# CHAPTER 34

# METAL FORMING, SHAPING, AND CASTING

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## 34.1 INTRODUCTION

Metal-forming processes use a remarkable property of metals—their ability to flow plastically in the solid state without concurrent deterioration of properties. Moreover, by simply moving the metal to the desired shape, there is little or no waste. Figure 34.1 shows some of the metal-forming processes. Metal-forming processes are classified into two categories: hot-working processes and cold-working processes.

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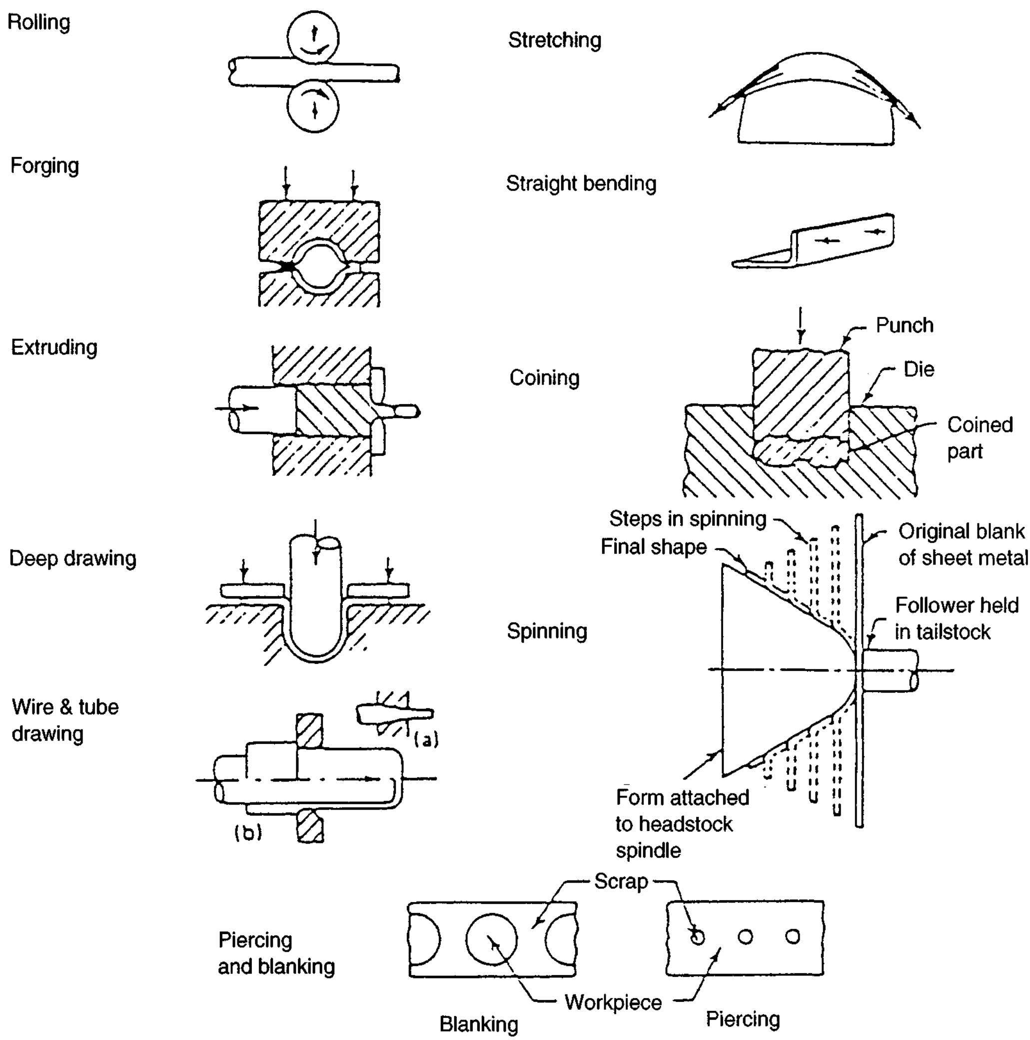


**Fig. 34.1** Metal-forming processes.

## 34.2 HOT-WORKING PROCESSES

Hot working is defined as the plastic deformation of metals above their recrystallization temperature. Here it is important to note that the crystallization temperature varies greatly with different materials. Lead and tin are hot worked at room temperature, while steels require temperatures of 2000°F (1100°C). Hot working does not necessarily imply high absolute temperatures.

Hot working can produce the following improvements:

1. Production of randomly oriented, spherical-shaped grain structure, which results in a net increase not only in the strength but also in ductility and toughness.
2. The reorientation of inclusions or impurity material in metal. The impurity material often distorts and flows along with the metal.

This material, however, does not recrystallize with the base metal and often produces a fiber structure. Such a structure clearly has directional properties, being stronger in one direction than in another. Moreover, an impurity originally oriented so as to aid crack movement through the metal is often reoriented into a "crack-arrestor" configuration perpendicular to crack propagation.

### 34.2.1 Classification of Hot-Working Processes

The most obvious reason for the popularity of hot working is that it provides an attractive means of forming a desired shape. Some of the hot-working processes that are of major importance in modern manufacturing are

1. Rolling
2. Forging
3. Extrusion and upsetting
4. Drawing
5. Spinning
6. Pipe welding
7. Piercing

### 34.2.2 Rolling

Hot rolling (Fig. 34.2) consists of passing heated metal between two rolls that revolve in opposite directions, the space between the rolls being somewhat less than the thickness of the entering metal. Many finished parts, such as hot-rolled structural shapes, are completed entirely by hot rolling. More often, however, hot-rolled products, such as sheets, plates, bars, and strips, serve as input material for other processes, such as cold forming or machining.

In hot rolling, as in all hot working, it is very important that the metal be heated uniformly throughout to the proper temperature, a procedure known as *soaking*. If the temperature is not uniform, the subsequent deformation will also be nonuniform, the hotter exterior flowing in preference to the cooler and, therefore, stronger, interior. Cracking, tearing, and associated problems may result.

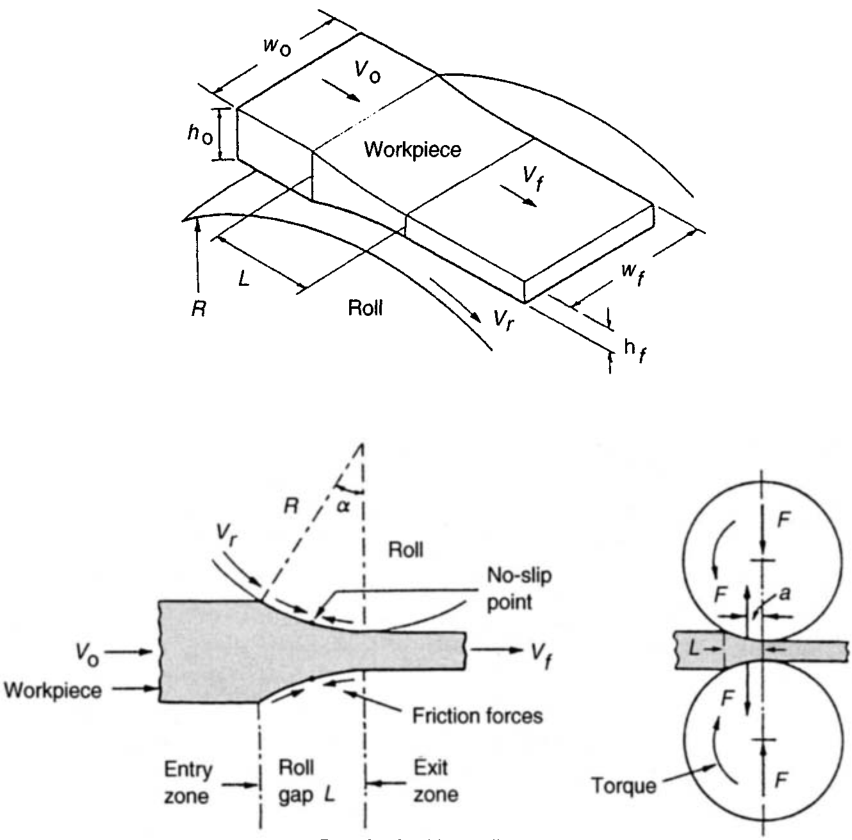


**Fig. 34.2** Hot rolling.

### Isothermal Rolling

The ordinary rolling of some high-strength metals, such as titanium and stainless steels, particularly in thicknesses below about 0.150 in. (3.8 mm), is difficult because the heat in the sheet is transferred rapidly to the cold and much more massive rolls. This has been overcome by isothermal rolling. Localized heating is accomplished in the area of deformation by the passage of a large electrical current between the rolls, through the sheet. Reductions up to 90% per roll have been achieved. The process usually is restricted to widths below 2 in. (50 mm).

The rolling strip contact length is given by

$$L \simeq \sqrt{R(h_0 - h)}$$

where $R$ = roll radius
$h_0$ = original strip thickness
$h$ = reduced thickness

The roll-force $F$ is calculated by

$$F = LwY_{avg} \tag{34.1}$$

where $w$ = width
$Y_{avg}$ = average true stress

Figure 34.3 gives the true stress for different material at the true stress $\epsilon$. The true stress $\epsilon$ is given by

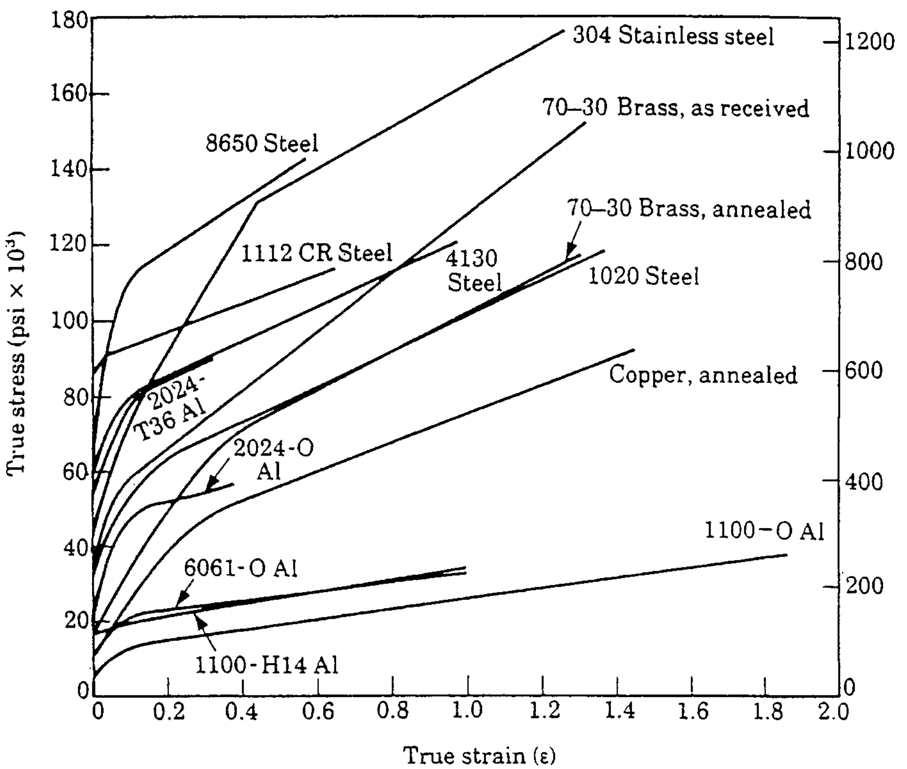


**Fig. 34.3** True stress–true strain curves.

$$\epsilon = \ln\left(\frac{h_o}{h}\right)$$

$$\text{power/roll} = \frac{2\pi FLN}{60{,}000} \quad \text{kW} \tag{34.2}$$

where $F$ = newtons
$L$ = meters
$N$ = rev per min

or

$$\text{power} = \frac{2\pi FLN}{33{,}000} \quad \text{hp} \tag{34.3}$$

where $F$ = lb
$L$ = ft

### 34.2.3 Forging

Forging is the plastic working of metal by means of localized compressive forces exerted by manual or power hammers, presses, or special forging machines.

Various types of forging have been developed to provide great flexibility, making it economically possible to forge a single piece or to mass produce thousands of identical parts. The metal may be

1. Drawn out, increasing its length and decreasing its cross section
2. Upset, increasing the cross section and decreasing the length, or
3. Squeezed in closed impression dies to produce multidirectional flow

The state of stress in the work is primarily uniaxial or multiaxial compression.

The common forging processes are

1. Open-die hammer
2. Impression-die drop forging
3. Press forging
4. Upset forging
5. Roll forging
6. Swaging

#### Open-Die Hammer Forging

Open-die forging, (Fig. 34.4) does not confine the flow of metal, the hammer and anvil often being completely flat. The desired shape is obtained by manipulating the workpiece between blows. Specially shaped tools or a slightly shaped die between the workpiece and the hammer or anvil are used to aid in shaping sections (round, concave, or convex), making holes, or performing cutoff operations.

