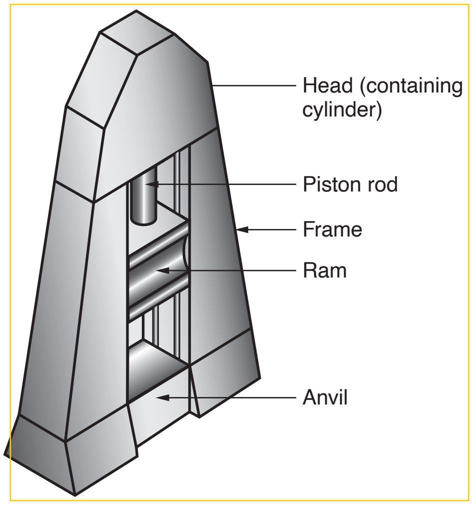


FIGURE 18.20 Diagram showing details of a drop hammer for impression-die forging.

a heavy ram. The force of the blow is determined by the height of the drop and the weight of the ram. ***Power drop hammers*** accelerate the ram by pressurized air or steam. One of the disadvantages of drop hammers is that a large amount of the impact energy is transmitted through the anvil and into the floor of the building.

Forging Presses Presses apply gradual pressure, rather than sudden impact, to accomplish the forging operation. Forging presses include mechanical presses, hydraulic presses, and screw presses. ***Mechanical presses*** operate by means of eccentrics, cranks, or knuckle joints, which convert the rotating motion of a drive motor into the translation motion of the ram. These mechanisms are very similar to those used in stamping presses (Section 19.5.2). Mechanical presses typically achieve very high forces at the bottom of the forging stroke. ***Hydraulic presses*** use a hydraulically driven piston to actuate the ram. ***Screw presses*** apply force by a screw mechanism that drives the vertical ram. Both screw drive and hydraulic drive operate at relatively low ram speeds and can provide a constant force throughout the stroke. These machines are therefore suitable for forging (and other forming) operations that require a long stroke.

Forging Dies Proper die design is important in the success of a forging operation. Parts to be forged must be designed based on knowledge of the principles and limitations of this process. The purpose here is to describe some of the terminology and guidelines used in the design of forgings and forging dies. Design of open dies is generally straightforward because the dies are relatively simple in shape. The following comments apply to impression dies and closed dies. Figure 18.21 defines some of the terminology in an impression die.

Some of the principles and limitations that must be considered in the part design or in the selection of forging as the manufacturing process is provided in the following discussion of forging die terminology [5]:

- ***Parting line***. The parting line is the plane that divides the upper die from the lower die. Called the flash line in impression-die forging, it is the plane where the two die halves meet. Its selection by the designer affects grain flow in the part, required load, and flash formation.
- ***Draft***. Draft is the amount of taper on the sides of the part required to remove it from the die. The term also applies to the taper on the sides of the die cavity. Typical draft angles are 3° on aluminum and magnesium parts and 5° to 7° on steel parts. Draft angles on precision forgings are near zero.
- ***Webs and ribs***. A web is a thin portion of the forging that is parallel to the parting line, while a rib is a thin portion that is perpendicular to the parting line. These part features cause difficulty in metal flow as they become thinner.
- ***Fillet and corner radii***. Fillet and corner radii are illustrated in Figure 18.21. Small radii tend to limit metal flow and increase stresses on die surfaces during forging.
- ***Flash***. Flash formation plays a critical role in impression-die forging by causing pressure buildup inside the die to promote filling of the cavity. This pressure buildup is controlled by designing a flash land and gutter into the die, as pictured in Figure 18.21. The land determines the surface area along which lateral flow of metal occurs, thereby controlling the pressure increase inside the die. The gutter permits excess metal to escape without causing the forging load to reach extreme values.

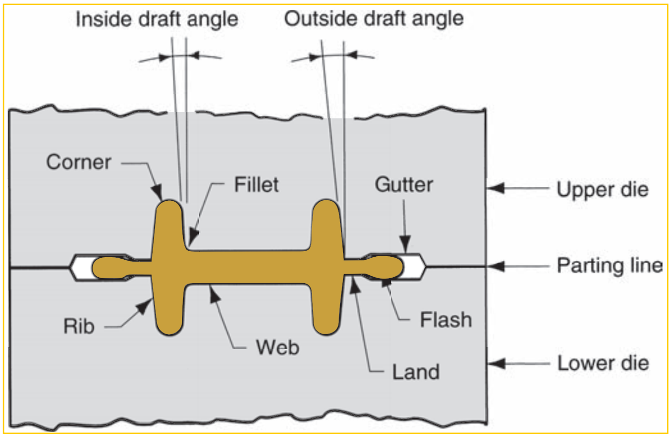


FIGURE 18.21 Terminology for a conventional impression-die in forging.

8.4 Other Deformation Processes Related to Forging

In addition to the conventional forging operations discussed in the preceding sections, other metal forming operations are closely associated with forging.

Upsetting and Heading Upsetting (also called ***upset forging***) is a deformation operation in which a cylindrical work part is increased in diameter and reduced in length. This operation is analyzed in the discussion of open-die forging (Section 18.3.1). However, as an industrial operation, it can also be performed as closed-die forging, as in Figure 18.22.

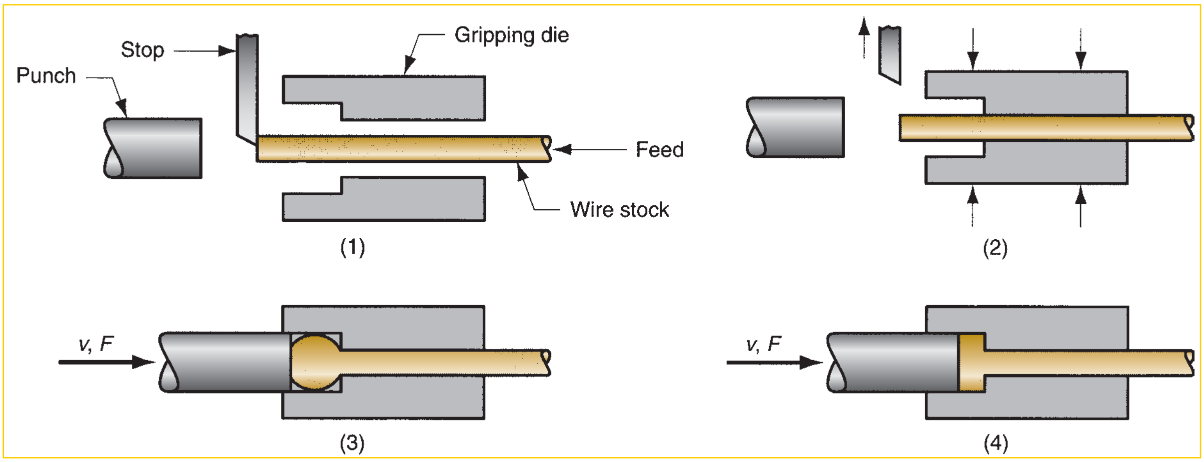


FIGURE 18.22 An upset forging operation to form a head on a bolt or similar hardware item. The cycle is as follows: (1) Wire stock is fed to the stop; (2) gripping dies close on the stock and the stop is retracted; (3) punch moves forward; and (4) bottoms to form the head.

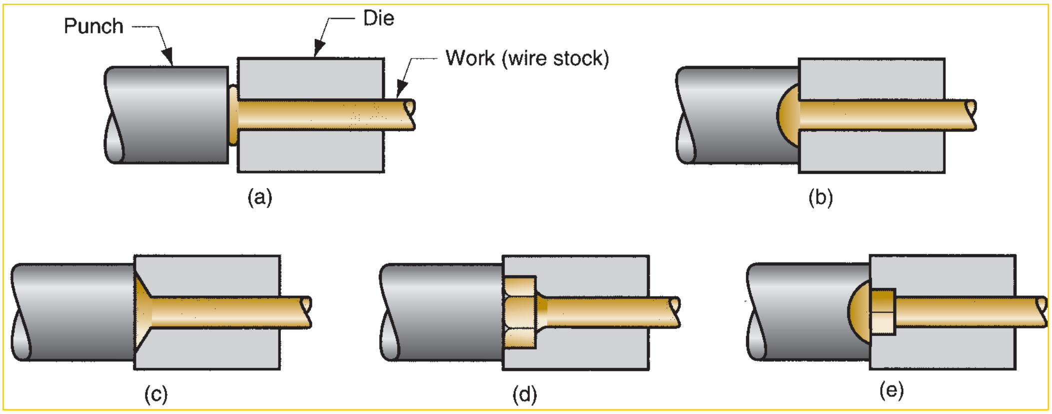


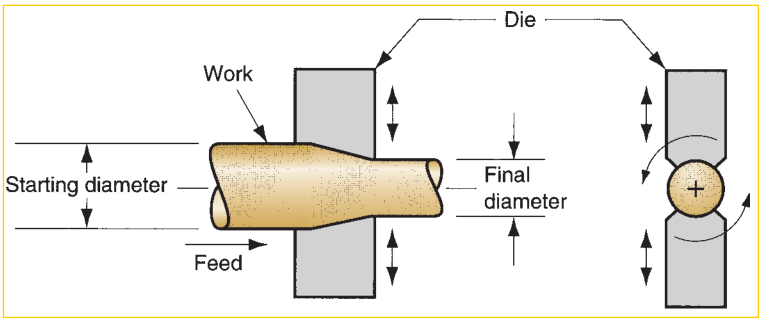
FIGURE 18.23 Examples of heading (upset forging) operations: (a) heading a nail using open dies, (b) round head formed by punch, (c) and (d) heads formed by die, and (e) carriage bolt head formed by punch and die.

