Sheet-Metal Forming Processes and Equipment

CHAPTER 16

- This chapter describes the important characteristics of sheet metals and the forming processes employed to produce a wide variety of products.
- The chapter opens with a discussion of the shearing operation, a process that takes place to cut sheet metal into blanks of desired shapes or to remove portions of the material such as for holes or slots.
- A discussion of sheet-metal formability follows, with special emphasis on the specific metal properties that affect formability.
- The chapter then presents various bending operations for sheets, plates, and tubes, as well as operations such as stretch forming, rubber forming, spinning, peen forming, and superplastic forming.
- The important process of deep drawing is then described, along with deep drawability, as it relates to the production of containers with thin walls.
- The chapter ends with a discussion of part designs, equipment characteristics, and the economic considerations for all these operations.

Typical parts made by sheet-metal forming: Car bodies, aircraft fuselages, trailers, office furniture, appliances, fuel tanks, and cookware.

Alternative process: Die casting, thermoforming, pultrusion, injection molding, blow molding.

16.1 Introduction

Products made of **sheet metals** are all around us. They include a very wide range of consumer and industrial products, such as beverage cans, cookware, file cabinets, metal desks, appliances, car bodies, trailers, and aircraft fuselages (Fig. 16.1). Sheet forming dates back to about 5000 B.C., when household utensils and jewelry were made by hammering and stamping gold, silver, and copper. Compared to those made by casting and by forging, sheet-metal parts offer the advantages of light weight and versatile shape.

As described throughout this chapter, there are numerous processes employed for making sheet-metal parts. However, the term **pressworking** or **press forming** is used commonly in industry to describe general sheet-forming operations, because they typically are performed on *presses* (described in Sections 14.8 and 16.14) using a

FIGURE 16.1 Examples of sheet-metal parts. (a) Stamped parts. (b) Parts produced by spinning. *Source*: (a) Courtesy of Williamsburg Metal Spinning & Stamping Corp.

set of dies. A sheet-metal part produced in presses is called a *stamping* (after the word *stamp*, first used around 1200 A.D. and meaning "to force downward" or "to pound"). Note that this is a term similar to *forging* or *casting*, commonly used to describe parts made by those individual processes using dies or molds, respectively.

Low-carbon steel is the most commonly used sheet metal because of its low cost and generally good strength and formability characteristics. More recently developed alloys, such as TRIP and TWIP steels (see Section 5.5.7), have become popular for automotive applications because of their high strength; they are well suited for providing good crash protection in a lightweight design. Aluminum is the most common material for such sheet-metal applications as beverage cans, packaging, kitchen utensils, and applications where corrosion resistance is a concern. The common metallic materials for aircraft and aerospace applications are aluminum and titanium, although they are being replaced increasingly with composite materials, as described in Chapters 9 and 19.

Most manufacturing processes involving sheet metal are performed at room temperature. Hot stamping is occasionally performed in order to increase formability and decrease forming loads on machinery. Typical materials in hot-stamping operations are titanium alloys and various high-strength steels.

This chapter first describes the methods by which blanks are cut from large rolled sheets then processed further into desired shapes by a wide variety of methods. The chapter also includes discussions on the characteristic features of sheet metals, the techniques employed to determine their formability, and the construction of forming-limit diagrams. All of the major processes of sheet forming and the equipment used to make sheet-metal products (as outlined in Table 16.1) are also described.

16.2 Shearing

Before a sheet-metal part is made, a *blank* of suitable dimensions first is removed from a large sheet (usually from a coil) by *shearing*. This sheet is cut by subjecting it to shear stresses, generally using a punch and a die (Fig. 16.2a). The typical features of the sheared edges of the sheet and of the slug are shown in Fig. 16.2b and c, respectively. Note that the edges are not smooth nor are they perpendicular to the plane of the sheet.