The force $F$ required for an open-die forging operation on a solid cylindrical piece can be calculated by

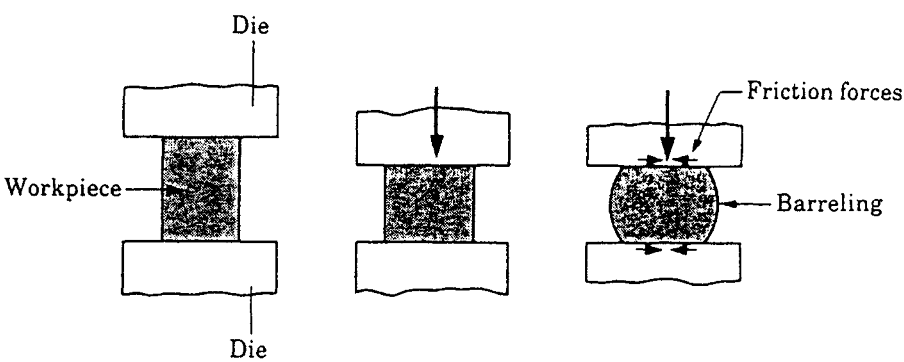


**Fig. 34.4** Open-die hammer forging.

$$F = Y_f \pi r^2 \left(1 + \frac{2\mu r}{3h}\right) \tag{34.4}$$

where $Y_f$ = flow stress at the specific $\epsilon$ [$\epsilon = \ln(h_0/h)$]
$\mu$ = coefficient of friction
$r$ and $h$ = radius and height of workpiece

### Impression-Die Drop Forging

In impression-die or closed-die drop forging (Fig. 34.5), the heated metal is placed in the lower cavity of the die and struck one or more blows with the upper die. This hammering causes the metal to flow so as to fill the die cavity. Excess metal is squeezed out between the die faces along the periphery of the cavity to form a flash. When forging is completed, the flash is trimmed off by means of a trimming die.

The forging force $F$ required for impression-die forging can be estimated by

$$F = KY_fA \tag{34.5}$$

where $K$ = multiplying factor (4–12) depending on the complexity of the shape
$Y_f$ = flow stress at forging temperature
$A$ = projected area, including flash

### Press Forging

Press forging employs a slow-squeezing action that penetrates throughout the metal and produces a uniform metal flow. In hammer or impact forging, metal flow is a response to the energy in the hammer–workpiece collision. If all the energy can be dissipated through flow of the surface layers of metal and absorption by the press foundation, the interior regions of the workpiece can go undeformed. Therefore, when the forging of large sections is required, press forging must be employed.

### Upset Forging

Upset forging involves increasing the diameter of the end or central portion of a bar of metal by compressing its length. Upset-forging machines are used to forge heads on bolts and other fasteners, valves, couplings, and many other small components.

### Roll Forging

Roll forging, in which round or flat bar stock is reduced in thickness and increased in length, is used to produce such components as axles, tapered levers, and leaf springs.

### Swaging

Swaging involves hammering or forcing a tube or rod into a confining die to reduce its diameter, the die often playing the role of the hammer. Repeated blows cause the metal to flow inward and take the internal form of the die.

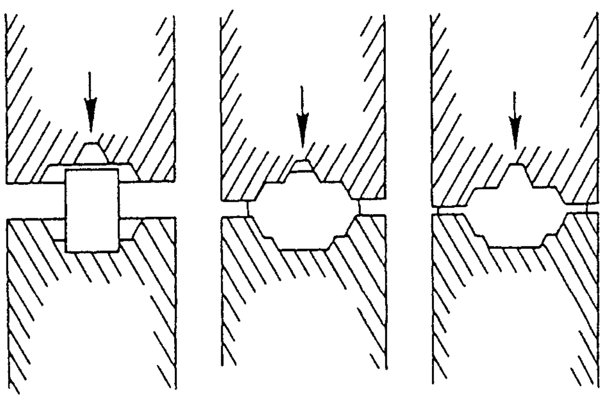

**Fig. 34.5** Impression-die drop forging.

### 34.2.4 Extrusion

In the extrusion process (Fig. 34.6), metal is compressively forced to flow through a suitably shaped die to form a product with reduced cross section. Although it may be performed either hot or cold, hot extrusion is employed for many metals to reduce the forces required, to eliminate cold-working effects, and to reduce directional properties. The stress state within the material is triaxial compression.

Lead, copper, aluminum, and magnesium, and alloys of these metals, are commonly extruded, taking advantage of the relatively low yield strengths and extrusion temperatures. Steel is more difficult to extrude. Yield strengths are high and the metal has a tendency to weld to the walls of the die and confining chamber under the conditions of high temperature and pressures. With the development and use of phosphate-based and molten glass lubricants, substantial quantities of hot steel extrusions are now produced. These lubricants adhere to the billet and prevent metal-to-metal contact throughout the process.

Almost any cross-section shape can be extruded from the nonferrous metals. Hollow shapes can be extruded by several methods. For tubular products, the stationary or moving mandrel process is often employed. For more complex internal cavities, a spider mandrel or torpedo die is used. Obviously, the cost for hollow extrusions is considerably greater than for solid ones, but a wide variety of shapes can be produced that cannot be made by any other process.

The extrusion force $F$ can be estimated from the formula

$$F = A_0 k \ln \left(\frac{A_0}{A}\right) \tag{34.6}$$

where $k$ = extrusion constant depends on material and temperature (see Fig. 34.7)
$A_0$ = billet area
$A_f$ = finished extruded area

### 34.2.5 Drawing

Drawing (Fig. 34.8) is a process for forming sheet metal between an edge-opposing punch and a die (draw ring) to produce a cup, cone, box, or shell-like part. The work metal is bent over and wrapped around the punch nose. At the same time, the outer portions of the blank move rapidly toward the center of the blank until they flow over the die radius as the blank is drawn into the die cavity by the punch. The radial movement of the metal increases the blank thickness as the metal moves toward the die radius; as the metal flows over the die radius, this thickness decreases because of the tension in the shell wall between the punch nose and the die radius and (in some instances) because of the clearance between the punch and the die.

The force (load) required for drawing a round cup is expressed by the following empirical equation:

$$L = \pi dtS \left(\frac{D}{d} - k\right) \tag{34.7}$$

where $L$ = press load, lbs
$d$ = cup diameter, in.

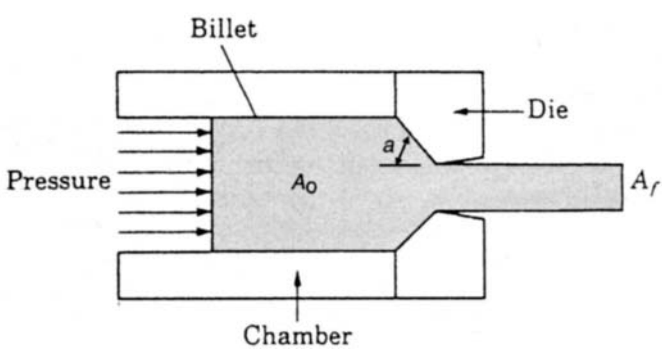

Fig. 34.6 Extrusion process.

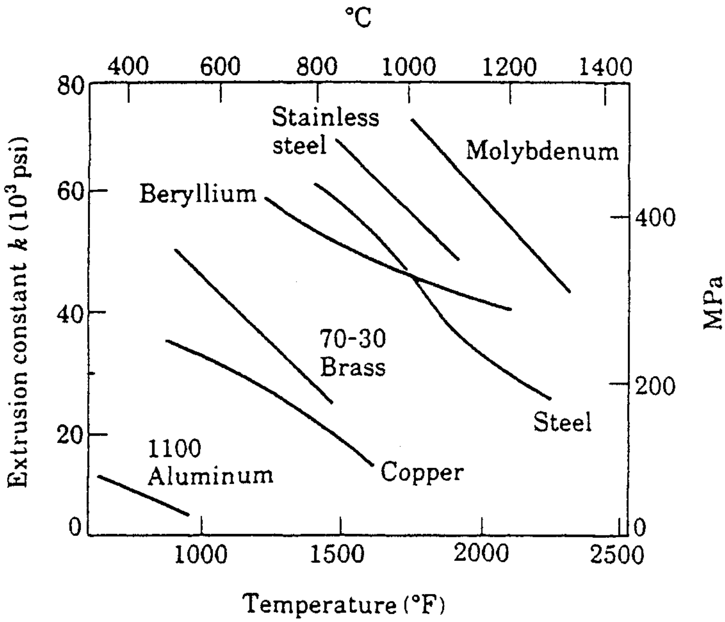


**Fig. 34.7** Extrusion constant *k*.

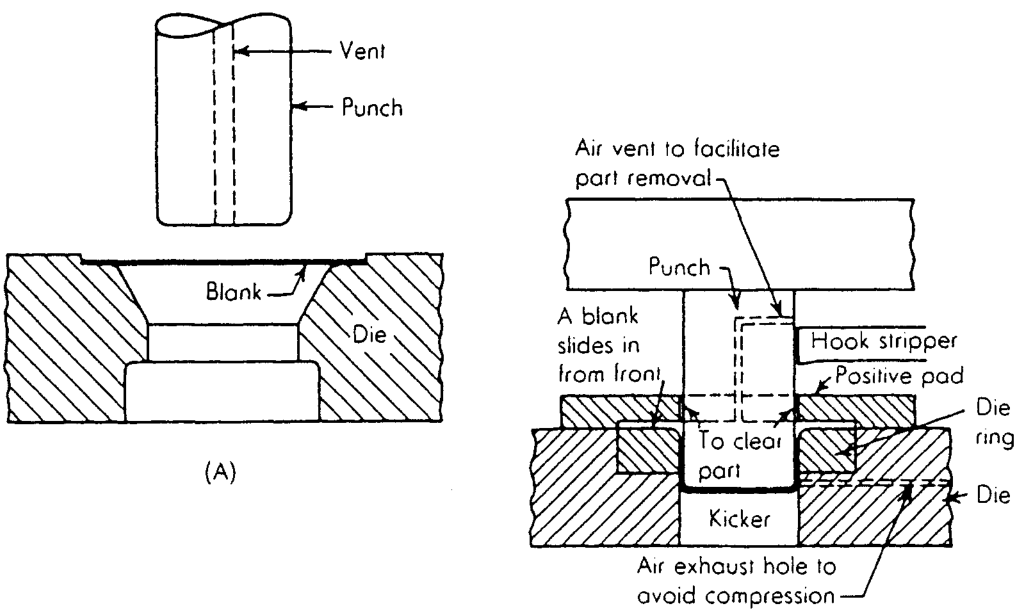


**Fig. 34.8** Drawing process.

$D$ = blank diameter, in.
$t$ = work-metal thickness, in.
$S$ = tensile strength, lbs/in.$^2$
$k$ = a constant that takes into account frictional and bending forces, usually 0.6–0.7

The force (load) required for drawing a rectangular cup can be calculated from the following equation:

$$L = tS(2\pi R k_A + l k_B) \tag{34.8}$$

where $L$ = press load, lbs
$t$ = work-metal thickness, in.
$S$ = tensile strength, lbs/in.$^2$
$R$ = corner radius of the cup, in.
$l$ = the sum of the lengths of straight sections of the sides, in.
$k_A$ and $k_B$ = constants

Values for $k_A$ range from 0.5 (for a shallow cup) to 2.0 (for a cup of depth five to six times the corner radius). Values for $k_B$ range from 0.2 (for easy draw radius, ample clearance, and no blank-holding force) and 0.3 (for similar free flow and normal blankholding force of about $L/3$) to a maximum of 1.0 (for metal clamped too tightly to flow).

Figure 34.9 can be used as a general guide for computing maximum drawing load for a round shell. These relations are based on a free draw with sufficient clearance so that there is no ironing, using a maximum reduction of 50%. The nomograph gives the load required to fracture the cup (1 ton = 8.9 KN).

### Blank Diameters

The following equations may be used to calculate the blank size for cylindrical shells of relatively thin metal. The ratio of the shell diameter to the corner radius ($d/r$) can affect the blank diameter and should be taken into consideration. When $d/r$ is 20 or more,

$$D = \sqrt{d^2 + 4dh} \tag{34.9}$$

When $d/r$ is between 15 and 20,

$$D = \sqrt{d^2 + 4dh - 0.5r} \tag{34.10}$$

When $d/r$ is between 10 and 15,

$$D = \sqrt{d^2 + 4dh - r} \tag{34.11}$$

When $d/r$ is below 10,

$$D = \sqrt{(d - 2r)^2 + 4d(h - r) + 2\pi r(d - 0.7r)} \tag{34.12}$$

where $D$ = blank diameter
$d$ = shell diameter
$h$ = shell height
$r$ = corner radius

The above equations are based on the assumption that the surface area of the blank is equal to the surface area of the finished shell.