Upsetting is widely used in the fastener industry to form heads on nails, bolts, and similar hardware products. In these applications, the term ***heading*** is often used to denote the operation. Figure 18.23 illustrates a variety of heading applications, indicating various possible die configurations. Owing to these types of applications, more parts are produced by upsetting than by any other forging operation. It is performed as a mass-production operation—cold, warm, or hot—on special upset forging machines, called headers or formers. These machines are usually equipped with horizontal slides, rather than vertical slides as in conventional forging hammers and presses. Long wire or bar stock is fed into the machines, the end of the stock is upset forged, and then the piece is cut to length to make the desired hardware item. For bolts and screws, thread rolling (Section 18.2) is used to form the threads.

There are limits on the amount of deformation that can be achieved in upsetting, usually defined as the maximum length of stock to be forged. The maximum length that can be upset in one blow is three times the diameter of the starting stock. Otherwise, the metal bends or buckles instead of compressing properly to fill the cavity.

Swaging and Radial Forging Swaging and radial forging are forging processes used to reduce the diameter of a tube or solid rod. Swaging is often performed on the end of a workpiece to create a tapered section. The ***swaging*** process, shown in Figure 18.24, is accomplished by means of rotating dies that hammer a workpiece

FIGURE 18.24 Swaging process to reduce solid rod stock; the dies rotate as they hammer the work. In radial forging, the workpiece rotates while the dies remain in a fixed orientation as they hammer the work.



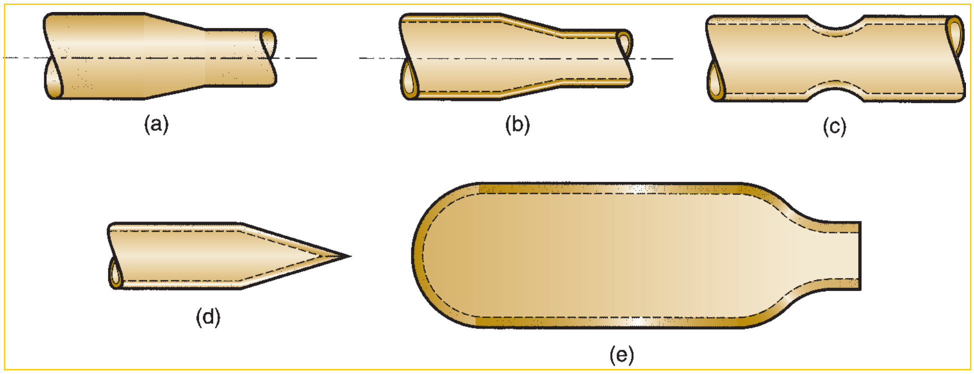


FIGURE 18.25 Examples of parts made by swaging: (a) reduction of solid stock, (b) tapering a tube, (c) swaging to form a groove on a tube, (d) pointing of a tube, and (e) swaging of neck on a gas cylinder.

radially inward to taper it as the piece is fed into the dies. Figure 18.25 illustrates some of the shapes and products that are made by swaging. A mandrel is sometimes required to control the shape and size of the internal diameter of tubular parts that are swaged. ***Radial forging*** is similar to swaging in its action against the work and is used to create similar part shapes. The difference is that in radial forging the dies do not rotate around the workpiece; instead the work is rotated as it feeds into the hammering dies.

Roll Forging Roll forging is a deformation process used to reduce the cross section of a cylindrical (or rectangular) workpiece by passing it through a set of opposing rolls that have grooves matching the desired shape of the final part. The typical operation is illustrated in Figure 18.26. Roll forging is generally classified as a forging process even though it utilizes rolls. The rolls do not turn continuously in roll forging, but rotate through only a portion of one revolution corresponding to the desired deformation to be accomplished on the part. Roll-forged parts are generally stronger and possess favorable grain structure compared to competing processes such as machining that might be used to produce the same part geometry.

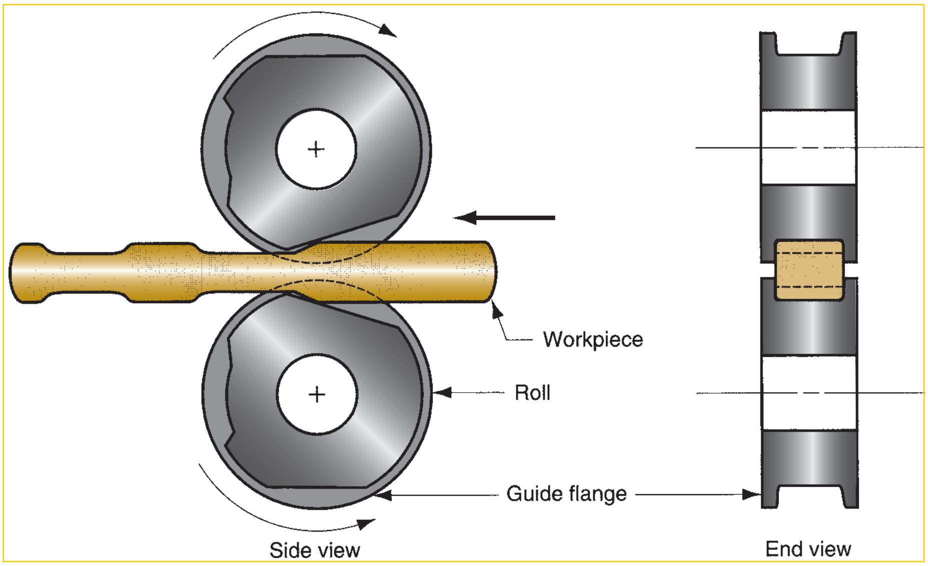


FIGURE 18.26 Roll forging.

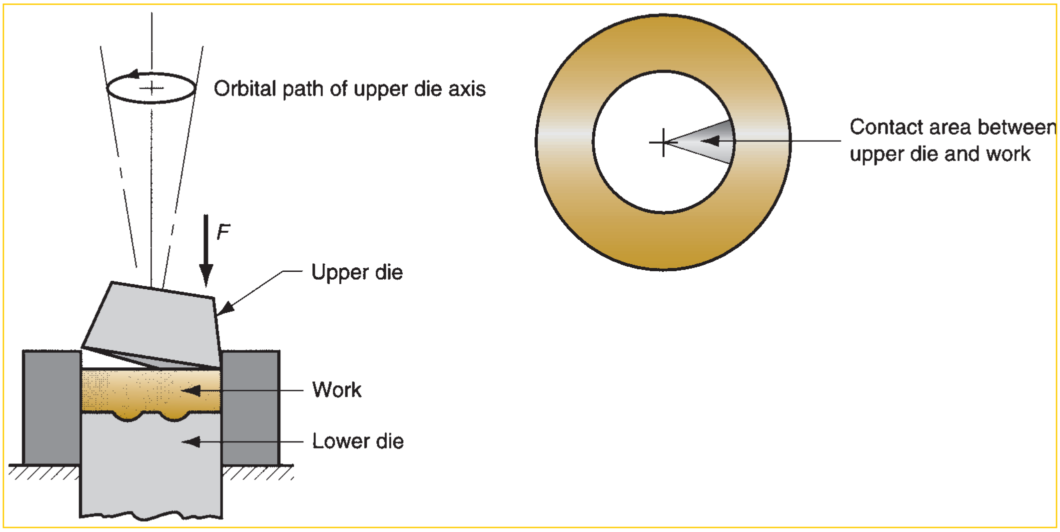


FIGURE 18.27 Orbital forging. At end of deformation cycle, lower die lifts to eject part.

Orbital Forging In this process, deformation occurs by means of a cone-shaped upper die that is simultaneously rolled and pressed into the work part. As illustrated in Figure 18.27, the work is supported on a lower die, which has a cavity into which the work is compressed. Because the axis of the cone is inclined, only a small area of the work surface is compressed at any moment. As the upper die revolves, the area under compression also revolves. These operating characteristics of orbital forging result in a substantial reduction in press load required to accomplish deformation of the work.

Hubbing Hubbing is a deformation process in which a hardened steel form is pressed into a soft steel (or other soft metal) block. The process is often used to make mold cavities for plastic molding and die casting, as sketched in Figure 18.28. The hardened steel form, called the ***hub***, is machined to the geometry of the part to be molded. Substantial pressures are required to force the hub into the soft block, and this is usually accomplished by a hydraulic press. Complete formation of the die cavity in the block often requires several steps—hubbing followed by annealing to recover the work metal from strain hardening. When significant amounts of material are deformed in the block, as shown in the figure, the excess must be machined away. The advantage of hubbing in this application is that it is generally easier to machine the positive form than the mating negative cavity. This advantage is multiplied in cases where more than one cavity are made in the die block.