Shearing generally starts with the formation of cracks on both the top and bottom edges of the workpiece (at points *A* and *B*, and *C* and *D*, in Fig. 16.2a). These

TABLE 16.1

General Characteristics of Sheet-metal Forming Processes (in alphabetic order)

Forming process	Characteristics
Drawing	Shallow or deep parts with relatively simple shapes, high production rates, high tooling and equipment costs
Explosive	Large sheets with relatively simple shapes, low tooling costs but high labor cost, low-quantity production, long cycle times
Incremental	Simple to moderately complex shapes with good surface finish; low production rates, but no dedicated tooling required; limited materials
Magnetic-pulse	Shallow forming, bulging, and embossing operations on relatively low strength sheets, requires special tooling
Peen	Shallow contours on large sheets, flexibility of operation, generally high equipment costs, process also used for straightening formed parts
Roll	Long parts with constant simple or complex cross sections, good surface finish, high production rates, high tooling costs
Rubber	Drawing and embossing of simple or relatively complex shapes, sheet surface protected by rubber membranes, flexibility of operation, low tooling costs
Spinning	Small or large axisymmetric parts; good surface finish; low tooling costs, but labor costs can be high unless operations are automated
Stamping	Includes a wide variety of operations, such as punching, blanking, embossing, bending, flanging, and coining; simple or complex shapes formed at high production rates; tooling and equipment costs can be high, but labor cost is low
Stretch	Large parts with shallow contours, low-quantity production, high labor costs, tooling and equipment costs increase with part size
Superplastic	Complex shapes, fine detail and close dimensional tolerances, long forming times (hence production rates are low), parts not suitable for high-temperature use

cracks eventually meet each other and complete separation occurs. The rough *fracture surfaces* are due to the cracks; the smooth and shiny *burnished surfaces* on the hole and the slug are from the contact and rubbing of the sheared edge against the walls of the punch and die, respectively.

The major processing parameters in shearing are

- The shape of the punch and die
- The speed of punching
- Lubrication
- The **clearance**, c, between the punch and the die.

The clearance is a major factor in determining the shape and the quality of the sheared edge. As the clearance increases, the zone of deformation (Fig. 16.3a) becomes larger and the sheared edge becomes rougher. The sheet tends to be pulled into the clearance region, and the perimeter or edges of the sheared zone become rougher. Unless such edges are acceptable as produced, secondary operations may be required to make them smoother (which will increase the production cost).

Edge quality can be improved with increasing punch speed; speeds may be as high as 10 to 12 m/s (30 to 40 ft/s). As shown in Fig. 16.3b, sheared edges can undergo severe cold working due to the high shear strains involved. Work hardening of the edges then will reduce the ductility of the edges and thus adversely affect the formability of the sheet during subsequent operations, such as bending and stretching.

The ratio of the burnished area to the rough areas along the sheared edge (a) increases with increasing ductility of the sheet metal and (b) decreases with increasing sheet thickness and clearance. The extent of the deformation zone in