In cases where the shell wall is to be ironed thinner than the shell bottom, the volume of metal in the blank must equal the volume of the metal in the finished shell. Where the wall-thickness reduction is considerable, as in brass shell cases, the final blank size is developed by trial. A tentative blank size for an ironed shell can be obtained from the equation

$$D = \sqrt{d^2 + 4dh \frac{t}{T}} \tag{34.13}$$

where $t$ = wall thickness
$T$ = bottom thickness

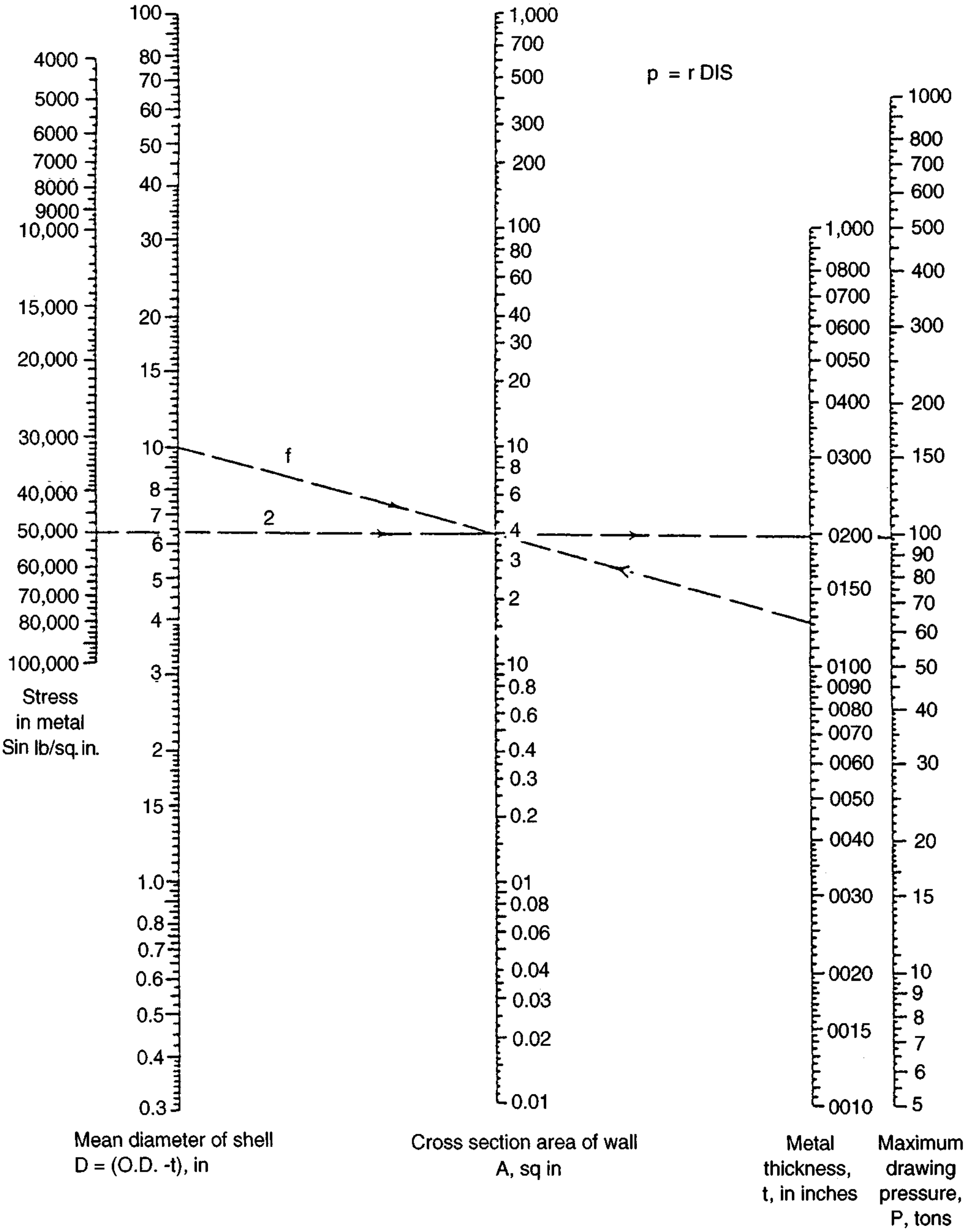


**Fig. 34.9** Nomograph for estimating drawing pressures.

### 34.2.6 Spinning

Spinning is a method of forming sheet metal or tubing into seamless hollow cylinders, cones, hemispheres, or other circular shapes by a combination of rotation and force. On the basis of techniques used, applications, and results obtainable, the method may be divided into two categories: *manual spinning* (with or without mechanical assistance to increase the force) and *power spinning.*

Manual spinning entails no appreciable thinning of metal. The operation ordinarily done in a lathe consists of pressing a tool against a circular metal blank that is rotated by the headstock.

Power spinning is also known as *shear spinning* because in this method metal is intentionally thinned, by shear forces. In power spinning, forces as great as 400 tons are used.

The application of shear spinning to conical shapes is shown schematically in Fig. 34.10. The metal deformation is such that forming is in accordance with the sine law, which states that the wall thickness of the starting blank and that of the finished workpiece are related as

$$t_2 = t_1 (\sin \alpha) \tag{34.14}$$

where $t_1$ = the thickness of the starting blank
$t_2$ = the thickness of the spun workpiece
$\alpha$ = one-half the apex angle of the cone

### Tube Spinning

Tube spinning is a rotary-point method of extruding metal, much like cone spinning, except that the sine law does not apply. Because the half-angle of a cylinder is zero, tube spinning follows a purely volumetric rule, depending on the practical limits of deformation that the metal can stand without intermediate annealing.

## 34.2.7 Pipe Welding

Large quantities of small-diameter steel pipe are produced by two processes that involve hot forming of metal strip and welding of its edges through utilization of the heat contained in the metal. Both of these processes, *butt welding* and *lap welding* of pipe, utilize steel in the form of skelp—long and narrow strips of the desired thickness. Because the skelp has been previously hot rolled and the welding process produces further compressive working and recrystallization, pipe welding by these processes is uniform in quality.

In the butt-welded pipe process, the skelp is unwound from a continuous coil and is heated to forging temperatures as it passes through a furnace. Upon leaving the furnace, it is pulled through forming rolls that shape it into a cylinder. The pressure exerted between the edges of the skelp as it passes through the rolls is sufficient to upset the metal and weld the edges together. Additional sets of rollers size and shape the pipe. Normal pipe diameters range from ⅛–3 in. (3–75 mm).

The lap-welding process for making pipe differs from butt welding in that the skelp has beveled edges and a mandrel is used in conjunction with a set of rollers to make the weld. The process is used primarily for larger sizes of pipe, from about 2–14 in. (50–400 mm) in diameter.

## 34.2.8 Piercing

Thick-walled and seamless tubing is made by the piercing process. A heated, round billet, with its leading end center-punched, is pushed longitudinally between two large, convex-tapered rolls that

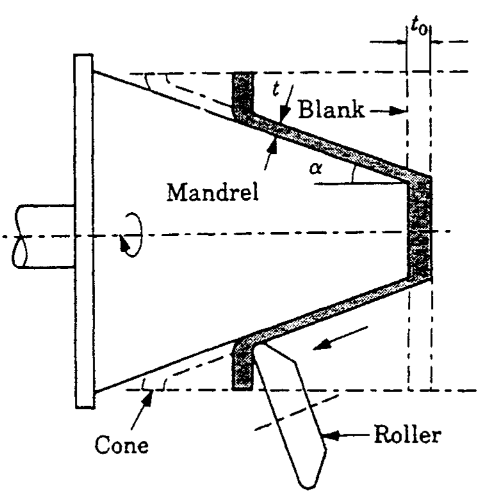


**Fig. 34.10** Setup and dimensional relations for one-operation power spinning of a cone.

revolve in the same direction, their axes being inclined at opposite angles of about 6° from the axis of the billet. The clearance between the rolls is somewhat less than the diameter of the billet. As the billet is caught by the rolls and rotated, their inclination causes the billet to be drawn forward into them. The reduced clearance between the rolls forces the rotating billet to deform into an elliptical shape. To rotate with an elliptical cross section, the metal must undergo shear about the major axis, which causes a crack to open. As the crack opens, the billet is forced over a pointed mandrel that enlarges and shapes the opening, forming a seamless tube (Fig. 34.11).

This procedure applies to seamless tubes up to 6 in. (150 mm) in diameter. Larger tubes up to 14 in. (355 mm) in diameter are given a second operation on piercing rolls. To produce sizes up to 24 in. (610 mm) in diameter, reheated, double-pierced tubes are processed on a rotary rolling mill, and are finally completed by reelers and sizing rolls, as described in the single-piercing process.

## 34.3 COLD-WORKING PROCESSES

Cold working is the plastic deformation of metals below the recrystallization temperature. In most cases of manufacturing, such cold forming is done at room temperature. In some cases, however, the working may be done at elevated temperatures that will provide increased ductility and reduced strength, but will be below the recrystallization temperature.

When compared to hot working, cold-working processes have certain distinct advantages:

1. No heating required
2. Better surface finish obtained
3. Superior dimension control
4. Better reproducibility and interchangeability of parts
5. Improved strength properties
6. Directional properties can be imparted
7. Contamination problems minimized

Some disadvantages associated with cold-working processes include:

1. Higher forces required for deformation
2. Heavier and more powerful equipment required
3. Less ductility available
4. Metal surfaces must be clean and scale-free
5. Strain hardening occurs (may require intermediate anneals)
6. Imparted directional properties may be detrimental
7. May produce undesirable residual stresses

### 34.3.1 Classification of Cold-Working Operations

The major cold-working operations can be classified basically under the headings of squeezing, bending, shearing, and drawing, as follows:

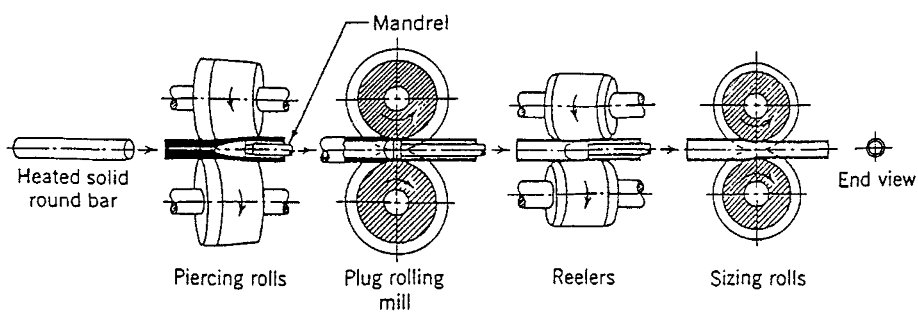


**Fig. 34.11** Principal steps in the manufacture of seamless tubing.

| Squeezing | Bending | Shearing | Drawing |
|---|---|---|---|
| 1. Rolling | 1. Angle | 1. Shearing | 1. Bar and tube drawing |
| 2. Swaging | 2. Roll | Slitting | 2. Wire drawing |
| 3. Cold forging | 3. Roll forming | 2. Blanking | 3. Spinning |
| 4. Sizing | 4. Drawing | 3. Piercing | 4. Embossing |
| 5. Extrusion | 5. Seaming | Lancing | 5. Stretch forming |
| 6. Riveting | 6. Flanging | Perforating | 6. Shell drawing |
| 7. Staking | 7. Straightening | 4. Notching | 7. Ironing |
| 8. Coining | | Nibbling | 8. High energy rate forming |
| 9. Peening | | 5. Shaving | |
| 10. Burnishing | | 6. Trimming | |
| 11. Die hobbing | | 7. Cutoff | |
| 12. Thread rolling | | 8. Dinking | |

### 34.3.2 Squeezing Processes

Most of the cold-working squeezing processes have identical hot-working counterparts or are extensions of them. The primary reasons for deforming cold rather than hot are to obtain better dimensional accuracy and surface finish. In many cases, the equipment is basically the same, except that it must be more powerful.

#### Cold Rolling

Cold rolling accounts for by far the greatest tonnage of cold-worked products. Sheets, strip, bars, and rods are cold-rolled to obtain products that have smooth surfaces and accurate dimensions.

#### Swaging

Swaging basically is a process for reducing the diameter, tapering, or pointing round bars or tubes by external hammering. A useful extension of the process involves the formation of internal cavities. A shaped mandrel is inserted inside a tube and the tube is then collapsed around it by swaging (Fig. 34.12).

#### Cold Forging

Extremely large quantities of products are made by cold forging, in which the metal is squeezed into a die cavity that imparts the desired shape. Cold heading is used for making enlarged sections on the ends of rod or wire, such as the heads on bolts, nails, rivets, and other fasteners.

#### Sizing

Sizing involves squeezing areas of forgings or ductile castings to a desired thickness. It is used principally on basses and flats, with only enough deformation to bring the region to a desired dimension.

#### Extrusion

This process is often called *impact extrusion* and was first used only with the low-strength ductile metals, such as lead, tin, and aluminum, for producing such items as collapsible tubes for toothpaste, medications, and so forth; small "cans" such as are used for shielding in electronics and electrical apparatus; and larger cans for food and beverages. In recent years, cold extrusion has been used for forming mild steel parts, often being combined with cold heading.