Isothermal Forging Isothermal forging is a term applied to a hot-forging operation in which the work part is maintained at or near its starting elevated temperature during deformation, usually by heating the forging dies to the same elevated temperature. By avoiding chill of the workpiece on contact with the cold die surfaces as in conventional forging, the metal flows more readily and the force required to perform the process is reduced. Isothermal forging is more expensive than conventional forging and is usually reserved for difficult-to-forge metals, such as titanium and

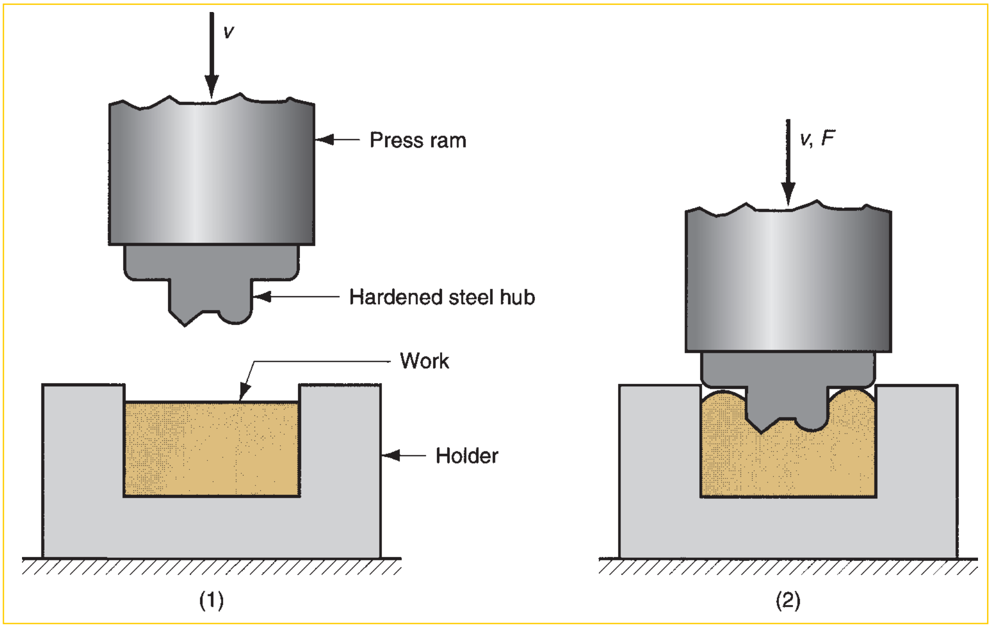


FIGURE 18.28 Hubbing: (1) before deformation, and (2) as the process is completed. Note that the excess material formed by the penetration of the hub must be machined away.

superalloys, and for complex part shapes. The process is sometimes carried out in a vacuum to avoid rapid oxidation of the die material. Similar to isothermal forging is ***hot-die forging***, in which the dies are heated to a temperature that is somewhat below that of the work metal.

Trimming Trimming is an operation used to remove flash on the work part in impression-die forging. In most cases, trimming is accomplished by shearing, as in Figure 18.29, in which a punch forces the work through a cutting die, the blades for which have the profile of the desired part. Trimming is usually done while the work is still hot, which means that a separate trimming press is included at each forging hammer or press. In cases where the work might be damaged by the cutting process, trimming may be done by alternative methods, such as grinding or sawing.

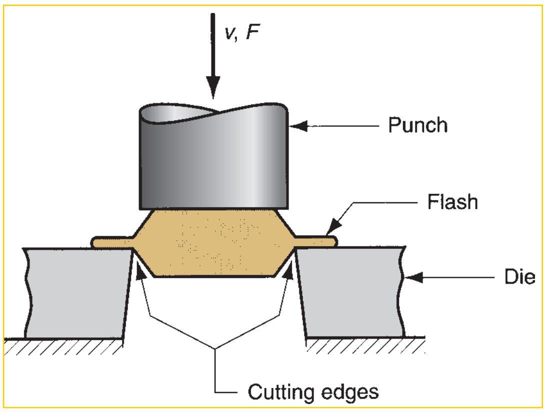


FIGURE 18.29 Trimming operation (shearing process) to remove the flash after impression-die forging.

18.5 Extrusion

Extrusion is a compression process in which the work metal is forced to flow through a die opening to produce a desired cross-sectional shape. The process can be likened to squeezing toothpaste out of a toothpaste tube. Extrusion dates from around 1800 (Historical Note 18.3). There are several advantages of the modern process: (1) a variety of shapes are possible, especially with hot extrusion; (2) grain structure and strength properties are enhanced in cold and warm extrusion; (3) fairly close tolerances are possible, especially in cold extrusion; and (4) in some extrusion operations, little or no wasted material is created. However, a limitation is that the cross section of the extruded part must be uniform throughout its length.

Historical Note 18.3 *Extrusion*

Extrusion as an industrial process was invented around 1800 in England, during the Industrial Revolution when that country was leading the world in technological innovations. The invention consisted of the first hydraulic press for extruding lead pipes. An important step forward was made in Germany around 1890, when the first horizontal extrusion press was built for extruding metals with higher melting points than lead. The feature that made this possible was the use of a dummy block that separated the ram from the work billet.

18.5.1 TYPES OF EXTRUSION

Extrusion is carried out in various ways. One important distinction is between direct extrusion and indirect extrusion. Another classification is by working temperature: cold, warm, or hot extrusion. Finally, extrusion is performed as either a continuous process or a discrete process.

Direct versus Indirect Extrusion Direct extrusion (also called ***forward extrusion***) is illustrated in Figure 18.30. A metal billet is loaded into a container, and a ram compresses the material, forcing it to flow through one or more openings in a die at the opposite end of the container. As the ram approaches the die, a small portion of the billet remains that cannot be forced through the die opening. This extra portion, called the ***butt***, is separated from the product by cutting it just beyond the exit of the die.

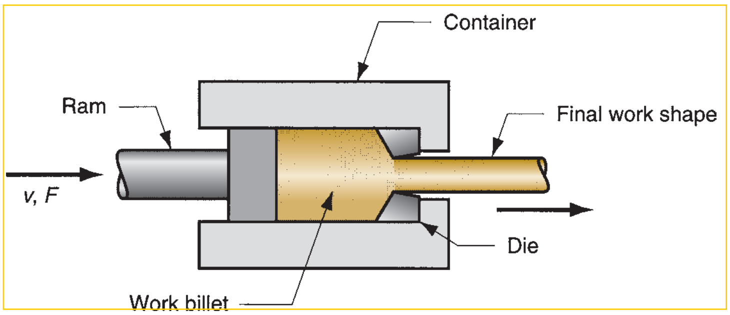


FIGURE 18.30 Direct extrusion.

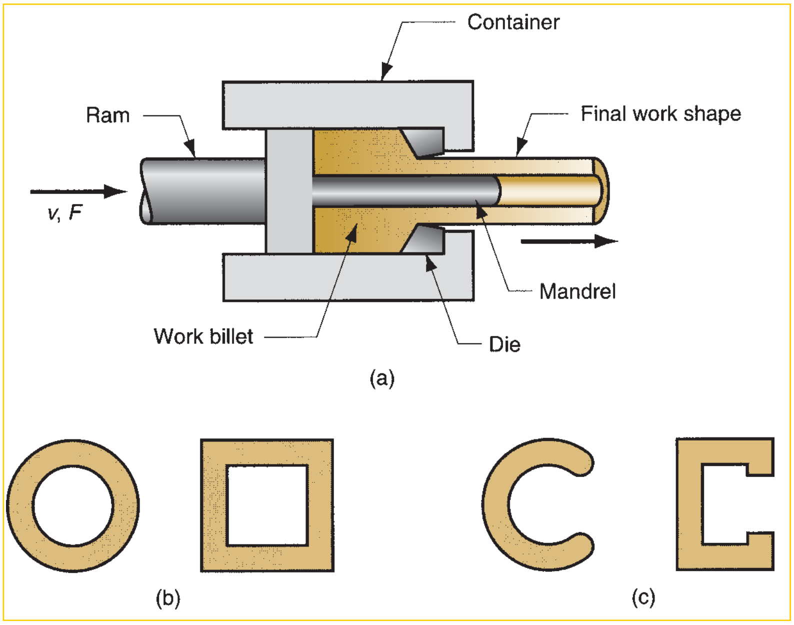


FIGURE 18.31 (a) Direct extrusion to produce a hollow or semi-hollow cross section; (b) hollow and (c) semi-hollow cross sections.

One of the problems in direct extrusion is the significant friction that exists between the work surface and the walls of the container as the billet is forced to slide toward the die opening. This friction causes a substantial increase in the ram force required in direct extrusion. In hot extrusion, the friction problem is aggravated by the presence of an oxide layer on the surface of the billet. This oxide layer can cause defects in the extruded product. To address these problems, a dummy block is often used between the ram and the work billet. The diameter of the dummy block is slightly smaller than the billet diameter, so that a narrow ring of work metal (mostly the oxide layer) is left in the container, leaving the final product free of oxides.

Hollow sections (e.g., tubes) are possible in direct extrusion by the process setup in Figure 18.31. The starting billet is prepared with a hole parallel to its axis. This allows passage of a mandrel that is attached to the dummy block. As the billet is compressed, the material is forced to flow through the clearance between the mandrel and the die opening. The resulting cross section is tubular. Semi-hollow cross-sectional shapes are usually extruded in the same way.

The starting billet in direct extrusion is usually round in cross section, but the final shape is determined by the shape of the die opening. Obviously, the largest dimension of the die opening must be smaller than the diameter of the billet.

In ***indirect extrusion***, also called ***backward extrusion*** and ***reverse extrusion***, Figure 18.32(a), the die is mounted to the ram rather than at the opposite end of the container. As the ram penetrates into the work, the metal is forced to flow through the clearance in a direction opposite to the motion of the ram. Since the billet is not forced to move relative to the container, there is no friction at the container walls, and the ram force is therefore lower than in direct extrusion. Limitations of indirect extrusion are imposed by the lower rigidity of the hollow ram and the difficulty in supporting the extruded product as it exits the die.

Indirect extrusion can produce hollow (tubular) cross sections, as in Figure 18.32(b). In this method, the ram is pressed into the billet, forcing the material to flow around the

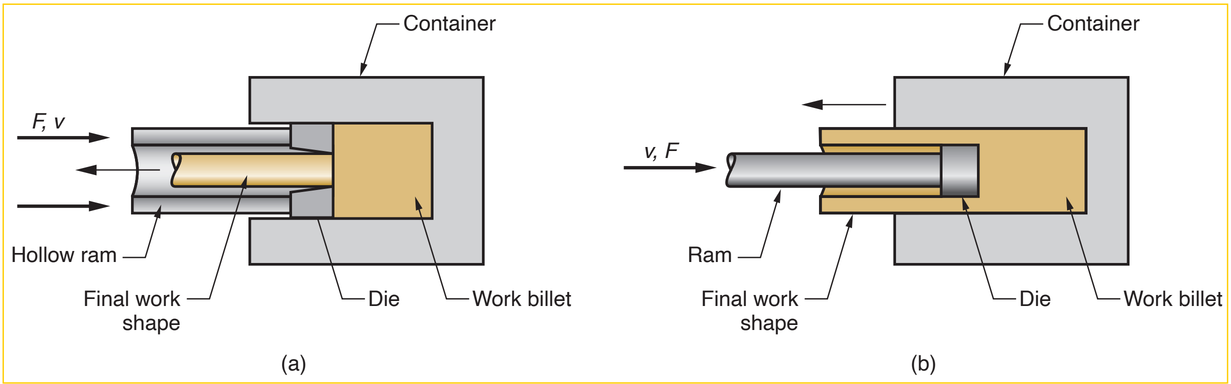


FIGURE 18.32 Indirect extrusion to produce (a) a solid cross section and (b) a hollow cross section.

ram and take a cup shape. There are practical limitations on the length of the extruded part that can be made by this method. Support of the ram becomes a problem as work length increases.