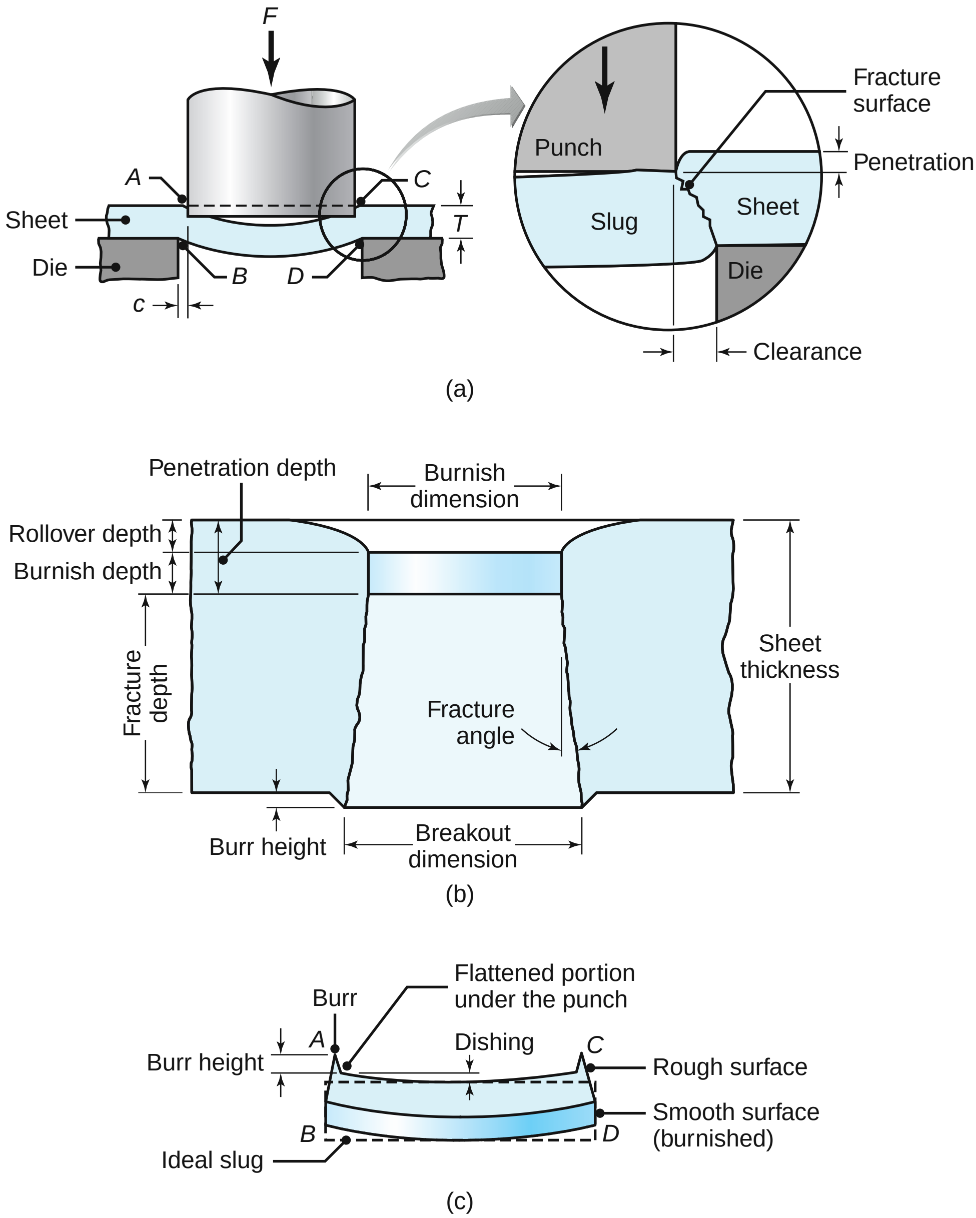


FIGURE 16.2 (a) Schematic illustration of shearing with a punch and die, indicating some of the process variables. Characteristic features of (b) a punched hole and (c) the slug. (Note that the scales of (b) and (c) are different.)

Fig. 16.3 depends on the punch speed. With increasing speed, the heat generated by plastic deformation is confined to a smaller and smaller zone. Consequently, the sheared zone is narrower, and the sheared surface is smoother and exhibits less burr formation. A **burr** is a thin edge or ridge, as shown in Fig. 16.2b and c. Burr height increases with increasing clearance and ductility of the sheet metal. Dull tool edges contribute greatly to large burr formation. The height, shape, and size of the burr can significantly affect subsequent forming operations. Several **deburring** processes are described in Section 26.8.

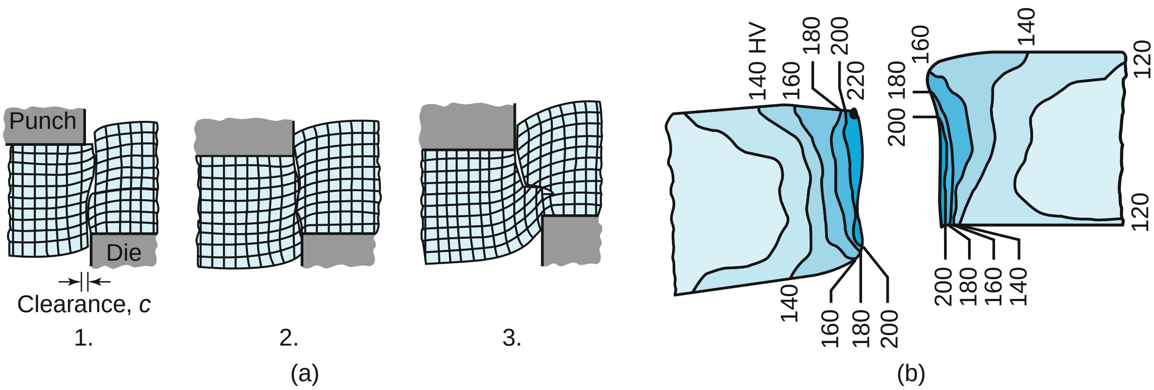


FIGURE 16.3 (a) Effect of the clearance, c, between punch and die on the deformation zone in shearing. As the clearance increases, the material tends to be pulled into the die rather than be sheared. In practice, clearances usually range between 2 and 10% of the thickness of the sheet. (b) Microhardness (HV) contours for a 6.4-mm (0.25-in.) thick AISI 1020 hot-rolled steel in the sheared region. *Source*: After H.P. Weaver and K.J. Weinmann.