Another type of cold extrusion, known as *hydrostatic extrusion,* used high fluid pressure to extrude a billet through a die, either into atmospheric pressure or into a lower-pressure chamber. The pressure-

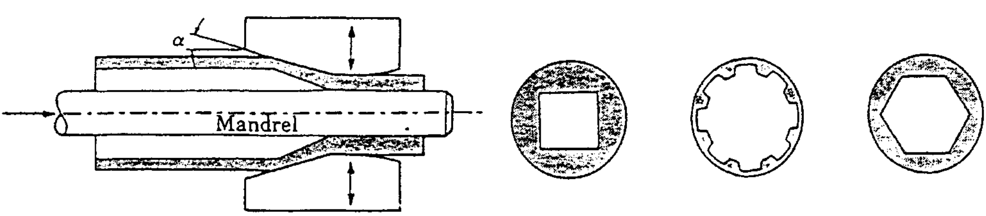


**Fig. 34.12** Cross sections of tubes produced by swaging on shaped mandrels. Rifling (spiral grooves) in small gun barrels can be made by this process.

to-pressure process makes possible the extrusion of relatively brittle materials, such as molybdenum, beryllium, and tungsten. Billet-chamber friction is eliminated, billet-die lubrication is enhanced by the pressure, and the surrounding pressurized atmosphere suppresses crack initiation and growth.

#### Riveting

In riveting, a head is formed on the shank end of a fastener to provide a permanent method of joining sheets or plates of metal together. Although riveting usually is done hot in structural work, in manufacturing it almost always is done cold.

#### Staking

Staking is a commonly used cold-working method for permanently fastening two parts together where one protrudes through a hole in the other. A shaped punch is driven into one of the pieces, deforming the metal sufficiently to squeeze it outward.

#### Coining

Coining involves cold working by means of positive displacement punch while the metal is completely confined within a set of dies.

#### Peening

Peening involves striking the surface repeated blows by impelled shot or a round-nose tool. The highly localized blows deform and tend to stretch the metal surface. Because the surface deformation is resisted by the metal underneath, the result is a surface layer under residual compression. This condition is highly favorable to resist cracking under fatigue conditions, such as repeated bending, because the compressive stresses are subtractive from the applied tensile loads. For this reason, shafting, crankshafts, gear teeth, and other cyclic-loaded components are frequently peened.

#### Burnishing

Burnishing involves rubbing a smooth, hard object under considerable pressure over the minute surface protrusions that are formed on a metal surface during machining or shearing, thereby reducing their depth and sharpness through plastic flow.

#### Hobbing

Hobbing is a cold-working process that is used to form cavities in various types of dies, such as those used for molding plastics. A male hob is made with the contour of the part that ultimately will be formed by the die. After the hob is hardened, it is slowly pressed into an annealed die block by means of hydraulic press until the desired impression is produced.

#### Thread Rolling

Threads can be rolled in any material sufficiently plastic to withstand the forces of cold working without disintegration. Threads can be rolled by flat or roller dies.

### 34.3.3 Bending

Bending is the uniform straining of material, usually flat sheet or strip metal, around a straight axis that lies in the neutral plane and normal to the lengthwise direction of the sheet or strip. Metal flow takes place within the plastic range of the metal, so that the bend retains a permanent set after removal of the applied stress. The inner surface of the bend is in compression; the outer surface is in tension.

Terms used in bending are defined and illustrated in Fig. 34.13. The neutral axis is the plane area in bent metal where all strains are zero.

#### Bend Allowances

Since bent metal is longer after bending, its increased length, generally of concern to the product designer, may also have to be considered by the die designer if the length tolerance of the bent part is critical. The length of bent metal may be calculated from the equation

$$B = \frac{A}{360} \times 2\pi(R_i + Kt) \qquad (34.14)$$

where $B$ = bend allowance, in. (mm) (along neutral axis)
$A$ = bend angle, deg
$R_i$ = inside radius of bend, in. (mm)
$t$ = metal thickness, in. (mm)
$K$ = 0.33 when $R_i$ is less than $2t$ and is 0.50 when $R_i$ is more than $2t$

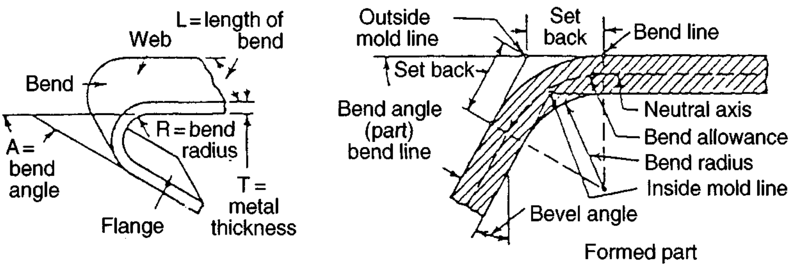


**Fig. 34.13** Bend terms.

### Bending Methods

Two bending methods are commonly made use of in press tools. Metal sheet or strip, supported by a V block (Fig. 34.14), is forced by a wedge-shaped punch into the block.

Edge bending (Fig. 34.14) is cantilever loading of a beam. The bending punch (1) forces the metal against the supporting die (2).

### Bending Force

The force required for V bending is as follows:

$$P = \frac{KLSt^2}{W} \tag{34.15}$$

where $P$ = bending force, tons (for metric usage, multiply number of tons by 8.896 to obtain kilonewtons)
$K$ = die opening factor: 1.20 for a die opening of 16 times metal thickness, 1.33 for an opening of eight times metal thickness
$L$ = length of part, in.
$S$ = ultimate tensile strength, tons/in.$^2$
$W$ = width of V or U die, in.
$t$ = metal thickness, in.

For U bending (channel bending), pressures will be approximately twice those required. For U bending, edge bending is required about one-half those needed for V bending. Table 34.1 gives the ultimate strength = $S$ for various materials.

Several factors must be considered when designing parts that are to be made by bending. Of primary importance is the minimum radius that can be bent successfully without metal cracking. This, of course, is related to the ductility of the metal.

### Angle Bending

Angle bends up to 150° in the sheet metal under about 1⁄16 in. (1.5 mm) in thickness may be made in a bar folder. Heavier sheet metal and more complex bends in thinner sheets are made on a press brake.

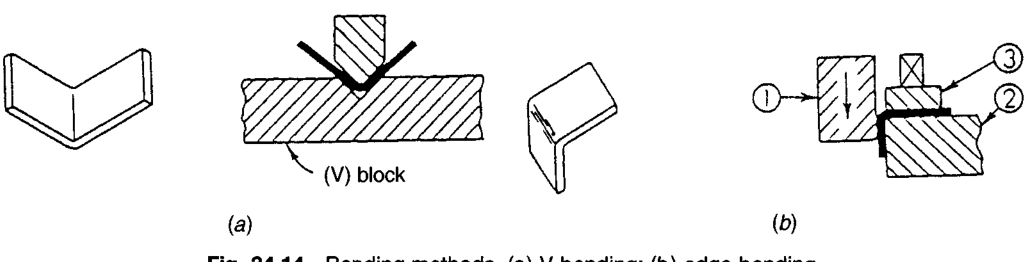


**Fig. 34.14** Bending methods. (*a*) V bending; (*b*) edge bending.

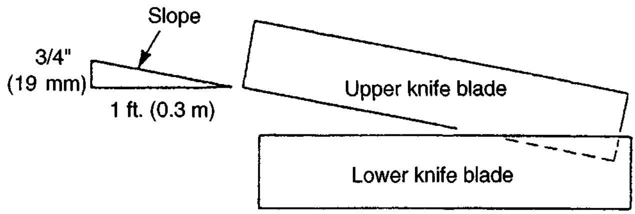


**Fig. 34.15** The rake is the angular slope formed by the cutting edges of the upper and lower knives.

### Roll Bending

Plates, heavy sheets, and rolled shapes can be bent to a desired curvature on forming rolls. These usually have three rolls in the form of a pyramid, with the two lower rolls being driven and the upper roll adjustable to control the degree of curvature. Supports can be swung clear to permit removal of a closed shape from the rolls. Bending rolls are available in a wide range of sizes, some being capable of bending plate up to 6 in. (150 mm) thick.

### Cold-Roll Forming

This process involves the progressive bending of metal strip as it passes through a series of forming rolls. A wide variety of moldings, channeling, and other shapes can be formed on machines that produce up to 10,000 ft (3000 m) of product per day.

### Seaming

Seaming is used to join ends of sheet metal to form containers such as cans, pails, and drums. The seams are formed by a series of small rollers on seaming machines that range from small hand-operated types to large automatic units capable of producing hundreds of seams per minute in the mass production of cans.

### Flanging

Flanges can be rolled on sheet metal in essentially the same manner as seaming is done. In many cases, however, the forming of flanges and seams involves drawing, since localized bending occurs on a curved axis.

### Straightening

Straightening or flattening has as its objective the opposite of bending and often is done before other cold-forming operations to ensure that flat or straight material is available. Two different techniques are quite common. *Roll straightening* or *roller leveling* involves a series of reverse bends. The rod, sheet, or wire is passed through a series of rolls having decreased offsets from a straight line. These bend the metal back and forth in all directions, stressing it slightly beyond its previous elastic limit and thereby removing all previous permanent set.

Sheet may also be straightened by a process called *stretcher leveling.* The sheets are grabbed mechanically at each end and stretched slightly beyond the elastic limit to remove previous stresses and thus produce the desired flatness.

## 34.3.4 Shearing

Shearing is the mechanical cutting of materials in sheet or plate form without the formation of chips or use of burning or melting. When the two cutting blades are straight, the process is called *shearing.*

**Table 34.1 Ultimate Strength**

| Metal | (ton/in.$^2$) |
|---|---|
| Aluminum and alloys | 6.5–38.0 |
| Brass | 19.0–38.0 |
| Bronze | 31.5–47.0 |
| Copper | 16.0–25.0 |
| Steel | 22.0–40.0 |
| Tin | 1.1–1.4 |
| Zinc | 9.7–13.5 |

Other processes, in which the shearing blades are in the form of curved edges or punches and dies, are called by other names, such as *blanking, piercing, notching, shaving,* and *trimming.* These all are basically shearing operations, however.

The required shear force can be calculated as

$$F = \left(\frac{S \times P \times t^2 \times 12}{R}\right)\left(1 - \frac{P}{2}\right) \tag{34.16}$$

where $F$ = shear force, lb
$S$ = shear strength (stress), psi
$P$ = penetration of knife into material, %
$t$ = thickness of material, in.
$R$ = rake of the knife blade, in./ft (Fig. 34.13)

For SI units, the force is multiplied by 4.448 to obtain newtons (N). Table 34.2 gives the values of $P$ and $S$ for various materials.

### Blanking

A blank is a shape cut from flat or preformed stock. Ordinarily, a blank serves as a starting workpiece for a formed part; less often, it is a desired end product.

Calculation of the forces and the work involved in blanking gives average figures that are applicable only when (a) the correct shear strength for the material is used, and (b) the die is sharp and the punch is in good condition, has correct clearance, and is functioning properly.

The total load on the press, or the press capacity required to do a particular job, is the sum of the cutting force and other forces acting at the same time, such as the blankholding force exerted by a die cushion.

### Cutting Force: Square-End Punches and Dies

When punch and die surfaces are flat and at right angles to the motion of the punch, the cutting force can be found by multiplying the area of the cut section by the shear strength of the work material:

**Table 34.2 Values of Percent Penetration and Shear Strength for Various Materials**

| Material | Percent Penetration | Shear Strength, psi (MPa) |
|---|---|---|
| Lead alloys | 50 | 3500 (24.1)–6000 (41.3) |
| Tin alloys | 40 | 5000 (34.5)–10,000 (69) |
| Aluminum alloys | 60 | 8000 (55.2)–45,000 (310) |
| Titanium alloys | 10 | 60,000 (413)–70,000 (482) |
| Zinc | 50 | 14,000 (96.5) |
| Cold worked | 25 | 19,000 (131) |
| Magnesium alloys | 50 | 17,000 (117)–30,000 (207) |
| Copper | 55 | 22,000 (151.7) |
| Cold worked | 30 | 28,000 (193) |
| Brass | 50 | 32,000 (220.6) |
| Cold worked | 30 | 52,000 (358.5) |
| Tobin bronze | 25 | 36,000 (248.2) |
| Cold worked | 17 | 42,000 (289.6) |
| Steel, 0.10C | 50 | 35,000 (241.3) |
| Cold worked | 38 | 43,000 (296.5) |
| Steel, 0.40C | 27 | 62,000 (427.5) |
| Cold worked | 17 | 78,000 (537.8) |
| Steel, 0.80C | 15 | 97,000 (668.8) |
| Cold worked | 5 | 127,000 (875.6) |
| Steel, 1.00C | 10 | 115,000 (792.9) |
| Cold worked | 2 | 150,000 (1034.2) |
| Silicon steel | 30 | 65,000 (448.2) |
| Stainless steel | 30 | 57,000 (363)–128,000 (882) |
| Nickel | 55 | 35,000 (241.3) |

$$L = Stl \tag{34.17}$$

where $L$ = load on the press, lb (cutting force)
$S$ = shear strength of the stock, psi
$t$ = stock thickness, in.
$l$ = the length or perimeter of cut, in.