Hot versus Cold Extrusion Extrusion can be performed either hot or cold, depending on work metal and amount of strain to which it is subjected during deformation. Metals that are typically extruded hot include aluminum, copper, magnesium, zinc, tin, and their alloys. These same metals are sometimes extruded cold. Steel alloys are usually extruded hot, although the softer, more ductile grades are sometimes cold extruded (e.g., low carbon steels and stainless steel). Aluminum is probably the most ideal metal for extrusion (hot and cold), and many commercial aluminum products are made by this process (structural shapes, door and window frames, etc.).

Hot extrusion involves prior heating of the billet to a temperature above its recrystallization temperature. This reduces strength and increases ductility of the metal, permitting more extreme size reductions and more complex shapes to be achieved in the process. Additional advantages include reduction of ram force, increased ram speed, and reduction of grain flow characteristics in the final product. Cooling of the billet as it contacts the container walls is a problem, and ***isothermal extrusion*** is sometimes used to overcome this problem. Lubrication is critical in hot extrusion for certain metals (e.g., steels), and special lubricants have been developed that are effective under the harsh conditions in hot extrusion. Glass is sometimes used as a lubricant in hot extrusion; in addition to reducing friction, it also provides effective thermal insulation between the billet and the extrusion container.

Cold extrusion and warm extrusion are generally used to produce discrete parts, often in finished (or near finished) form. The term ***impact extrusion*** is used to indicate high-speed cold extrusion, and this method is described in Section 18.5.4. Some important advantages of cold extrusion include increased strength due to strain hardening, close tolerances, improved surface finish, absence of oxide layers, and high production rates. Cold extrusion at room temperature also eliminates the need for heating the starting billet.

Continuous versus Discrete Processing A true continuous process operates in steady state mode for an indefinite period of time. Some extrusion operations approach this ideal by producing very long sections in one cycle, but these operations are ultimately limited by the size of the starting billet that can be loaded into the extrusion container. These processes are more accurately described as semi-continuous operations. In nearly all cases, the long section is cut into smaller lengths in a subsequent sawing or shearing operation.

In a discrete extrusion operation, a single part is produced in each extrusion cycle. Impact extrusion is an example of the discrete processing case.

18.5.2 ANALYSIS OF EXTRUSION

Reference Figure 18.33 as some of the parameters in extrusion are discussed. The diagram assumes that both billet and extrudate are round in cross section. One important parameter is the ***extrusion ratio***, also called the ***reduction ratio***. The ratio is defined:

$$r_x = \frac{A_o}{A_f} \tag{18.19}$$

where $r_x =$ extrusion ratio; $A_o =$ cross-sectional area of the starting billet, mm^2 (in^2); and $A_f =$ final cross-sectional area of the extruded section, mm^2 (in^2). The ratio applies for both direct and indirect extrusion. The value of r_x can be used to determine true strain in extrusion, given that ideal deformation occurs with no friction and no redundant work:

$$\epsilon = \ln r_x = \ln \frac{A_o}{A_f} \tag{18.20}$$

Under the assumption of ideal deformation (no friction and no redundant work), the pressure applied by the ram to compress the billet through the die opening depicted in the figure can be computed as follows:

$$p = \overline{Y}_f \ln r_x \tag{18.21}$$

where $\overline{Y}_f =$ average flow stress during deformation, MPa (lb/in^2). For convenience, Equation (17.2) is restated from the previous chapter:

$$\overline{Y}_f = \frac{K\epsilon^n}{1 + n}$$

In fact, extrusion is not a frictionless process, and the previous equations grossly underestimate the strain and pressure in an extrusion operation. Friction exists

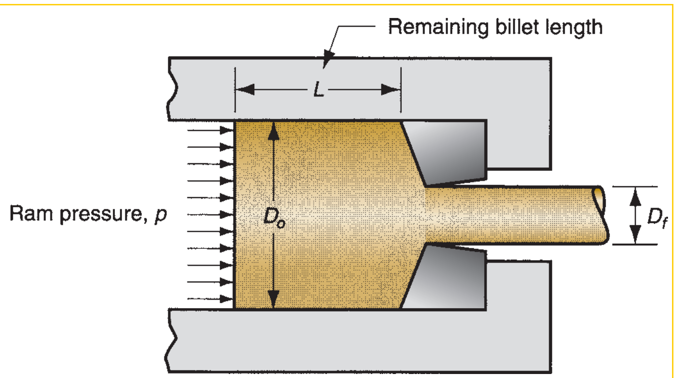


FIGURE 18.33 Pressure and other variables in direct extrusion.

between the die and the work as the billet squeezes down and passes through the die opening. In direct extrusion, friction also exists between the container wall and the billet surface. The effect of friction is to increase the strain experienced by the metal. Thus, the actual pressure is greater than that given by Equation (18.21), which assumes no friction.

Various methods have been suggested to calculate the actual true strain and associated ram pressure in extrusion [1], [3], [6], [11], [12], and [19]. The following empirical equation proposed by Johnson [11] for estimating extrusion strain has gained considerable recognition:

$$\epsilon_x = a + b \ln r_x \tag{18.22}$$

where $\epsilon_x =$ extrusion strain; and a and b are empirical constants for a given die angle. Typical values of these constants are: $a = 0.8$ and $b = 1.2$ to 1.5. Values of a and b tend to increase with increasing die angle.

The ram pressure to perform ***indirect extrusion*** can be estimated based on Johnson's extrusion strain formula as follows:

$$p = \bar{Y}_f \epsilon_x \tag{18.23a}$$

where $\bar{Y}_f$ is calculated based on ideal strain from Equation (18.20), rather than extrusion strain in Equation (18.22).

In ***direct extrusion***, the effect of friction between the container walls and the billet causes the ram pressure to be greater than for indirect extrusion. The following expression isolates the friction force in the direct extrusion container:

$$\frac{p_f \pi D_o^2}{4} = \mu p_c \pi D_o L$$

where $p_f =$ additional pressure required to overcome friction, MPa (lb/in^2); $\pi D_o^2/4 =$ billet cross-sectional area, mm^2 (in^2); $\mu =$ coefficient of friction at the container wall; $p_c =$ pressure of the billet against the container wall, MPa (lb/in^2); and $\pi D_o L =$ area of the interface between billet and container wall, mm^2 (in^2). The right-hand side of this equation indicates the billet-container friction force, and the left-hand side gives the additional ram force to overcome that friction. In the worst case, sticking occurs at the container wall so that friction stress equals shear yield strength of the work metal:

$$\mu p_c \pi D_o L = Y_s \pi D_o L$$

where $Y_s =$ shear yield strength, MPa (lb/in^2). If it is assumed that $Y_s = \bar{Y}_f/2$, then p_f reduces to the following:

$$p_f = \bar{Y}_f \frac{2L}{D_o}$$

Based on this reasoning, the following formula can be used to compute ram pressure in direct extrusion:

$$p = \bar{Y}_f \left(\epsilon_x + \frac{2L}{D_o} \right) \tag{18.23b}$$

where the term $2L/D_o$ accounts for the additional pressure due to friction at the container-billet interface. L is the portion of the billet length remaining to be

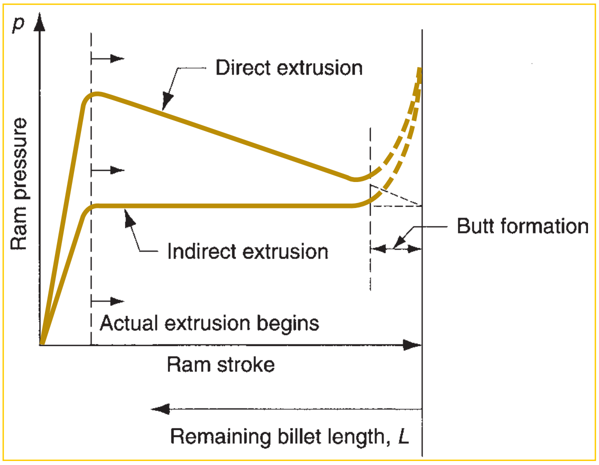


FIGURE 18.34 Typical plots of ram pressure versus ram stroke (and remaining billet length) for direct and indirect extrusion. The higher values in direct extrusion result from friction at the container wall. The shape of the initial pressure buildup at the beginning of the plot depends on die angle (higher die angles cause steeper pressure buildups). The pressure increase at the end of the stroke is related to formation of the butt.

extruded, and D_o is the original diameter of the billet. Note that p is reduced as the remaining billet length decreases during the process. Typical plots of ram pressure as a function of ram stroke for direct and indirect extrusion are presented in Figure 18.34. Equation (18.23b) probably overestimates ram pressure. With good lubrication, ram pressures would be lower than values calculated by this equation.

Ram force in indirect or direct extrusion is simply pressure p from Equations (18.23a) or (18.23b), respectively, multiplied by billet area A_o:

$$F = pA_o \tag{18.24}$$

where F = ram force in extrusion, N (lb). Power required to carry out the extrusion operation is simply

$$P = Fv \tag{18.25}$$

where P = power, J/s (in-lb/min); F = ram force, N (lb); and v = ram velocity, m/s (in/min).