Punch Force. The force required to punch out a blank is basically the product of the shear strength of the sheet metal and the total area being sheared along the periphery. The *maximum punch force*, F, can be estimated from the equation

$$F = 0.7TL(\mathrm{UTS}), \tag{16.1}$$

where T is the sheet thickness, L is the total length sheared (such as the perimeter of a hole), and UTS is the ultimate tensile strength of the material. As the clearance increases, the punch force decreases, and the wear on dies and punches also is reduced. The effects of punch shape and die shape on punch forces are described in Section 16.2.3.

Friction between the punch and the workpiece can, however, increase punch force significantly. Furthermore, in addition to the punch force, a force is required to strip the punch from the sheet during its return stroke. This second force, which is in opposite direction of the punch force, is difficult to estimate because of the many factors involved in the operation.

EXAMPLE 16.1 Calculation of Punch Force

Estimate the force required for punching a 1-in. (25-mm) diameter hole through a $\frac{1}{8}$-in. (3.2-mm) thick annealed titanium-alloy Ti-6Al-4V sheet at room temperature.

Solution The force is estimated from Eq. (16.1), where the UTS for this alloy is found from Table 6.10 to be 1000 MPa or 140,000 psi. Thus,

$$F = 0.7\left(\frac{1}{8}\right)(\pi)(1)(140{,}000) = 38{,}500\ \mathrm{lb} = 19.25\ \mathrm{tons}$$
$$= 0.17\ \mathrm{MN}.$$

16.2.1 Shearing Operations

The most common shearing operations are **punching**—where the sheared slug is scrap (Fig. 16.4a) or may be used for some other purpose—and **blanking**—where the slug is the part to be used and the rest is scrap. The operations described next, as

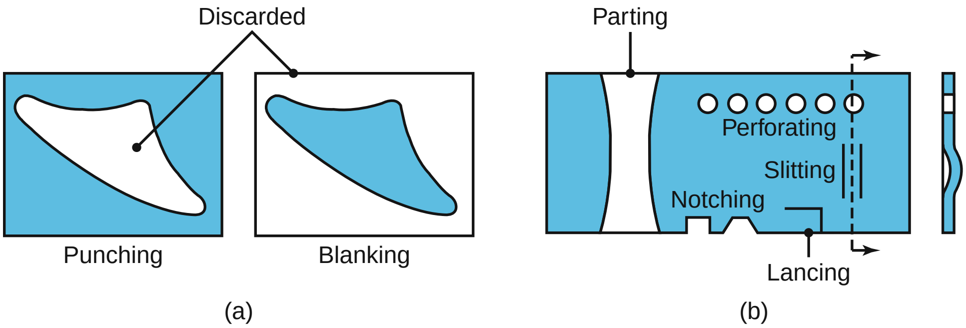


FIGURE 16.4 (a) Punching (piercing) and blanking. (b) Examples of various die-cutting operations on sheet metal. Lancing involves slitting the sheet to form a tab.

well as those described throughout the rest of this chapter, generally are carried out on computer-numerical-controlled machines with quick-change toolholders. Such machines are useful, particularly in making prototypes of sheet-metal parts requiring several operations to produce.

Die Cutting. This is a shearing operation that consists of the following basic processes (Fig. 16.4b):

- **Perforating**: punching a number of holes in a sheet
- **Parting**: shearing the sheet into two or more pieces
- **Notching**: removing pieces (or various shapes) from the edges
- **Lancing**: leaving a tab without removing any material.