### Piercing

Piercing is a shearing operation wherein the shearing blades take the form of closed, curved lines on the edges of a punch and die. Piercing is basically the same as blanking except that the piece punched out is the scrap and the remainder of the strip becomes the desired workpiece.

### Lancing

Lancing is a piercing operation that may take the form of a slit in the metal or an actual hole. The purpose of lancing is to permit adjacent metal to flow more readily in subsequent forming operations.

### Perforating

Perforating consists of piercing a large number of closely spaced holes.

### Notching

Notching is essentially the same as piercing except that the edge of the sheet of metal forms a portion of the periphery of the piece that is punched out. It is used to form notches of any desired shape along the edge of a sheet.

### Nibbling

Nibbling is a variation of notching in which a special machine makes a series of overlapping notches, each farther into the sheet of metal.

### Shaving

Shaving is a finished operation in which a very small amount of metal is sheared away around the edge of a blanked part. Its primary use is to obtain greater dimensional accuracy, but it also may be used to obtain a square of smoother edge.

### Trimming

Trimming is used to remove the excess metal that remains after a drawing, forging, or casting operation. It is essentially the same as blanking.

### Cutoff

A cutoff operation is one in which a stamping is removed from a strip of stock by means of a punch and die. The cutoff punch and die cut across the entire width of the strip. Frequently, an irregularly shaped cutoff operation may simultaneously give the workpiece all or part of the desired shape.

### Dinking

Dinking is a modified shearing operation that is used to blank shapes from low-strength materials, primarily rubber, fiber, and cloth.

## 34.3.5 Drawing

### Cold Drawing

*Cold drawing* is a term that can refer to two somewhat different operations. If the stock is in the form of sheet metal, cold drawing is the forming of parts wherein plastic flow occurs over a curved axis. This is one of the most important of all cold-working operations because a wide range of parts, from small caps to large automobile body tops and fenders, can be drawn in a few seconds each. Cold drawing is similar to hot drawing, but the higher deformation forces, thinner metal, limited ductility, and closer dimensional tolerance create some distinctive problems.

If the stock is wire, rod, or tubing, *cold drawing* refers to the process of reducing the cross section of the material by pulling it through a die, a sort of tensile equivalent to extrusion.

### Cold Spinning

Cold spinning is similar to hot spinning, discussed above.

### Stretch Forming

In stretch forming, only a single male form block is required. The sheet of metal is gripped by two or more sets of jaws that stretch it and wrap it around the form block as the latter raises upward.

Various combinations of stretching, wrapping, and upward motion of the blocks are used, depending on the shape of the part.

### Shell or Deep Drawing

The drawing of closed cylindrical or rectangular containers, or a variation of these shapes, with a depth frequently greater than the narrower dimension of their opening, is one of the most important and widely used manufacturing processes. Because the process had its earliest uses in manufacturing artillery shells and cartridge cases, it is sometimes called *shell drawing.* When the depth of the drawn part is less than the diameter, or minimum surface dimension, of the blank, the process is considered to be *shallow drawing.* If the depth is greater than the diameter, it is considered to be *deep drawing.*

The design of complex parts that are to be drawn has been aided considerably by computer techniques, but is far from being completely and successfully solved. Consequently, such design still involves a mix of science, experience, empirical data, and actual experimentation. The body of known information is quite substantial, however, and is being used with outstanding results.

### Forming with Rubber or Fluid Pressure

Several methods of forming use rubber or fluid pressure (Fig. 34.16) to obtain the desired information and thereby eliminate either the male or female member of the die set. Blanks of sheet metal are placed on top of form blocks, which usually are made of wood. The upper ram, which contains a pad of rubber 8–10 in. (200–250 mm) thick in a steel container, then descends. The rubber pad is confined and transmits force to the metal, causing it to bend to the desired shape. Since no female die is used and form blocks replace the male die, die cost is quite low.

The hydroform process or "rubber bag forming" replaces the rubber pad with a flexible diaphragm backed by controlled hydraulic pressure. Deeper parts can be formed with truly uniform fluid pressure.

The bulging oil or rubber is used for applying an internal bulging force to expand a metal blank or tube outward against a female mold or die, thereby eliminating the necessity for a complicated, multiple-piece male die member.

### Ironing

*Ironing* is the name given to the process of thinning the walls of a drawn cylinder by passing it between a punch and a die where the separation is less than the original wall thickness. The walls are elongated and thinned while the base remains unchanged. The most common example of an ironed product is the thin-walled all-aluminum beverage can.

### Embossing

Embossing is a method for producing lettering or other designs in thin sheet metal. Basically, it is a very shallow drawing operation, usually in open dies, with the depth of the draw being from one to three times the thickness of the metal.

### High-Energy-Rate Forming

A number of methods have been developed for forming metals through the release and application of large amounts of energy in a very short interval (Fig. 34.17). These processes are called *high-energy-rate forming processes* (HERF). Many metals tend to deform more readily under the ultrarapid rates of load application used in these processes, a phenomenon apparently related to the relative rates of load application and the movement of dislocations through the metal. As a consequence, HERF makes it possible to form large workpieces and difficult-to-form metals with less expensive equipment and tooling than would otherwise be required.

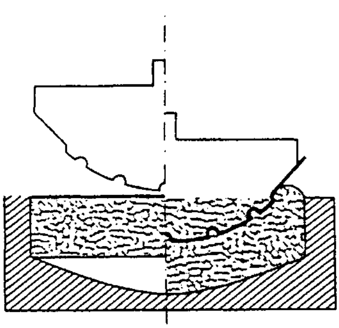

**Fig. 34.16** Form with rubber.

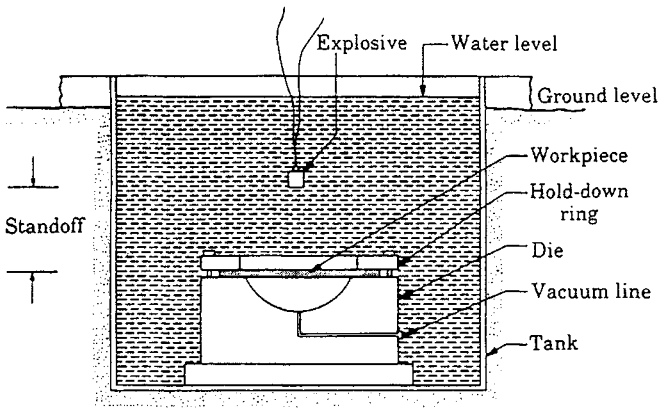


**Fig. 34.17** High-energy-rate forming.

The high energy-release rates are obtained by five methods:

1. Underwater explosions
2. Underwater spark discharge (electrohydraulic techniques)
3. Pneumatic–mechanical means
4. Internal combustion of gaseous mixtures
5. Rapidly formed magnetic fields (electromagnetic techniques)

## 34.4 METAL CASTING AND MOLDING PROCESSES

Casting provides a versatility and flexibility that have maintained casting position as a primary production method for machine elements. Casting processes are divided according to the specific type of molding method used in casting, as follows:

1. Sand
2. Centrifugal
3. Permanent
4. Die
5. Plaster-mold
6. Investment

### 34.4.1 Sand Casting

Sand casting consists basically of pouring molten metal into appropriate cavities formed in a sand mold (Fig. 34.18). The sand may be natural, synthetic, or an artificially blended material.

#### Molds

The two common types of sand molds are the *dry sand mold* and the *green sand mold*. In the dry sand mold, the mold is dried thoroughly prior to closing and pouring, while the green sand mold is used without any preliminary drying. Because the dry sand mold is more firm and resistant to collapse than the green sand mold, core pieces for molds are usually made in this way. Cores are placed in mold cavities to form the interior surfaces of castings.

#### Patterns

To produce a mold for a conventional sand cast part, it is necessary to make a pattern of the part. Patterns are made from wood or metal to suit a particular design, with allowances to compensate for such factors as natural metal shrinkage and contraction characteristics. These and other effects, such as mold resistance, distortion, casting design, and mold design, which are not entirely within the range of accurate prediction, generally make it necessary to adjust the pattern in order to produce castings of the required dimensions.

Access to the mold cavity for entry of the molten metal is provided by sprues, runners, and gates.

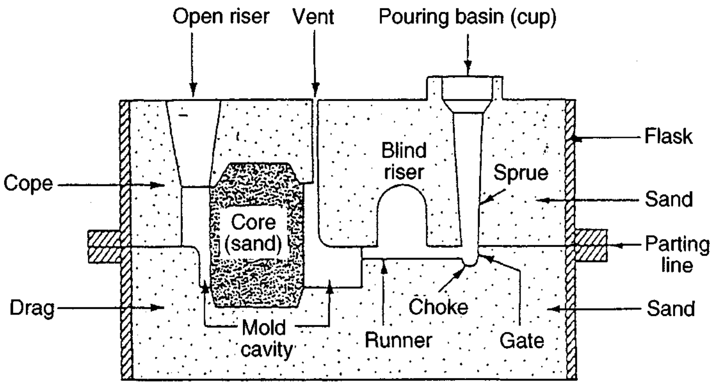


**Fig. 34.18** Sectional view of casting mold.

### Shrinkage

Allowances must be made on patterns to counteract the contraction in size as the metal cools. The amount of shrinkage is dependent on the design of the coating, type of metal used, solidification temperature, and mold resistance. Table 34.3 gives average shrinkage allowance values used in sand casting. Smaller values apply generally to large or cored castings of intricate design. Larger values apply to small to medium simple castings designed with unrestrained shrinkage.

### Machining

Allowances are required in many cases because of unavoidable surface impurities, warpage, and surface variations. Average machining allowances are given in Table 34.4. Good practice dictates use of minimum section thickness compatible with the design. The normal minimum section recommended for various metals is shown in Table 34.5.

## 34.4.2 Centrifugal Casting

Centrifugal casting consists of having a sand, metal, or ceramic mold that is rotated at high speeds. When the molten metal is poured into the mold, it is thrown against the mold wall, where it remains until it cools and solidifies. The process is increasingly being used for such products as cast-iron pipes, cylinder liners, gun barrels, pressure vessels, brake drums, gears, and flywheels. The metals used include almost all castable alloys. Most dental tooth caps are made by a combined lost-wax process and centrifugal casting.

### Advantages and Limitations

Because of the relatively fast cooling time, centrifugal castings have a fine grain size. There is a tendency for the lighter nonmetallic inclusion, slag particles, and dross to segregate toward the inner

**Table 34.3 Pattern Shrinkage Allowance (in./ft)**

| Metal | Shrinkage |
|---|---|
| Aluminum alloys | 1/10–5/32 |
| Beryllium copper | 1/8–5/32 |
| Copper alloys | 3/16–7/32 |
| Everdur | 3/16 |
| Gray irons | 1/8 |
| Hastelloy alloys | 1/4 |
| Magnesium alloys | 1/8–11/64 |
| Malleable irons | 1/16–3/16 |
| Meehanite | 1/10–5/32 |
| Nickel and nickel alloys | 1/4 |
| Steel | 1/8–1/4 |
| White irons | 3/16–1/4 |

**Table 34.4 Machining Allowances for Sand Castings (in.)**

| Metal | Casting Size | Finish Allowance |
|---|---|---|
| Cast irons | up to 12 in. | 3/32 |
| | 13–24 in. | 1/8 |
| | 25–42 in. | 3/16 |
| | 43–60 in. | 1/4 |
| | 61–80 in. | 5/16 |
| | 81–120 in. | 3/8 |
| Cast steels | up to 12 in. | 1/8 |
| | 13–24 in. | 3/16 |
| | 25–42 in. | 5/16 |
| | 43–60 in. | 3/8 |
| | 61–80 in. | 7/16 |
| | 81–120 in. | 1/2 |
| Malleable irons | up to 8 in. | 1/16 |
| | 9–12 in. | 3/32 |
| | 13–24 in. | 1/8 |
| | 25–36 in. | 3/16 |
| Nonferrous metals | up to 12 in. | 1/16 |
| | 13–24 in. | 1/8 |
| | 25–36 in. | 5/32 |

radius of the castings (Fig. 34.19), where it can be easily removed by machining. Owing to the high purity of the outer skin, centrifugally cast pipes have a high resistance to atmospheric corrosion. Figure 34.19 shows a schematic sketch of how a pipe would be centrifugally cast in a horizontal mold.

Parts that have diameters exceeding their length are produced by vertical-axis casting (see Fig. 34.20).

If the centrifugal force is too low or too great, abnormalities will develop. Most horizontal castings are spun so that the force developed is about 65 g's. Vertically cast parts force is about 90–100 g's.