Example 18.3 Extrusion pressures

A billet 75 mm long and 25 mm in diameter is to be extruded in a direct extrusion operation with extrusion ratio $r_x = 4.0$. The extrudate has a round cross section. The die angle (half-angle) = 90°. The work metal has a strength coefficient = 415 MPa, and strain hardening exponent = 0.18. Use the Johnson formula with $a = 0.8$ and $b = 1.5$ to estimate extrusion strain. Determine the pressure applied to the end of the billet as the ram moves forward.

Solution: The ram pressure will be calculated at billet lengths of $L = 75$ mm (starting value), $L = 50$ mm, $L = 25$ mm, and $L = 0$. The ideal true strain, extrusion strain using Johnson's formula, and average flow stress are computed as follows:

$$\epsilon = \ln r_x = \ln 4.0 = 1.3863$$

$$\epsilon_x = 0.8 + 1.5(1.3863) = 2.8795$$

$$\overline{Y}_f = \frac{415(1.3863)^{0.18}}{1.18} = 373 \text{ MPa}$$

$L = 75$ mm: With a die angle of $90°$, the billet metal is assumed to be forced through the die opening almost immediately; thus, the calculation assumes that maximum pressure is reached at the billet length of 75 mm. For die angles less than $90°$, the pressure would build to a maximum as in Figure 18.34 as the starting billet is squeezed into the cone-shaped portion of the extrusion die. Using Equation (18.23b),

$$p = 373\left(2.8795 + 2\frac{75}{25}\right) = \mathbf{3312\ MPa}$$

$$L = 50 \text{ mm}: p = 373\left(2.8795 + 2\frac{50}{25}\right) = \mathbf{2566\ MPa}$$

$$L = 25 \text{ mm}: p = 373\left(2.8795 + 2\frac{25}{25}\right) = \mathbf{1820\ MPa}$$

$L = 0$: Zero length is a hypothetical value in direct extrusion. In reality, it is impossible to squeeze all of the metal through the die opening. Instead, a portion of the billet (the "butt") remains unextruded and the pressure begins to increase rapidly as L approaches zero. This increase in pressure at the end of the stroke is seen in the plot of ram pressure versus ram stroke in Figure 18.34. Calculated below is the hypothetical minimum value of ram pressure that would result at $L = 0$.

$$p = 373\left(2.8795 + 2\frac{0}{25}\right) = \mathbf{1074\ MPa}$$

This is also the value of ram pressure that would be associated with indirect extrusion throughout the length of the billet.

18.5.3 EXTRUSION DIES AND PRESSES

Important factors in an extrusion die are die angle and orifice shape. Die angle, more precisely die half-angle, is shown as α in Figure 18.35(a). For low angles, surface area of the die is large, leading to increased friction at the die-billet interface. Higher friction results in larger ram force. On the other hand, a large die angle causes more turbulence in the metal flow during reduction, increasing the ram force required. Thus, the effect of die angle on ram force is a U-shaped function, as in Figure 18.35(b). An optimum die angle exists, as suggested by the hypothetical plot. The optimum angle depends on various factors (e.g., work material, billet temperature, and lubrication) and is therefore difficult to determine for a given extrusion job. Die designers rely on rules of thumb and judgment to decide the appropriate angle.

The previous equations for ram pressure, Equations (18.23a), apply to a circular die orifice. The shape of the die orifice affects the ram pressure required to perform an extrusion operation. A complex cross section, such as the one shown in Figure 18.36, requires a higher pressure and greater force than a circular shape. The effect of the

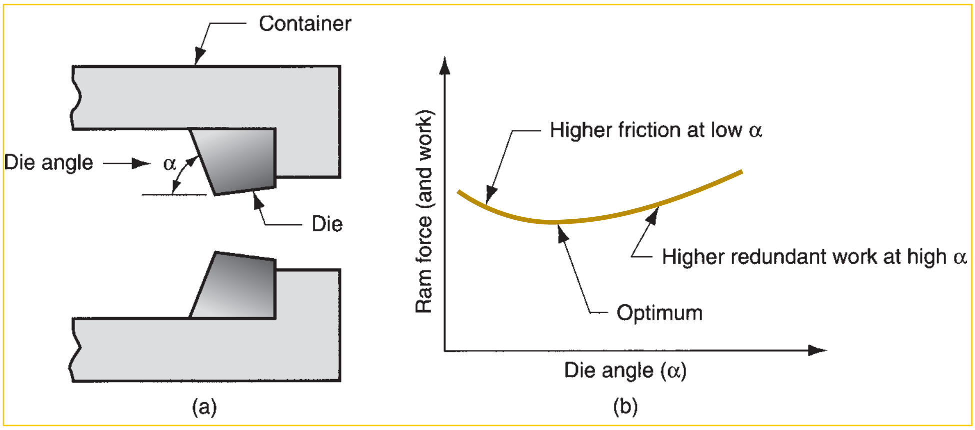


FIGURE 18.35 (a) Definition of die angle in direct extrusion; (b) effect of die angle on ram force.

die orifice shape can be assessed by the die ***shape factor***, defined as the ratio of the pressure required to extrude a cross section of a given shape relative to the extrusion pressure for a round cross section of the same area. The shape factor can be expressed as follows:

$$K_x = 0.98 + 0.02\left(\frac{C_x}{C_c}\right)^{2.25} \tag{18.26}$$

where K_x = die shape factor in extrusion; C_x = perimeter of the extruded cross section, mm (in); and C_c = perimeter of a circle of the same area as the extruded shape,

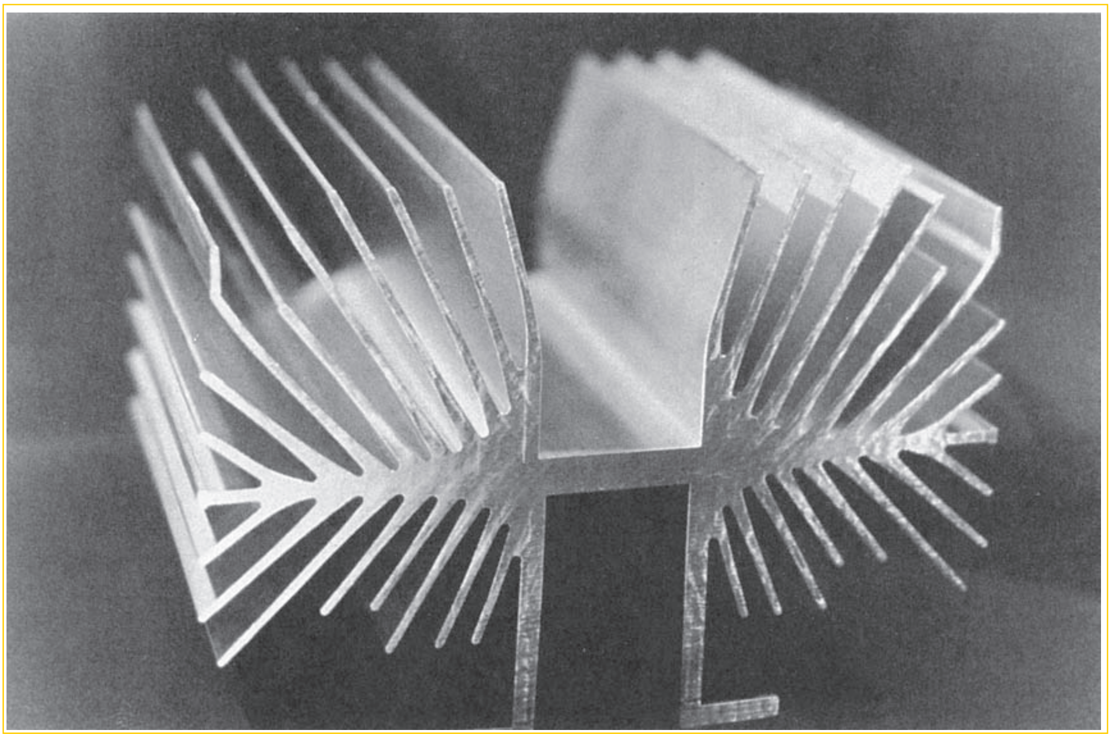


FIGURE 18.36 A complex extruded cross section for a heat sink. (Photo courtesy of Aluminum Company of America.)

mm (in). Equation (18.26) is based on empirical data in Altan et al. [1] over a range of C_x/C_c values from 1.0 to about 6.0. The equation may be invalid much beyond the upper limit of this range.

As indicated by Equation (18.26), the shape factor is a function of the perimeter of the extruded cross section divided by the perimeter of a circular cross section of equal area. A circular shape is the simplest shape, with a value of $K_x = 1.0$. Hollow, thin-walled sections have higher shape factors and are more difficult to extrude. The increase in pressure is not included in the previous pressure equations, Equations (18.23(a) and (b)), which apply only to round cross sections. For shapes other than round, the corresponding expression for indirect extrusion is

$$p = K_x \bar{Y}_f \epsilon_x \tag{18.27a}$$

and for direct extrusion,

$$p = K_x \bar{Y}_f \left(\epsilon_x + \frac{2L}{D_o} \right) \tag{18.27b}$$

where $p =$ extrusion pressure, MPa (lb/in^2); $K_x =$ shape factor; and the other terms have the same interpretation as before. Values of pressure given by these equations can be used in Equation (18.24) to determine ram force.

Die materials used for hot extrusion include tool and alloy steels. Important properties of these die materials include high wear resistance, high hot hardness, and high thermal conductivity to remove heat from the process. Die materials for cold extrusion include tool steels and cemented carbides. Wear resistance and ability to retain shape under high stress are desirable properties. Carbides are used when high production rates, long die life, and good dimensional control are required.