Parts produced by these processes have various uses, particularly in assembly with other components. Perforated sheet metals with hole diameters ranging from around 1 mm (0.040 in.) to 75 mm (3 in.) have uses as filters, as screens, in ventilation, as guards for machinery, in noise abatement, and in weight reduction of fabricated parts and structures. They are punched in crank presses (see Fig. 14.17a) at rates as high as 300,000 holes per minute, using special dies and equipment.

Fine Blanking. Very smooth and square edges can be produced by *fine blanking* (Fig. 16.5a). One basic die design is shown in Fig. 16.5b. A V-shaped stinger or impingement mechanically locks the sheet tightly in place and prevents the type of distortion of the material shown in Figs. 16.2b and 16.3. The fine-blanking process, which was developed in the 1960s, involves clearances on the order of 1% of the sheet thickness and that may range from 0.5 to 13 mm (0.02 to 0.5 in.) in most cases. Dimensional tolerances are on the order of ± 0.05 mm (0.002 in.) and less than ± 0.025 mm (0.001 in.) in the case of edge perpendicularity.

Slitting. Shearing operations can be carried out by means of a pair of circular blades similar to those in a can opener (Fig. 16.6). In *slitting*, the blades follow either a straight line, a circular path, or a curved path. A slit edge normally has a burr, which may be folded over the sheet surface by rolling it (flattening) between two rolls. If not performed properly, slitting operations can cause various distortions of the sheared edges.

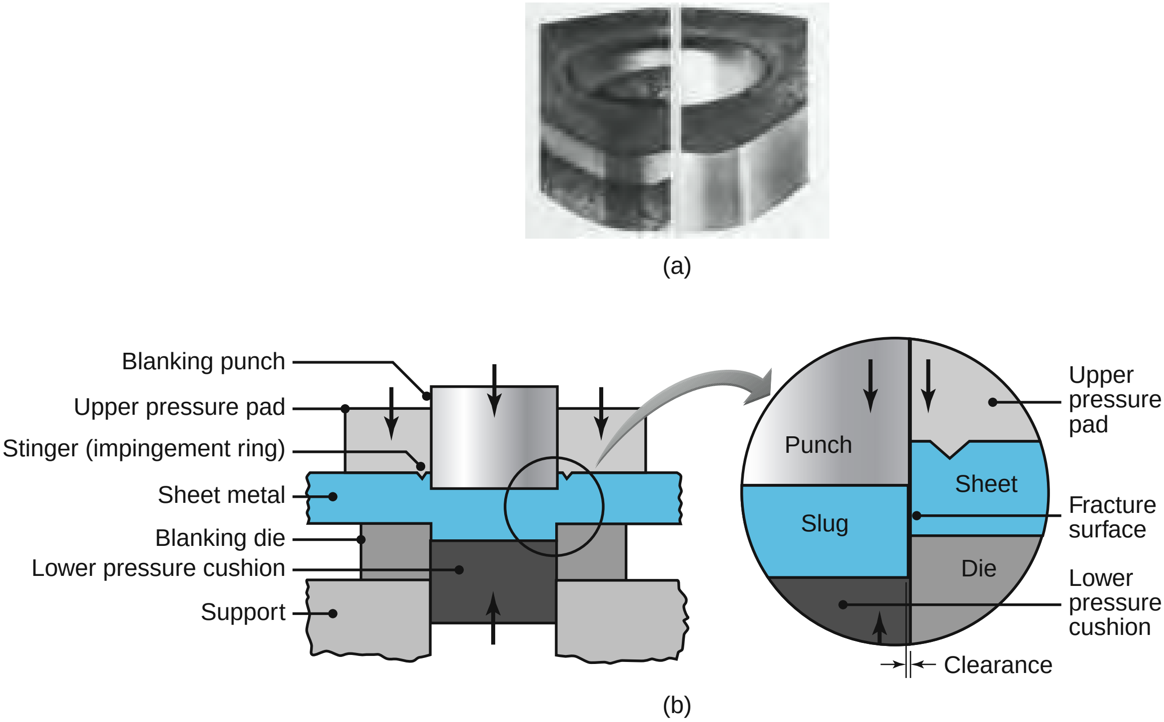


FIGURE 16.5 (a) Comparison of sheared edges produced by conventional (left) and by fine-blanking (right) techniques. (b) Schematic illustration of one setup for fine blanking. *Source*: Courtesy of Feintool U.S. Operations.