The centrifugal force (*CF*) is calculated from

$$CF = \frac{mv^2}{r}\ lb$$

$$m = \text{Mass} = \frac{W}{g} = \frac{\text{Weight, lb}}{\text{Acceleration of gravity (ft/s)}^2} = \frac{W}{32.2}$$

where $v$ = velocity, ft/s = r × w
$r$ = radius, ft = ½ D
$w$ = angular velocity, rad/s
$w = 2\pi/60 \times$ rpm
$D$ = inside diameter, ft

The number of g's is

$$g\text{'s} = CF/W$$

**Table 34.5 Minimum Sections for Sand Castings (in.)**

| Metal | Section |
|---|---|
| Aluminum alloys | 3/16 |
| Copper alloys | 3/32 |
| Gray irons | 1/8 |
| Magnesium alloys | 5/32 |
| Malleable irons | 1/8 |
| Steels | 1/4 |
| White irons | 1/8 |

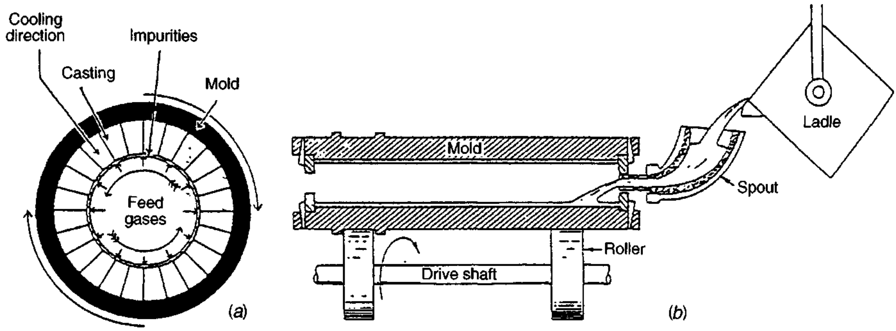


**Fig. 34.19** The principle of centrifugal casting is to produce the high-grade metal by throwing the heavier metal outward and forcing the impurities to congregate inward (*a*). Shown at (*b*) is a schematic of how a horizontal-bond centrifugal casting is made.

Hence,

$$\begin{aligned} \text{g's} &= \frac{1}{W} \times \left[\frac{W}{32.2 \times r}\left(\frac{r \times 2\pi}{60}\right)^2\right] \\ &= r \times 3.41 \times 10^{-4}\ \text{rpm}^2 \\ &= 1.7 \times 10^{-4} \times D \times (\text{rpm})^2 \end{aligned}$$

The spinning speed for horizontal-axis molds may be found in English units from the equation

$$N = \sqrt{(\text{Number of g's}) \times \frac{70{,}500}{D}}$$

where $N$ = rpm
$D$ = inside diameter of mold, ft

### 34.4.3 Permanent-Mold Casting

As demand for quality castings in production quantities increased, the attractive possibilities of metal molds brought about the development of the permanent-mold process. Although not as flexible regarding design as sand casting, metal-mold casting made possible the continuous production of quantities of casting from a single mold as compared to batch production of individual sand molds.

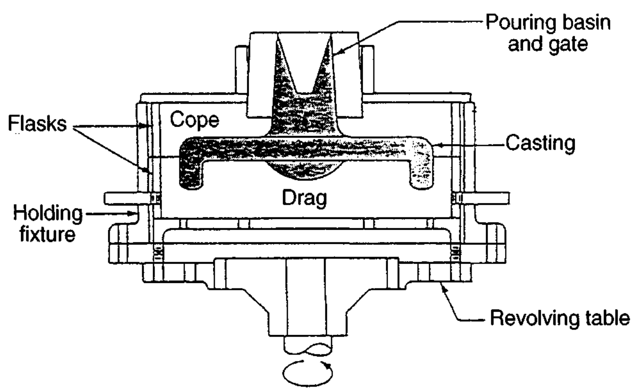


**Fig. 34.20** Floor-type vertical centrifugal casting machine for large-diameter parts.

### Metal Molds and Cores

In permanent-mold casting, both metal molds and cores are used, the metal being poured into the mold cavity with the usual gravity head as in sand casting. Molds are normally made of dense iron or meehanite, large cores of cast iron, and small or collapsible cores of alloy steel. All necessary sprues, runners, gates, and risers must be machined into the mold, and the mold cavity itself is made with the usual metal-shrinkage allowances. The mold is usually composed of one, two, or more parts, which may swing or slide for rapid operation. Whereas in sand casting the longest dimension is always placed in a horizontal position, in permanent-mold casting the longest dimension of a part is normally placed in a vertical position.

### Production Quantities

Wherever quantities are in the range of 500 pieces or more, permanent-mold casting becomes competitive in cost with sand casting, and if the design is simple, runs as small as 200 pieces are often economical. Production runs of 1000 pieces or more will generally produce a favorable cost difference. High rates of production are possible, and multiple-cavity dies with as many as 16 cavities can be used. In casting gray iron in multiple molds, as many as 50,000 castings per cavity are common with small parts. With larger parts of gray iron, weighing from 12–15 lb, single-cavity molds normally yield 2000–3000 pieces per mold on an average. Up to 100,000 parts per cavity or more are not uncommon with nonferrous metals, magnesium providing the longest die life. Low-pressure permanent mold casting is economical for quantities up to 40,000 pieces (Fig. 34.21).

### Die Casting

Die casting may be classified as a permanent-mold casting system; however, it differs from the process just described in that the molten metal is forced into the mold or die under high pressure [1000–30,000 psi (6.89–206.8 MPa)]. The metal solidifies rapidly (within a fraction of a second) because the die is water-cooled. Upon solidification, the die is opened and ejector pins automatically knock the casting out of the die. If the parts are small, several of them may be made at one time in what is termed a *multicavity die.*

There are two main types of machines used: the hot-chamber and the cold-chamber types.

***Hot-Chamber Die Casting.*** In the hot-chamber machine, the metal is kept in a heated holding pot. As the plunger descends, the required amount of alloy is automatically forced into the die. As the piston retracts, the cylinder is again filled with the right amount of molten metal. Metals such as aluminum, magnesium, and copper tend to alloy with the steel plunger and cannot be used in the hot chamber.

***Cold-Chamber Die Casting.*** This process gets its name from the fact that the metal is ladled into the cold chamber for each shot. This procedure is necessary to keep the molten-metal contact time with the steel cylinder to a minimum. Iron pickup is prevented, as is freezing of the plunger in the cylinder.

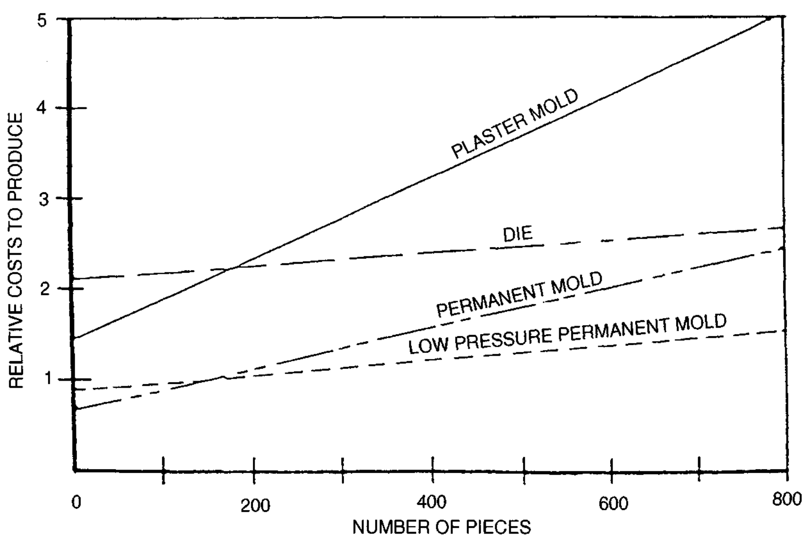


**Fig. 34.21** Cost comparison of various casting systems.

### Advantages and Limitations

Die-casting machines can produce large quantities of parts with close tolerances and smooth surfaces. The size is limited only by the capacity of the machine. Most die castings are limited to about 75 lb (34 kg) of zinc; 65 lb (30 kg) of aluminum; and 44 lb (20 kg) of magnesium. Die castings can provide thinner sections than any other casting process. Wall thickness as thin as 0.015 in. (0.38 mm) can be achieved with aluminum in small items. However, a more common range on larger sizes will be 0.105–0.180 in. (2.67–4.57 mm).

Some difficulty is experienced in getting sound castings in the larger capacities. Gases tend to be entrapped, which results in low strength and annoying leaks. Of course, one way to reduce metal sections without sacrificing strength is to design in ribs and bosses. Another approach to the porosity problem has been to operate the machine under vacuum. This process is now being developed.

The surface quality is dependent on that of the mold. Parts made from new or repolished dies may have a surface roughness of 24 $\mu$in. (0.61 $\mu$m). The high surface finish available means that, in most cases, coatings such as chromeplating, anodizing, and painting may be applied directly. More recently, decorative finishes of texture, as obtained by photoetching, have been applied. The technique has been used to simulate woodgrain finishes, as well as textile and leather finishes, and to obtain checkering and crosshatching.

## 34.4.4 Plaster-Mold Casting

In general, the various methods of plaster-mold casting are similar. The plaster, also known as *gypsum* or *calcium sulfate,* is mixed dry with other elements, such as talc, sand, asbestos, and sodium silicate. To this mix is added a controlled amount of water to provide the desired permeability in the mold. The slurry that results is heated and delivered through a hose to the flasks, all surfaces of which have been sprayed with a parting compound. The plaster slurry readily fills in and around the most minute details in the highly polished brass patterns. Following filling, the molds are subjected to a short period of vibration and the slurry sets in 5–10 min.

### Molds

Molds are extracted from the flask with a vacuum head, following which drying is completed in a continuous oven. Copes and drags are then assembled, with cores when required, and the castings are poured. Upon solidification, the plaster is broken away and any cores used are washed out with a high-pressure jet of water.

## 34.4.5 Investment Casting

Casting processes in which the pattern is used only once are variously referred to as *lost-wax* or *precision-casting* processes. They involve making a pattern of the desired form out of wax or plastic (usually polystyrene). The expendable pattern may be made by pressing the wax into a split mold or by the use of an injection-molding machine. The patterns may be gated together so that several parts can be made at once. A metal flask is placed around the assembled patterns and a refractory mold slurry is poured in to support the patterns and form the cavities. A vibrating table equipped with a vacuum pump is used to eliminate all the air from the mold. Formerly, the standard procedure was to dip the patterns in the slurry several times until a coat was built up. This is called the *investment process.* After the mold material has set and dried, the pattern material is melted and allowed to run out of the mold.

The completed flasks are heated slowly to dry the mold and to melt out the wax, plastic, or whatever pattern material was used. When the molds have reached a temperature of 100°F (37.8°C), they are ready for pouring. Vacuum may be applied to the flasks to ensure complete filling of the mold cavities.

When the metal has cooled, the investment material is removed by vibrating hammers or by tumbling. As with other castings, the gates and risers are cut off and ground down.

### Ceramic Process

The ceramic process is somewhat similar to the investment-casting in that a creamy ceramic slurry is poured over a pattern. In this case, however, the pattern, made out of plastic, plaster, wood, metal, or rubber, is reusable. The slurry hardens on the pattern almost immediately and becomes a strong green ceramic of the consistency of vulcanized rubber. It is lifted off the pattern while it is still in the rubberlike phase. The mold is ignited with a torch to burn off the volatile portion of the mix. It is then put in a furnace and baked at 1800°F (982°C), resulting in a rigid refractory mold. The mold can be poured while still hot.

### Full-Mold Casting

Full-mold casting may be considered a cross between conventional sand casting and the investment technique of using lost wax. In this case, instead of a conventional pattern of wood, metals, or plaster, a polystyrene foam or styrofoam is used. The pattern is left in the mold and is vaporized by the molten metal as it rises in the mold during pouring. Before molding, the pattern is usually coated with a zirconite wash in an alcohol vehicle. The wash produces a relatively tough skin separating the metal from the sand during pouring and cooling. Conventional foundry sand is used in backing up the mold.

## 34.5 PLASTIC-MOLDING PROCESSES

Plastic molding is similar in many ways to metal molding. For most molding operations, plastics are heated to a liquid or a semifluid state and are formed in a mold under pressure. Some of the most common molding processes are discussed below.

### 34.5.1 Injection Molding

The largest quantity of plastic parts is made by injection molding. Plastic compound is fed in powdered or granular form from a hopper through metering and melting stages and then injected into a mold. After a brief cooling period, the mold is opened and the solidified part is ejected.

### 34.5.2 Coinjection Molding

Coinjection molding makes it possible to mold articles with a solid skin of one thermoplastic and a core of another thermoplastic. The skin material is usually solid while the core material contains blowing agents.

The basic process may be one-, two-, or three-channel technology. In one-channel technology, the two melts are injected into the mold, one after the other. The skin material cools and adheres to the colder surface; a dense skin is formed under proper parameter settings. The thickness of the skin can be controlled by adjustment of injection speed, stock temperature, mold temperature, and flow compatibility of the two melts.