Extrusion presses are either horizontal or vertical, depending on orientation of the work axis. Horizontal types are more common. Extrusion presses are usually hydraulically driven. This drive is especially suited to semi-continuous production of long sections, as in direct extrusion. Mechanical drives are often used for cold extrusion of individual parts, such as in impact extrusion.

18.5.4 OTHER EXTRUSION PROCESSES

Direct and indirect extrusion are the principal methods of extrusion. Various names are given to operations that are special cases of the direct and indirect methods described here. Other extrusion operations are unique. This section examines some of these special forms of extrusion and related processes.

Impact Extrusion Impact extrusion is performed at higher speeds and shorter strokes than conventional extrusion. It is used to make individual components. As the name suggests, the punch impacts the work part rather than simply applying pressure to it. Impacting can be carried out as forward extrusion, backward extrusion, or combinations of these. Some representative examples are shown in Figure 18.37.

Impact extrusion is usually done cold on a variety of metals. Backward impact extrusion is most common. Products made by this process include toothpaste tubes and battery cases. As indicated by these examples, very thin walls are possible on impact extruded parts. The high speed characteristics of impacting permit large reductions and high production rates, making this an important commercial process.

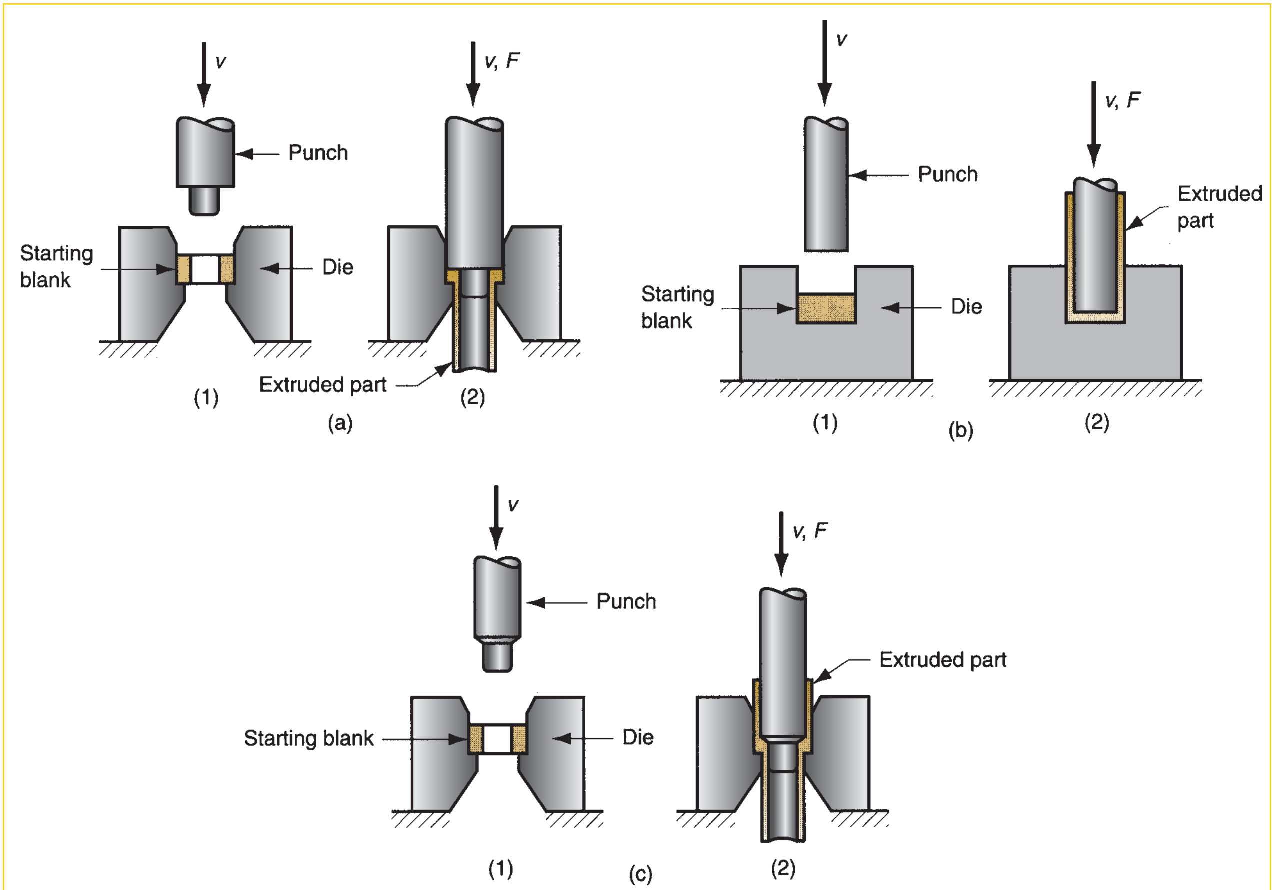


FIGURE 18.37 Several examples of impact extrusion: (a) forward, (b) backward, and (c) combination of forward and backward.

Hydrostatic Extrusion One of the problems in direct extrusion is friction along the billet–container interface. This problem can be addressed by surrounding the billet with fluid inside the container and pressurizing the fluid by the forward motion of the ram, as in Figure 18.38. This way, there is no friction inside the container, and friction at the die opening is reduced. Consequently, ram force is significantly lower than in

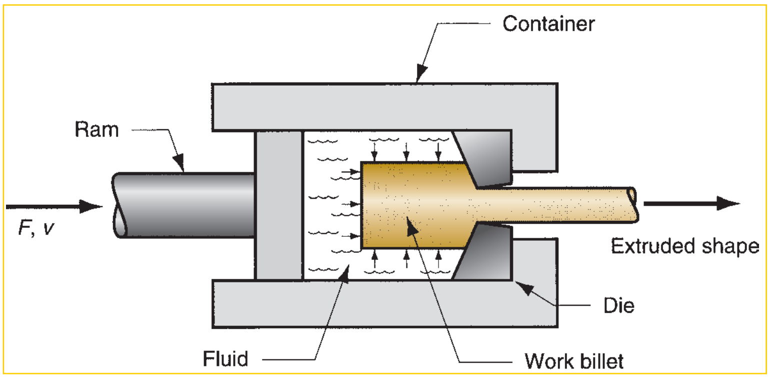


FIGURE 18.38 Hydrostatic extrusion.

direct extrusion. The fluid pressure acting on all surfaces of the billet gives the process its name. It can be carried out at room temperature or at elevated temperatures. Special fluids and procedures must be used at elevated temperatures. Hydrostatic extrusion is an adaptation of direct extrusion.

Hydrostatic pressure on the work increases the material's ductility. Accordingly, this process can be used on metals that would be too brittle for conventional extrusion operations. Ductile metals can also be hydrostatically extruded, and high reduction ratios are possible on these materials. One of the disadvantages of the process is the required preparation of the starting work billet. The billet must be formed with a taper at one end to fit snugly into the die entry angle. This establishes a seal to prevent fluid from squirting out the die hole when the container is initially pressurized.

18.5.5 DEFECTS IN EXTRUDED PRODUCTS

Owing to the considerable deformation associated with extrusion operations, a number of defects can occur in extruded products. The defects can be classified into the following categories, illustrated in Figure 18.39:

(a) ***Centerburst***. This defect is an internal crack that develops as a result of tensile stresses along the centerline of the work part during extrusion. Although tensile stresses may seem unlikely in a compression process such as extrusion, they tend to occur under conditions that cause large deformation in the regions of the work away from the central axis. The significant material movement in these outer regions stretches the material along the center of the work. If stresses are great enough, bursting occurs. Conditions that promote centerburst are high die angles, low extrusion ratios, and impurities in the work metal that serve as starting points for crack defects. The difficult aspect of centerburst is its detection. It is an internal defect that is usually not noticeable by visual observation. Other names sometimes used for this defect include ***arrowhead fracture***, ***center cracking***, and ***chevron cracking***.

(b) ***Piping***. Piping is a defect associated with direct extrusion. As in Figure 18.39(b), it is the formation of a sink hole in the end of the billet. The use of a dummy block whose diameter is slightly less than that of the billet helps to avoid piping. Other names given to this defect include ***tailpipe*** and ***fishtailing***.

(c) ***Surface cracking***. This defect results from high work part temperatures that cause cracks to develop at the surface. They often occur when extrusion speed is too high, leading to high strain rates and associated heat generation. Other factors contributing to surface cracking are high friction and surface chilling of high temperature billets in hot extrusion.

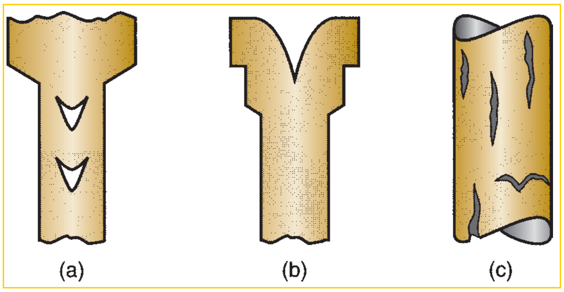


FIGURE 18.39 Some common defects in extrusion: (a) centerburst, (b) piping, and (c) surface cracking.

8.6 Wire and Bar Drawing

In the context of bulk deformation, drawing is an operation in which the cross section of a bar, rod, or wire is reduced by pulling it through a die opening, as in Figure 18.40. The general features of the process are similar to those of extrusion. The difference is that the work is pulled through the die in drawing, whereas it is pushed through the die in extrusion. Although the presence of tensile stresses is obvious in drawing, compression also plays a significant role because the metal is squeezed down as it passes through the die opening. For this reason, the deformation that occurs in drawing is sometimes referred to as indirect compression. Drawing is a term also used in sheet metalworking (Section 19.3). The term ***wire and bar drawing*** is used to distinguish the drawing process discussed here from the sheet metal process of the same name.