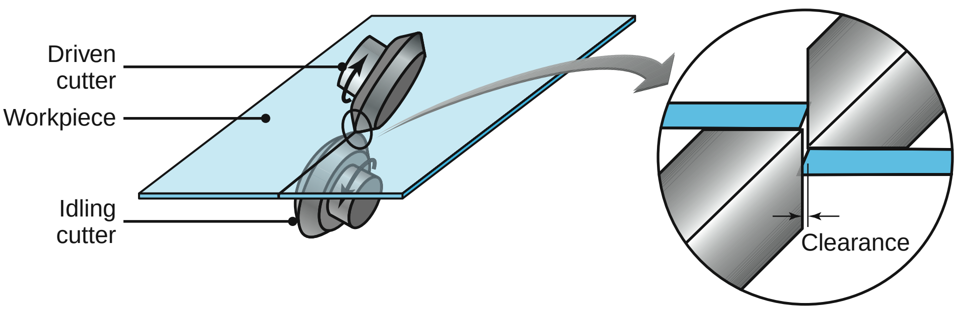


FIGURE 16.6 Slitting with rotary knives. This process is similar to opening cans.

Steel Rules. Soft metals (as well as paper, leather, and rubber) can be blanked with a *steel-rule die*. Such a die consists of a thin strip of hardened steel bent into the shape to be produced (a concept similar to that of a cookie cutter) and held on its edge on a flat wood or polymer base. The die is pressed against the sheet, which rests on the flat surface, and it shears the sheet along the shape of the steel rule.

Nibbling. In *nibbling*, a machine called a *nibbler* moves a small straight punch up and down rapidly into a die. A sheet is fed through the gap and many overlapping holes are made. With manual or automatic control, sheets can be cut along any desired path. In addition to its flexibility, an advantage of nibbling is that intricate slots and notches, such as those shown in Fig. 16.4b, can be produced with standard punches. The process is economical for small production runs because no special dies are required.

Scrap in Shearing. The amount of scrap (*trim loss*) produced in shearing operations can be significant and can be as high as 30% on large stampings (see Table 40.3). Scrap can be a significant factor in manufacturing cost, and it can be reduced substantially by efficient arrangement of the shapes on the sheet to be cut (**nesting**, see Fig. 16.55). Computer-aided design techniques have been developed to minimize the scrap from shearing operations.

16.2.2 Tailor-welded Blanks

In the sheet-metal-forming processes to be described throughout this chapter, the blank is usually a one-piece sheet of one thickness cut from a large sheet. An important variation from these conditions involves *laser-beam butt welding* (see Section 30.7) of two or more pieces of sheet metal with different shapes and thicknesses. The strips are welded to obtain a locally thicker sheet or add a different material and are then coiled.

Because of the small thicknesses involved, the proper alignment of the sheets prior to welding is important. The welded assembly subsequently is formed into a final shape (see Example 16.2). This technique is becoming increasingly important, particularly to the automotive industry. Because each subpiece now can have a different thickness, grade, coating, or other property, tailor-welded blanks possess the needed properties in the desired locations in the blank. The result is

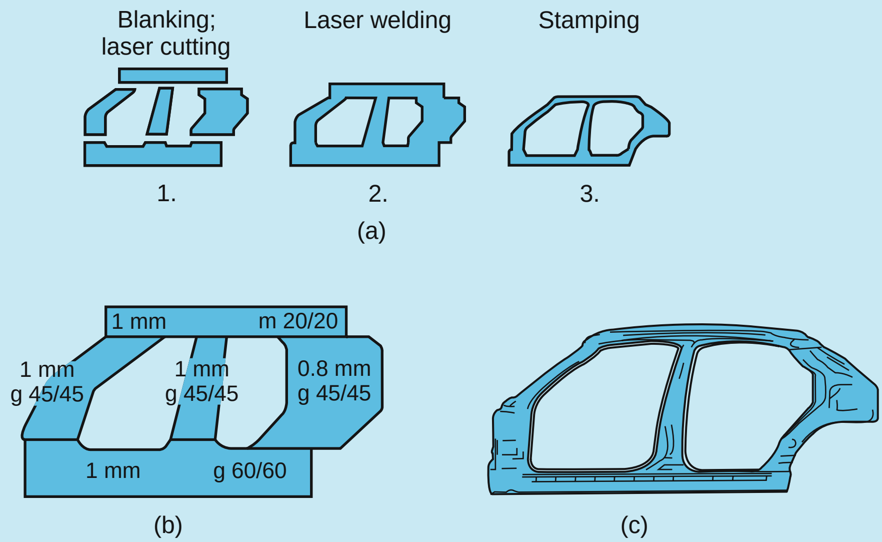
- Reduction in scrap
- Elimination of the need for subsequent spot welding (i.e., in the making of the car body)
- Better control of dimensions
- Improved productivity.