In two- and three-channel techniques, both plastic melts may be introduced simultaneously. This allows for better control of wall thickness of the skin, especially in gate areas on both sides of the part.

#### Injection-Molded Carbon-Fiber Composites

By mixing carbon or glass fibers in injection-molded plastic parts, they can be made lightweight yet stiffer than steel.

### 34.5.3 Rotomolding

In rotational molding, the product is formed inside a closed mold that is rotated about two axes as heat is applied. Liquid or powdered thermoplastic or thermosetting plastic is poured into the mold, either manually or automatically.

### 34.5.4 Expandable-Bead Molding

The expandable-bead process consists of placing small beads of polystyrene along with a small amount of blowing agent in a tumbling container. The polystyrene beads soften under heat, which allows a blowing agent to expand them. When the beads reach a given size, depending on the density required, they are quickly cooled. This solidifies the polystyrene in its larger foamed size. The expanded beads are then placed in a mold until it is completely filled. The entrance port is then closed and steam is injected, resoftening the beads and fusing them together. After cooling, the finished, expanded part is removed from the mold.

### 34.5.5 Extruding

Plastic extrusion is similar to metal extrusion in that a hot material (plastic melt) is forced through a die having an opening shaped to produce a desired cross section. Depending on the material used, the barrel is heated anywhere from 250–600°F (121–316°C) to transform the thermoplastic from a solid to a melt. At the end of the extruder barrel is a screen pack for filtering and building back pressure. A breaker plate serves to hold the screen pack in place and straighten the helical flow as it comes off the screen.

### 34.5.6 Blow Molding

Blow molding is used extensively to make bottles and other lightweight, hollow plastic parts. Two methods are used: injection blow molding and extrusion blow molding.

Injection blow molding is used primarily for small containers. The parison (molten-plastic pipe) or tube is formed by the injection of plasticized material around a hollow mandrel. While the material is still molten and still on the mandrel, it is transferred into the blowing mold where air is used to inflate it. Accurate threads may be formed at the neck.

In extrusion-type blow molding, parison is inflated under relatively low pressure inside a split-metal mold. The die closes, pinching the end and closing the top around the mandrel. Air enters through the mandrel and inflates the tube until the plastic contacts the cold wall, where it solidifies. The mold opens, the bottle is ejected, and the tailpiece falls off.

### 34.5.7 Thermoforming

*Thermoforming* refers to heating a sheet of plastic material until it becomes soft and pliable and then forming it either under vacuum, by air pressure, or between matching mold halves.

### 34.5.8 Reinforced-Plastic Molding

*Reinforced plastics* generally refers to polymers that have been reinforced with glass fibers. Other materials used are asbestos, sisal, synthetic fibers such as nylon and polyvinyl chloride, and cotton fibers. High-strength composites using graphite fibers are now commercially available with moduli of 50,000,000 psi (344,700,000 MPa) and tensile strengths of about 300,000 psi (2,068,000 MPa). They are as strong as or stronger than the best alloy steels and are lighter than aluminum.

### 34.5.9 Forged-Plastic Parts

The forging of plastic materials is a relatively new process. It was developed to shape materials that are difficult or impossible to mold and is used as a low-cost solution for small production runs.

The forging operation starts with a blank or billet of the required shape and volume for the finished part. The blank is heated to a preselected temperature and transferred to the forging dies, which are closed to deform the work material and fill the die cavity. The dies are kept in the closed position for a definite period of time, usually 15–60 sec. When the dies are opened, the finished forging is removed. Since forging involves deformation of the work material in a heated and softened condition, the process is applicable only to thermoplastics.

## 34.6 POWDER METALLURGY

In powder metallurgy (P/M), fine metal powders are pressed into a desired shape, usually in a metal die and under high pressure, and the compacted powder is then heated (sintered), with a protective atmosphere. The density of sintered compacts may be increased by repressing. Repressing is also performed to improve the dimensional accuracy, either concurrently or subsequently, for a period of time at a temperature below the melting point of the major constituent. P/M has a number of distinct advantages that account for its rapid growth in recent years, including (1) no material is wasted, (2) usually no machining is required, (3) only semiskilled labor is required, and (4) some unique properties can be obtained, such as controlled degrees of porosity and built-in lubrication.

A crude form of powder metallurgy appears to have existed in Egypt as early as 3000 BC, using particles of sponge iron. In the 19th century, P/M was used for producing platinum and tungsten wires. However, its first significant use related to general manufacturing was in Germany, following World War I, for making tungsten carbide cutting-tool tips. Since 1945 the process has been highly developed, and large quantities of a wide variety of P/M products are made annually, many of which could not be made by any other process. Most are under 2 in. (50.8 mm) in size, but many are larger, some weighing up to 50 lb (22.7 kg) and measuring up to 20 in. (508 mm).

Powder metallurgy normally consists of four basic steps:

1. Producing a fine metallic powder
2. Mixing and preparing the powder for use
3. Pressing the powder into the desired shape
4. Heating (sintering) the shape at an elevated temperature

Other operations can be added to obtain special results.

The pressing and sintering operations are of special importance. The pressing and repressing greatly affect the density of the product, which has a direct relationship to the strength properties. Sintering strips contaminants from the surface of the powder particles, permitting diffusion bonding to occur and resulting in a single piece of material. Sintering usually is done in a controlled, inert atmosphere, but sometimes it is done by the discharge of spark through the powder while it is under compaction in the mold.

### 34.6.1 Properties of P/M Products

Because the strength properties of powder metallurgy products depend on so many variables—type and size of powder, pressing pressure, sintering temperature, finishing treatments, and so on—it is difficult to give generalized information. In general, the strength properties of products that are made from pure metals (unalloyed) are about the same as those made from the same wrought metals. As alloying elements are added, the resulting strength properties of P/M products fall below those of wrought products by varying, but usually substantial, amounts. The ductility usually is markedly less, as might be expected because of the lower density. However, tensile strengths of 40,000–50,000 psi (275.8–344.8 MPa) are common, and strengths above 100,000 psi (689.5 MPa) can be obtained. As larger presses and forging combined with P/M preforms are used, to provide greater density, the strength properties of P/M materials will more nearly equal those of wrought materials. Coining can also be used to increase the strength properties of P/M products and to improve their dimensional accuracy.

## 34.7 SURFACE TREATMENT

Products that have been completed to their proper shape and size frequently require some type of surface finishing to enable them to satisfactorily fulfill their function. In some cases, it is necessary to improve the physical properties of the surface material for resistance to penetration or abrasion.

Surface finishing may sometimes become an intermediate step in processing. For instance, cleaning and polishing are usually essential before any kind of plating process. Another important need for surface finishing is for corrosion protection in a variety of environments. The type of protection provided will depend largely on the anticipated exposure, with due consideration to the material being protected and the economic factors involved.

Satisfying the above objectives necessitates the use of many surface-finishing methods that involve chemical change of the surface; mechanical work affecting surface properties, cleaning by a variety of methods; and the application of protective coatings organic and metallic.

### 34.7.1 Cleaning

Few, if any, shaping and sizing processes produce products that are usable without some type of cleaning unless special precautions are taken. Figure 34.22 indicates some of the cleaning methods available. Some cleaning methods provide multiple benefits. Cleaning and finish improvements are often combined. Probably of even greater importance is the combination of corrosion protection with finish improvement, although corrosion protection is more often a second step that involves coating an already cleaned surface with some other material or chemical conversion.

#### Liquid and Vapor Baths

***Liquid and Vapor Solvents.*** The most widely used cleaning methods make use of a cleaning medium in liquid or vapor form. These methods depend on a solvent or chemical action between the surface contaminants and the cleaning material.

***Petroleum Solvents.*** Among the more common cleaning jobs required is the removal of grease and oil deposited during manufacturing or intentionally coated on the work to provide protection. One of the most efficient ways to remove this material is by use of solvents that dissolve the grease and oil but have no effect on the base metal. Petroleum derivatives, such as Stoddard solvent and kerosene, are common for this purpose, but, since they introduce some danger of fire, chlorinated solvents, such as trichlorethylene, that are free of this fault are sometimes substituted.

***Conditioned Water.*** One of the most economical cleaning materials is water. However, it is seldom used alone, even if the contaminant is fully water soluble, because the impurity of the water itself may contaminate the work surface. Depending on its use, water is treated with various acids and alkalies to suit the job being performed.

***Pickling.*** Water containing sulfuric acid in a concentration from about 10–25% and at a temperature of approximately 149°F (65°C) is commonly used in a process called *pickling* for removal of surface oxides or scale or iron and steel.

***Mechanical Work Frequently Combined with Chemical Action.*** Spraying, brushing, and dipping methods are also used with liquid cleaners. In nearly all cases, mechanical work to cause surface film breakdown and particle movement is combined with chemical and solvent action. The mechanical work may be agitation of the product, as in dipping, movement of the cleaning agent, as in spraying, or use of a third element, as in rubbing brushing. In some applications, sonic or ultrasonic vibrations are applied to either the solution or the workpieces to speed the cleaning action. Chemical activity is increased with higher temperatures and optimum concentration of the cleaning agent, both of which must in some cases be controlled closely for efficient action.

#### Blasting

The term *blasting* is used to refer to all those cleaning methods in which the cleaning medium is accelerated to high velocity and impinged against the surface to be cleaned. The high velocity may be provided by air or water directed through a nozzle or by mechanical means with a revolving slinger. The cleaning agent may be either dry or wet solid media, such as sand, abrasive, steel grit, or shot, or may be liquid or vapor solvents combined with abrasive material. In addition to cleaning, solid particles can improve finish and surface properties of the material on which they are used. Blasting tends to increase the surface area and thus set up compressive stresses that may cause a warping of thin sections, but in other cases, it may be very beneficial in reducing the likelihood of

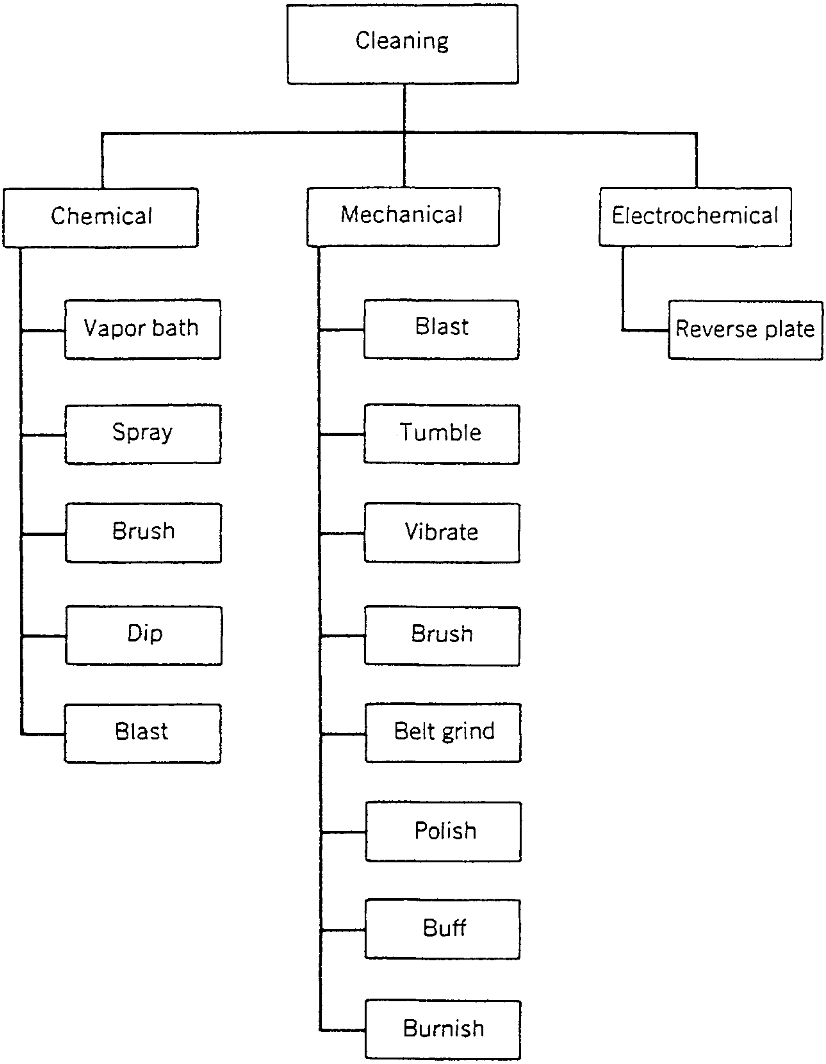


**Fig. 34.22** Cleaning methods.

fatigue failure. When used for the latter purpose, the process is more commonly known as *shot peening*.

***Water Slurries.*** Liquid or vaporized solvents may, by themselves, be blasted against a surface for high-speed cleaning of oil and grease films with both chemical and mechanical action. Water containing rust-inhibiting chemicals may carry, in suspension, fine abrasive particles that provide a grinding cutting-type action for finish improvement along with cleaning. The blasting method using this medium is commonly known as *liquid honing*.