The basic difference between bar drawing and wire drawing is the stock size that is processed. ***Bar drawing*** is the term used for large diameter bar and rod stock, while ***wire drawing*** applies to small diameter stock. Wire sizes down to 0.03 mm (0.001 in) are possible in wire drawing. Although the mechanics of the process are the same for the two cases, the methods, equipment, and even the terminology are somewhat different.

Bar drawing is generally accomplished as a ***single-draft*** operation—the stock is pulled through one die opening. Because the beginning stock has a large diameter, it is in the form of a straight cylindrical piece rather than coiled. This limits the length of the work that can be drawn, necessitating a batch type operation. By contrast, wire is drawn from coils consisting of several hundred (or even several thousand) feet of wire and is passed through a series of draw dies. The number of dies varies typically between 4 and 12. The term ***continuous drawing*** is used to describe this type of operation because of the long production runs that are achieved with the wire coils, which can be butt-welded each to the next to make the operation truly continuous.

In a drawing operation, the change in size of the work is usually given by the area reduction, defined as follows:

$$r = \frac{A_o - A_f}{A_o} \tag{18.28}$$

where $r =$ area reduction in drawing; $A_o =$ original area of work, mm^2 (in^2); and $A_f =$ final area, mm^2 (in^2). Area reduction is often expressed as a percentage.

In bar drawing, rod drawing, and in drawing of large diameter wire for upsetting and heading operations, the term draft is used to denote the before and after difference in

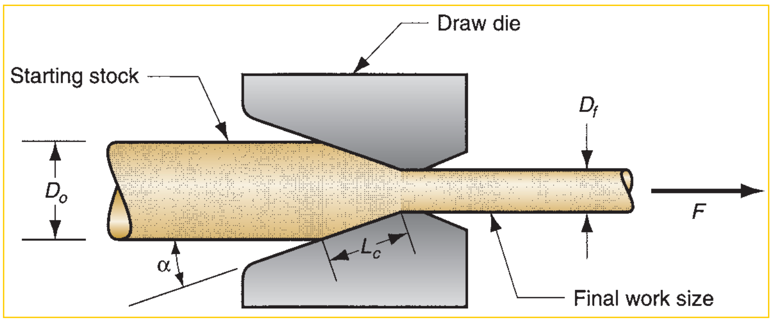


FIGURE 18.40 Drawing of bar, rod, or wire.

size of the processed work. The ***draft*** is simply the difference between original and final stock diameters:

$$d = D_o - D_f \tag{18.29}$$

where d = draft, mm (in); D_o = original diameter of work, mm (in); and D_f = final work diameter, mm (in).

18.6.1 ANALYSIS OF DRAWING

This section considers the mechanics of wire and bar drawing. How are stresses and forces computed in the process? How large a reduction is possible in a drawing operation?

Mechanics of Drawing If no friction or redundant work occurred in drawing, true strain could be determined as follows:

$$\epsilon = \ln \frac{A_o}{A_f} = \ln \frac{1}{1 - r} \tag{18.30}$$

where A_o and A_f are the original and final cross-sectional areas of the work, as previously defined; and r = drawing reduction as given by Equation (18.28). The stress that results from this ideal deformation is given by

$$\sigma = \overline{Y}_f \epsilon = \overline{Y}_f \ln \frac{A_o}{A_f} \tag{18.31}$$

where $\overline{Y}_f = \frac{K \epsilon^n}{1 + n}$ = average flow stress based on the value of strain given by Equation (18.30).

Because friction is present in drawing and the work metal experiences inhomogeneous deformation, the actual stress is larger than provided by Equation (18.31). In addition to the ratio A_o/A_f, other variables that influence draw stress are die angle and coefficient of friction at the work-die interface. A number of methods have been proposed for predicting draw stress based on values of these parameters [1], [3], and [19]. The equation suggested by Schey [19] is the following:

$$\sigma_d = \overline{Y}_f \left(1 + \frac{\mu}{\tan \alpha}\right) \phi \ln \frac{A_o}{A_f} \tag{18.32}$$

where σ_d = draw stress, MPa (lb/in^2); μ = die-work coefficient of friction; α = die angle (half-angle) as defined in Figure 18.40; and ϕ is a factor that accounts for inhomogeneous deformation which is determined as follows for a round cross section:

$$\phi = 0.88 + 0.12 \frac{D}{L_c} \tag{18.33}$$

where D = average diameter of work during drawing, mm (in); and L_c = contact length of the work with the draw die in Figure 18.40, mm (in). Values of D and L_c can be determined from the following:

$$D = \frac{D_o + D_f}{2} \tag{18.34a}$$

$$L_c = \frac{D_o - D_f}{2 \sin \alpha} \tag{18.34b}$$

The corresponding draw force is then the area of the drawn cross section multiplied by the draw stress:

$$F = A_f \sigma_d = A_f \bar{Y}_f \left(1 + \frac{\mu}{\tan \alpha}\right) \phi \ln \frac{A_o}{A_f} \tag{18.35}$$

where $F =$ draw force, N (lb); and the other terms are defined above. The power required in a drawing operation is the draw force multiplied by exit velocity of the work.

Example 18.4 Stress and force in wire drawing

Wire is drawn through a draw die with entrance angle $= 15°$. Starting diameter is 2.5 mm and final diameter $= 2.0$ mm. The coefficient of friction at the work-die interface $= 0.07$. The metal has a strength coefficient $K = 205$ MPa and a strain hardening exponent $n = 0.20$. Determine the draw stress and draw force in this operation.

Solution: The values of D and L_c for Equation (18.33) can be determined using Equations (18.34). $D = 2.25$ mm and $L_c = 0.966$ mm. Thus,

$$\phi = 0.88 + 0.12 \frac{2.25}{0.966} = 1.16$$

The areas before and after drawing are computed as $A_o = 4.91$ mm^2 and $A_f = 3.14$ mm^2. The resulting true strain $\epsilon = \ln(4.91/3.14) = 0.446$, and the average flow stress in the operation is computed:

$$\bar{Y}_f = \frac{205(0.446)^{0.20}}{1.20} = 145.4 \text{ MPa}$$

Draw stress is given by Equation (18.32):

$$\sigma_d = (145.4)\left(1 + \frac{0.07}{\tan 15}\right)(1.16)(0.446) = \mathbf{94.1\ MPa}$$

Finally, the draw force is this stress multiplied by the cross-sectional area of the exiting wire:

$$F = 94.1(3.14) = \mathbf{295.5\ N}$$

Maximum Reduction per Pass A question that may occur to the reader is: Why is more than one step required to achieve the desired reduction in wire drawing? Why not take the entire reduction in a single pass through one die, as in extrusion? The answer can be explained as follows. From the preceding equations, it is clear that as the reduction increases, draw stress increases. If the reduction is large enough, draw stress will exceed the yield strength of the exiting metal. When that happens, the drawn wire will simply elongate instead of new material being squeezed through the die opening. For wire drawing to be successful, maximum draw stress must be less than the yield strength of the exiting metal.

It is a straightforward matter to determine this maximum draw stress and the resulting maximum possible reduction that can be made in one pass, under certain assumptions. Assume a perfectly plastic metal ($n = 0$), no friction, and no redundant work. In this ideal case, the maximum possible draw stress is equal to the yield strength of the work material. Expressing this using the equation for draw stress under conditions of ideal deformation, Equation (18.31), and setting $\bar{Y}_f = Y$ (because $n = 0$),

$$\sigma_d = \bar{Y}_f \ln \frac{A_o}{A_f} = Y \ln \frac{A_o}{A_f} = Y \ln \frac{1}{1-r} = Y$$

This means that $\ln(A_o/A_f) = \ln(1/(1-r)) = 1$. That is, $\epsilon_{max} = 1.0$. In order for ϵ_{max} to be zero, then $A_o/A_f = 1/(1-r)$ must equal the natural logarithm base e. Accordingly, the maximum possible area ratio is

$$\frac{A_o}{A_f} = e = 2.7183 \tag{18.36}$$

and the maximum possible reduction is

$$r_{max} = \frac{e-1}{e} = 0.632 \tag{18.37}$$

The value given by Equation (18.37) is often used as the theoretical maximum reduction possible in a single draw, even though it ignores (1) the effects of friction and redundant work, which would reduce the maximum possible value, and (2) strain hardening, which would increase the maximum possible reduction because the exiting wire would be stronger than the starting metal. In practice, draw reductions per pass are quite below the theoretical limit. Reductions of 0.50 for single-draft bar drawing and 0.30 for multiple-draft wire drawing seem to be the upper limits in industrial operations.

18.6.2 DRAWING PRACTICE

Drawing is usually performed as a cold-working operation. It is most frequently used to produce round cross sections, but squares and other shapes are also drawn. Wire drawing is an important industrial process, providing commercial products such as electrical wire and cable; wire stock for fences, coat hangers, and shopping carts; and rod stock to produce nails, screws, rivets, springs, and other hardware items. Bar drawing is used to produce metal bars for machining, forging, and other processes.

Advantages of drawing in these applications include (1) close dimensional control, (2) good surface finish, (3) improved mechanical properties such as strength and hardness, and (4) adaptability to economical batch or mass production. Drawing speeds are as high as 50 m/s (10,000 ft/min) for very fine wire. In the case of bar drawing to provide stock for machining, the operation improves the machinability of the bar (Section 23.1).

Drawing Equipment Bar drawing is accomplished on a machine called a ***draw bench***, consisting of an entry table, die stand (which contains the draw die), carriage, and exit rack. The arrangement is shown in Figure 18.41. The carriage is used to pull the stock through the draw die. It is powered by hydraulic cylinders or motor-driven chains. The die stand is often designed to hold more than one die, so that several bars can be pulled simultaneously through their respective dies.