EXAMPLE 16.2 Tailor-welded Sheet Metal for Automotive Applications

An example of the use of tailor-welded sheet metals in automobile bodies is shown in Fig. 16.7. Note that five different pieces are blanked first, which includes cutting by laser beams. Four of these pieces are 1 mm thick, and one is 0.8 mm thick. The pieces are laser butt welded and then stamped into the final shape. In this manner, the blanks can be tailored to a particular application, not only as to shape and thickness, but also by using different-quality sheets—with or without coatings.

Laser-welding techniques are highly developed; as a consequence, weld joints are very strong and reliable. The growing trend toward welding and forming sheet-metal pieces makes possible significant flexibility in the product design, structural stiffness, formability, and crash behavior of an automobile. It also makes possible the use of different materials in one component, weight savings, and cost reduction in materials, scrap, equipment, assembly, and labor.

There are increasing applications for this type of production in automobiles. The various components shown in Fig. 16.8 utilize the advantages outlined above. For example, note in Fig. 16.8(b) that the strength and stiffness required for the support of the shock absorber are achieved by welding a round piece onto the surface of the large sheet. The sheet thickness in such components is varied (depending on its location and on its contribution to such characteristics as stiffness and strength) and thereby makes possible significant weight savings without loss of structural strength and stiffness.



Legend

g 60/60 (45/45) Hot-galvanized alloy steel sheet. Zinc amount: 60/60 (45/45) g/m^2.

m 20/20 Double-layered iron–zinc alloy electroplated steel sheet. Zinc amount 20/20 g/m^2.

FIGURE 16.7 Production of an outer side panel of a car body by laser butt welding and stamping. *Source*: After M. Geiger and T. Nakagawa.

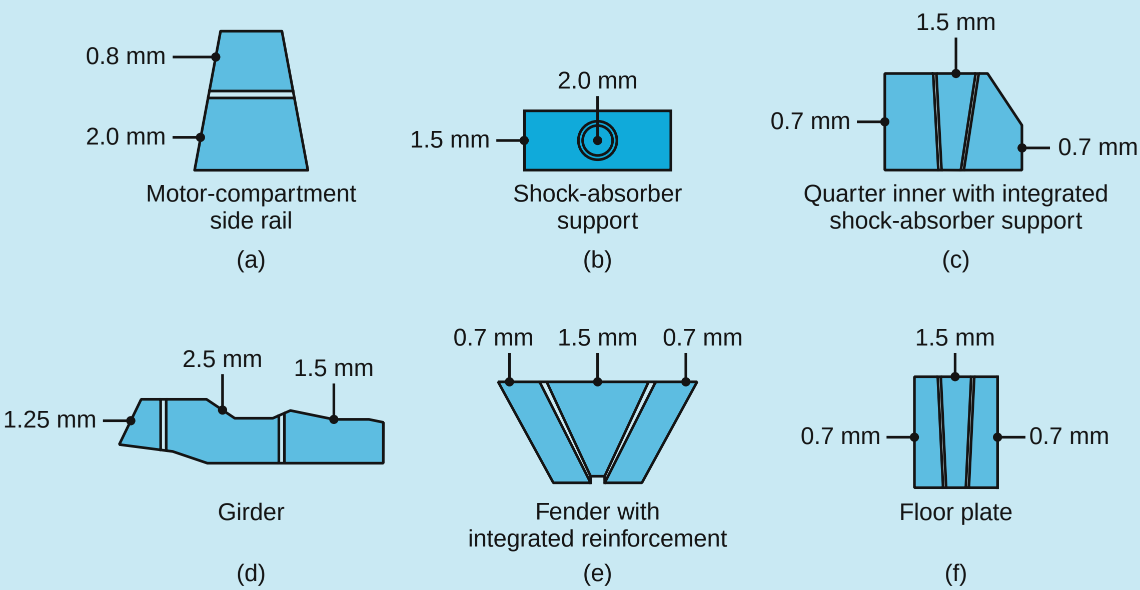


FIGURE 16.8 Examples of laser butt-welded and stamped automotive-body components. *Source*: After M. Geiger and T. Nakagawa.