### Abrasive Barrel Finishing

*Barrel finishing, rolling, tumbling,* and *rattling* are terms used to describe similar operations that consist of packing parts together with some cleaning media in a cylinder or drum, which can be rotated to cause movement among them. The media may be abrasive (either fine or coarse); metal stars, slugs, or balls; stones; wood chips; sawdust; or cereals. The work may be done wet or dry, depending on the materials being worked with, the kind of surface finish desired, and the kind of equipment available.

### Wire Brushing

A number of cleaning operations can be quickly and easily performed by use of a high-speed rotating wire brush. In addition to cleaning, the contact rubbing of the wire ends across the work surface produce surface improvement by a burnishing-type action. Sharp edges and burrs can be removed.

### Abrasive Belt Finishing

Continuous fabric belts coated with abrasive can be driven in several kinds of machines to provide a straight-line cutting motion for grinding, smoothing, and polishing work surfaces. Plane surfaces are the most common surfaces worked on with fabric belts.

### Polishing

The term *polishing* may be interpreted to mean any nonprecision procedure providing a glossy surface, but is most commonly used to refer to a surface-finishing process using a flexible abrasive wheel. The wheels may be constructed of felt or rubber with an abrasive band, of multiple coated abrasive discs, of leaves of coated abrasive, of felt or fabric to which loose abrasive is added as needed, or of abrasives in a rubber matrix.

### Buffing

About the only difference between buffing and polishing is that, for buffing, a fine abrasive carried in wax or a similar substance is charged on the surface of a flexible level.

### Electropolishing

If a workpiece is suspended in an electrolyte and connected to the anode in an electrical circuit, it will supply metal to the electrolyte in a reverse plating process. Material will be removed faster from the high spots of the surface than from the depressions and will thereby increase the average smoothness. The cost of the process is prohibitive for very rough surfaces because larger amounts of metal must be removed to improve surface finish than would be necessary for the same degree of improvement by mechanical polishing. Electropolishing is economical only for improving a surface that is already good or for polishing complex and irregular shapes, the surfaces of which are not accessible to mechanical polishing and buffing equipment.

## 34.7.2 Coatings

Many products, particularly those exposed to view and those subject to change by the environment with which they are in contact, need some type of coating for improved appearance or for protection from chemical attack. The need for corrosion protection for maintenance and appearance is important. In addition to change of appearance, loss of actual material, change of dimensions, and decrease of strength, corrosion may be the cause of eventual loss of service or failure of a product. Material that must carry loads in structural applications, especially when the loads are cyclic in nature, may fail with fatigue if corrosion is allowed to take place. Corrosion occurs more readily in highly stressed material, where it attacks grain boundaries in such a way as to form points of stress concentration that may be nuclei for fatigue failure.

Harness and wear resistance, however, can be provided on a surface by plating with hard metals. Chromium plating of gages and other parts subject to abrasion is frequently used to increase their wear life. Coatings of plastic material and asphaltic mixtures are sometimes placed on surfaces to provide sound-deadening. The additional benefit of protection from corrosion is usually acquired at the same time.

Plastics of many kinds, mostly of the thermoplastic type because they are easier to apply and also easier to remove later if necessary, are used for mechanical protection. Highly polished material may be coated with plastic, which may be stripped off later, to prevent abrasion and scratches during processing. It is common practice to coat newly sharpened cutting edges of tools by dipping them in thermoplastic material to provide mechanical protection during handling and storage.

### Organic Coatings

Organic coatings are used to provide pleasing colors, to smooth surfaces, to provide uniformity in both color and texture, and to act as a protective film for control of corrosion. Organic resin coatings do not ordinarily supply any chemical-inhibiting qualities. Instead, they merely provide a separating film between the surface to be protected and the corrosive environment. The important properties, therefore, are continuity, permeability, and adhesion characteristics.

### Paints, Varnishes, and Enamels

***Paints.*** Painting is a generic term that has come to mean the application of almost any kind of organic coating by any method. Because of this interpretation, it is also used generally to describe a broad class of products. As originally defined and as used most at present, paint is a mixture of pigment in a drying oil. The oil serves as a carrier for the pigment and in addition creates a tough continuous film as it dries. Drying oils, one of the common ones of which is linseed oil, become solid when large surface areas are exposed to air. Drying starts with a chemical reaction of oxidation. Nonreversible polymerization accompanies oxidation to complete the change from liquid to solid.

***Varnish.*** Varnish is a combination of natural or synthetic resins and drying oil, sometimes containing volatile solvents as well. The material dries by a chemical reaction in the drying oil to a clear or slightly amber-colored film.

***Enamel.*** Enamel is a mixture of pigment in varnish. The resins in the varnish cause the material to dry to a smoother, harder, and glossier surface than is produced by ordinary paints. Some enamels are made with thermosetting resins that must be baked for complete dryness. These baking enamels provide a toughness and durability not usually available with ordinary paints and enamels.

### Lacquers

The term *lacquer* is used to refer to finishes consisting of thermoplastic materials dissolved in fast-drying solvents. One common combination is cellulose nitrate dissolved in butyl acetate. Present-day lacquers are strictly air-drying and form films very quickly after being applied, usually by spraying. No chemical change occurs during the hardening of lacquers; consequently, the dry film can be redissolved in the thinner. Cellulose acetate is used in place of cellulose nitrate in some lacquers because it is nonflammable. Vinyls, chlorinated hydrocarbons, acrylics, and other synthetic thermoplastic resins are also used in the manufacture of lacquers.

### Vitreous Enamels

Vitreous, or porcelain, enamel is actually a thin layer of glass fused onto the surface of a metal, usually steel or iron. Shattered glass, ball milled in a fine particle size, is called *frit.* Frit is mixed with clay, water, and metal oxides, which produce the desired color, to form a thin slurry called *slip.* This is applied to the prepared metal surface by dipping or spraying and, after drying, is fired at approximately 1470°F (800°C) to fuse the material to the metal surface.

### Metallizing

Metal spraying, or metallizing, is a process in which metal wire or powder is fed into an oxyacetylene heating flame and then, after melting, is carried by high-velocity air to be impinged against the work surface. The small droplets adhere to the surface and bond together to build up a coating.

### Vacuum Metallizing

Some metals can be deposited in very thin films, usually for reflective or decorative purposes, as a vapor deposit. The metal is vaporized in a high-vacuum chamber containing the parts to be coated. The metal vapor condenses on the exposed surfaces in a thin film that follows the surface pattern. The process is cheap for coating small parts, considering the time element only, but the cost of special equipment needed is relatively high.

Aluminum is the most used metal for deposit by this method and is used frequently for decorating or producing a mirror surface on plastics. The thin films usually require mechanical protection by covering with lacquer or some other coating material.

### Hot-Dip Plating

Several metals, mainly zinc, tin, and lead, are applied to steel for corrosion protection by a hot-dip process. Steel in sheet, rod, pipe, or fabricated form, properly cleansed and fluxed, is immersed in molten plating metal. As the work is withdrawn, the molten metal that adheres solidifies to form a protective coat. In some of the large mills, the application is made continuously to coil stock that is fed through the necessary baths and even finally inspected before being recoiled or cut into sheets.

### Electroplating

Coatings of many metals can be deposited on other metals, and on nonmetals when suitably prepared, by electroplating. The objectives of plating are to provide protection against corrosion, to improve appearance, to establish wear- and abrasion-resistant surfaces, to add material for dimensional increase, and to serve as an intermediate step of multiple coating. Some of the most common metals deposited in this way are copper, nickel, cadmium, zinc, tin, silver, and gold. The majority are used to provide some kind of corrosion protection but appearance also plays a strong part in their use.

### Temporary Corrosion Protection

It is not uncommon in industry for periods of time, sometimes quite long periods, to elapse between manufacture, assembly, shipment, and use of parts. Unless a new processing schedule can be worked out, about the only cure for the problem is corrosion protection suitable for the storage time and exposure. The coatings used are usually nondrying organic materials, called *shushing compounds,* that can be removed easily. The two principal types of compounds used for this purpose are petroleum-based materials, varying from extremely light oils to semisolids, and thermoplastics. The most common method of application of shushing compounds for small parts is by dipping. Larger parts that cannot be handled easily may be sprayed, brushed, or flow coated with the compound.

## 34.7.3 Chemical Conversions

A relatively simple and often fully satisfactory method for protection from corrosion is by conversion of some of the surface material to a chemical composition that resists from the environment. These converted metal surfaces consist of relatively thin (seldom more than 0.001 in. (0.025 mm) thick) inorganic films that are formed by chemical reaction with the base material. One important feature of the conversion process is that the coatings have little effect on the product dimensions.

### Anodizing

Aluminum, magnesium, and zinc can be treated electrically in a suitable electrolyte to produce a corrosion-resistant oxide coating. The metal being treated is connected to the anode in the circuit, which provides the name *anodizing* for the process. Aluminum is commonly treated by anodizing that produces an oxide film thicker than, but similar to, that formed naturally with exposure to air. Anodizing of zinc has very limited use. The coating produced on magnesium is not as protective as that formed on aluminum, but does provide some protective value and substantially increases protection when used in combination with paint coatings.

### Chromate Coatings

Zinc is usually considered to have relatively good corrosion resistance. This is true when the exposure is to normal outdoor atmosphere where a relatively thin corrosion film forms. Contact with either highly aerated water films or immersion in stagnant water containing little oxygen causes uneven corrosion and pitting. The corrosion products of zinc are less dense than the base material, so that heavy corrosion not only destroys the product appearance, but also may cause malfunction by binding moving parts. Corrosion of zinc can be substantially slowed by the production of chromium salts on its surface. The corrosion resistance of magnesium alloys can be increased by immersion of anodic treatment in acid baths containing dichromates. Chromate treatment of both zinc and magnesium improves corrosion resistance, but is used also to improve adhesion of paint.

### Phosphate Coatings

Phosphate coatings, used mostly on steel, result from a chemical reaction of phosphoric acid with the metal to form a nonmetallic coating that is essentially phosphoric salts. The coating is produced by immersing small items or spraying large items with the phosphating solution. Phosphate surfaces may be used alone for corrosion resistance, but their most common application is as a base for paint coatings. Two of the most common application methods are called *parkerizing* and *bonderizing.*

### Chemical Oxide Coatings

A number of proprietary blacking processes, used mainly on steel, produce attractive black oxide coatings. Most of the processes involve the immersing of steel in a caustic soda solution, heated to about 300°F (150°C) and made strongly oxidizing by the addition of nitrites or nitrates. Corrosion resistance is rather poor unless improved by application of oil, lacquer, or wax. As in the case of most of the other chemical-conversion procedures, this procedure also finds use as a base for paint finishes.

## BIBLIOGRAPHY

Alting, L., *Manufacturing Engineering Processes,* Marcel Dekker, New York, 1982.

Amstead, B. H., P. F. Ostwald, and M. L. Begeman, *Manufacturing Processes,* 8th ed., Wiley, New York, 1988.

DeGarmo, E. P., J. T. Black, and R. A. Kohser, *Material and Processes in Manufacturing,* 7th ed., Macmillan, New York, 1988.

Doyle, L. E., G. F. Schrader, and M. B. Singer, *Manufacturing Processes and Materials for Engineers,* Prentice-Hall, Englewood Cliffs, NJ, 1985.

LeGrand, R. (ed.), *American Machinist's Handbook,* McGraw-Hill, New York, 1973.

Kalpakjian, S., *Manufacturing Processes for Engineering Materials,* Addison-Wesley, Reading, MA, 1994.

Kronenberg, M., *Machining Science and Application,* Pergamon, London, 1966.

Lindberg, R. A., *Processes and Materials of Manufacture,* 2nd ed., Allyn and Bacon, Boston, MA, 1977.

*Machining Data Handbook,* 3rd ed., Machinability Data Center, Cincinnati, OH, 1980.

*Metals Handbook,* 8th ed., Vol. 4, *Forming,* Vol. 5, *Forging and Casting,* American Society for Metals, Metals Park, OH, 1985.

Moore, H. D., and D. R. Kibbey, *Manufacturing Materials and Processes,* 3rd ed., Wiley, New York, 1982.

Niebel, B. W., and A. B. Draper, *Product Design and Process Engineering,* McGraw-Hill, New York, 1974.

Schey, J. A., *Introduction to Manufacturing Processes,* McGraw-Hill, New York, 1977.

Shaw, M. C., *Metal Cutting Principles,* Oxford University Press, Oxford, 1984.

Society of Manufacturing Engineers, *Tool and Manufacturing Engineers Handbook,* Vol. 2, *Forming;* Vol. 3, *Materials, Finishing and Coating,* McGraw-Hill, New York, 1985.

Zohdi, M. E., "Statistical Analysis, Estimation and Optimization of Surface Finish," in *Proceedings of International Conference on Development of Production Systems,* Copenhagen, Denmark, 1974.