Wire drawing is done on continuous drawing machines that consist of multiple draw dies, separated by accumulating drums between the dies, as in Figure 18.42. Each drum, called a ***capstan***, is motor-driven to provide the proper pull force to

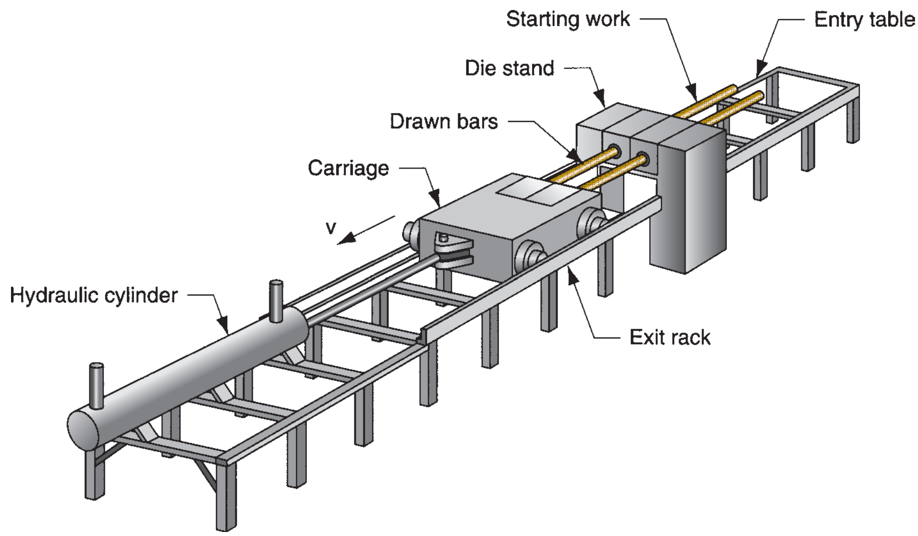


FIGURE 18.41 Hydraulically operated draw bench for drawing metal bars.

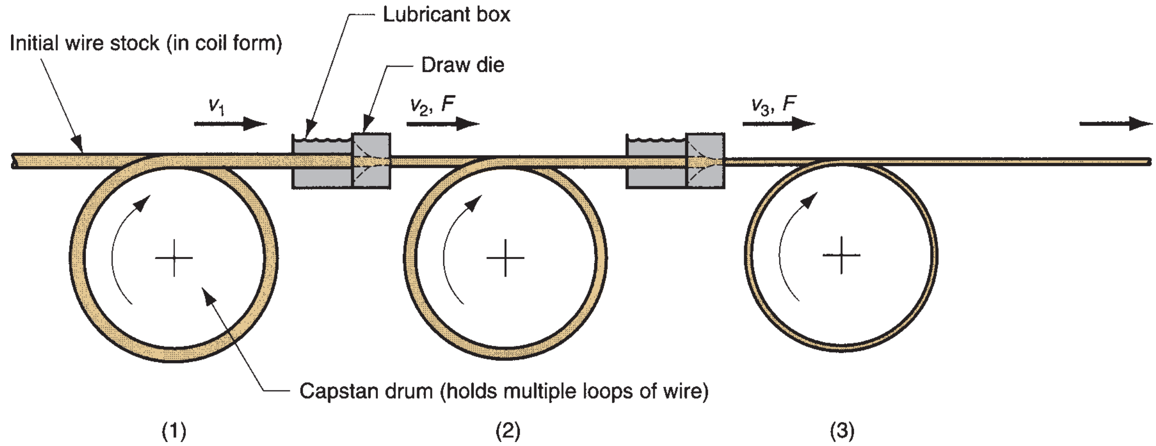


FIGURE 18.42 Continuous drawing of wire.

draw the wire stock through the upstream die. It also maintains a modest tension on the wire as it proceeds to the next draw die in the series. Each die provides a certain amount of reduction in the wire, so that the desired total reduction is achieved by the series. Depending on the metal to be processed and the total reduction, annealing of the wire is sometimes required between groups of dies in the series.

Draw Dies Figure 18.43 identifies the features of a typical draw die. Four regions of the die can be distinguished: (1) entry, (2) approach angle, (3) bearing surface (land), and (4) back relief. The ***entry*** region is usually a bell-shaped mouth that does not contact the work. Its purpose is to funnel the lubricant into the die and prevent scoring of work and die surfaces. The ***approach*** is where the drawing process occurs. It is cone-shaped with an angle (half-angle) normally ranging from about 6° to 20°. The proper angle varies according to work material. The ***bearing surface***, or ***land***, determines the size of the final drawn stock. Finally, the ***back relief*** is the exit zone.

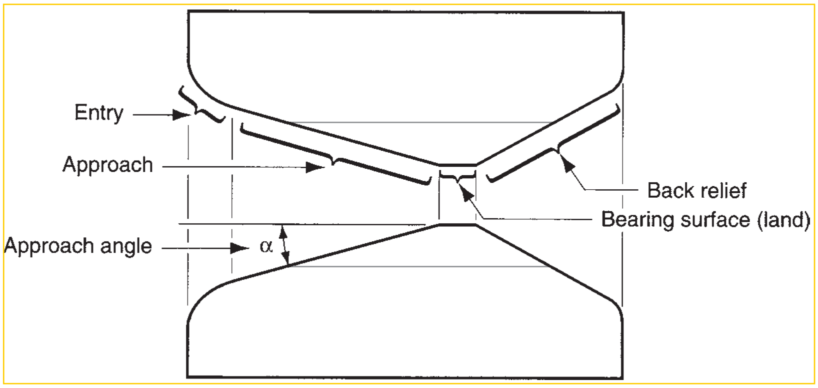


FIGURE 18.43 Draw die for drawing of round rod or wire.

It is provided with a back relief angle (half-angle) of about 30°. Draw dies are made of tool steels or cemented carbides. Dies for high-speed wire drawing operations frequently use inserts made of diamond (both synthetic and natural) for the wear surfaces.

Preparation of the Work Prior to drawing, the beginning stock must be properly prepared. This involves three steps: (1) annealing, (2) cleaning, and (3) pointing. The purpose of annealing is to increase the ductility of the stock to accept deformation during drawing. As previously mentioned, annealing is sometimes needed between steps in continuous drawing. Cleaning of the stock is required to prevent damage of the work surface and draw die. It involves removal of surface contaminants (e.g., scale and rust) by means of chemical pickling or shot blasting. In some cases, prelubrication of the work surface is accomplished subsequent to cleaning.

Pointing involves the reduction in diameter of the starting end of the stock so that it can be inserted through the draw die to start the process. This is usually accomplished by swaging, rolling, or turning. The pointed end of the stock is then gripped by the carriage jaws or other device to initiate the drawing process.

18.6.3 TUBE DRAWING

Drawing can be used to reduce the diameter or wall thickness of seamless tubes and pipes, after the initial tubing has been produced by some other process such as extrusion. Tube drawing can be carried out either with or without a mandrel. The simplest method uses no mandrel and is used for diameter reduction, as in Figure 18.44. The term ***tube sinking*** is sometimes applied to this operation.

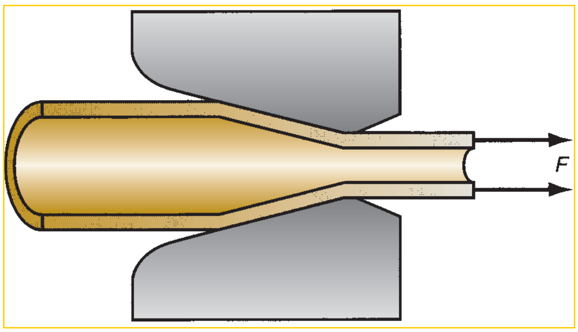


FIGURE 18.44 Tube drawing with no mandrel (tube sinking).

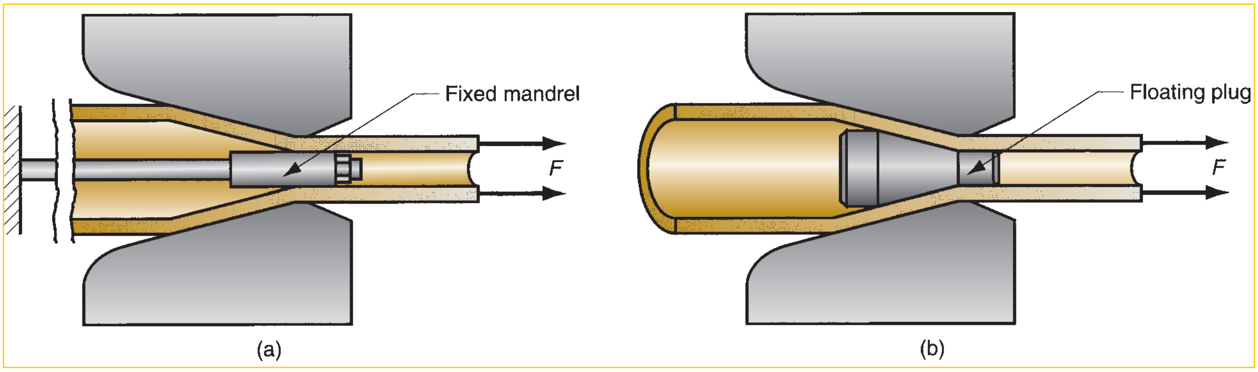


FIGURE 18.45 Tube drawing with mandrels: (a) fixed mandrel, (b) floating plug.

The problem with tube drawing in which no mandrel is used, as in Figure 18.44, is that it lacks control over the inside diameter and wall thickness of the tube. This is why mandrels of various types are used, two of which are illustrated in Figure 18.45. The first, Figure 18.45(a), uses a ***fixed mandrel*** attached to a long support bar to establish inside diameter and wall thickness during the operation. Practical limitations on the length of the support bar in this method restrict the length of the tube that can be drawn. The second type, shown in (b), uses a ***floating plug*** whose shape is designed so that it finds a "natural" position in the reduction zone of the die. This method removes the limitations on work length present with the fixed mandrel.

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