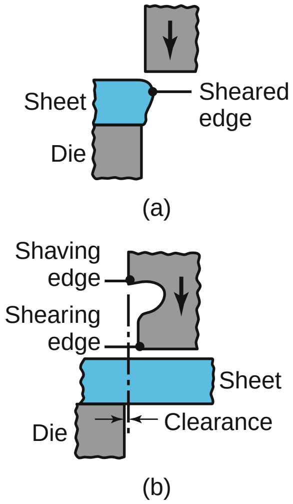


FIGURE 16.9 Schematic illustrations of the shaving process. (a) Shaving a sheared edge. (b) Shearing and shaving combined in one stroke.

16.2.3 Characteristics and Type of Shearing Dies

Clearance. Because the formability of the sheared part can be influenced by the quality of its sheared edges, clearance control is important. The appropriate clearance depends on

- The type of material and its temper
- The thickness and size of the blank
- Its proximity to the edges of other sheared edges or the edges of the original blank.

Clearances generally range between 2 and 8% of the sheet thickness, but they may be as small as 1% (as in fine blanking) or as large as 30%. The smaller the clearance, the better is the quality of the edge. If the sheared edge is rough and not acceptable, it can be subjected to a process called **shaving** (Fig. 16.9a), whereby the extra material from the edge is trimmed by cutting, as also depicted in Fig. 21.3.

As a general guideline, (a) clearances for soft materials are less than those for harder grades; (b) the thicker the sheet, the larger the clearance must be; and (c) as the ratio of hole diameter to sheet thickness decreases, clearances should be larger. In using larger clearances, attention must be paid to the rigidity and the alignment of the presses, the dies, and their setups.

Punch and Die Shape. Note in Fig. 16.2a that the surfaces of the punch and of the die are both flat. Because the entire thickness is sheared at the same time, the punch force increases rapidly during shearing. The location of the regions being sheared at any particular instant can be controlled by *beveling* the punch and die surfaces (Fig. 16.10). This shape is similar to that of some paper punches, which you can observe by looking closely at the tip of the punch. Beveling is suitable particularly for shearing thick sheets because it reduces the force at the beginning of the stroke. It also reduces the operation's noise level, because the operation is smoother.

Note in Fig. 16.10c that the punch tip is symmetrical and in Fig. 16.10d that the die is symmetrical. Hence, there are no lateral forces acting on the punch to cause distortion. By contrast, the punch in Fig. 16.10b has a single taper and thus is subjected to a lateral force. Consequently, the punch and press setups in this latter case must both have sufficient lateral stiffness so that they neither produce a hole that is located improperly nor allow the punch to hit the edge of the lower die (as it might at point *B* or *D* in Fig. 16.2a), causing damage.

Compound Dies. Several operations on the same sheet may be performed in one stroke at one station with a *compound die* (Fig. 16.11). Such combined operations usually are limited to relatively simple shapes, because (a) the process is somewhat slow and (b) the dies rapidly become much more expensive to produce than those for individual shearing operations, especially for complex dies.

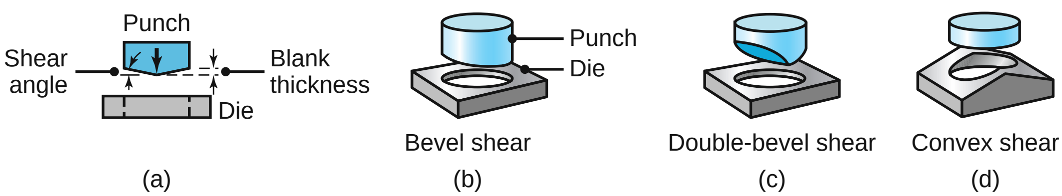


FIGURE 16.10 Examples of the use of shear angles on punches and dies.

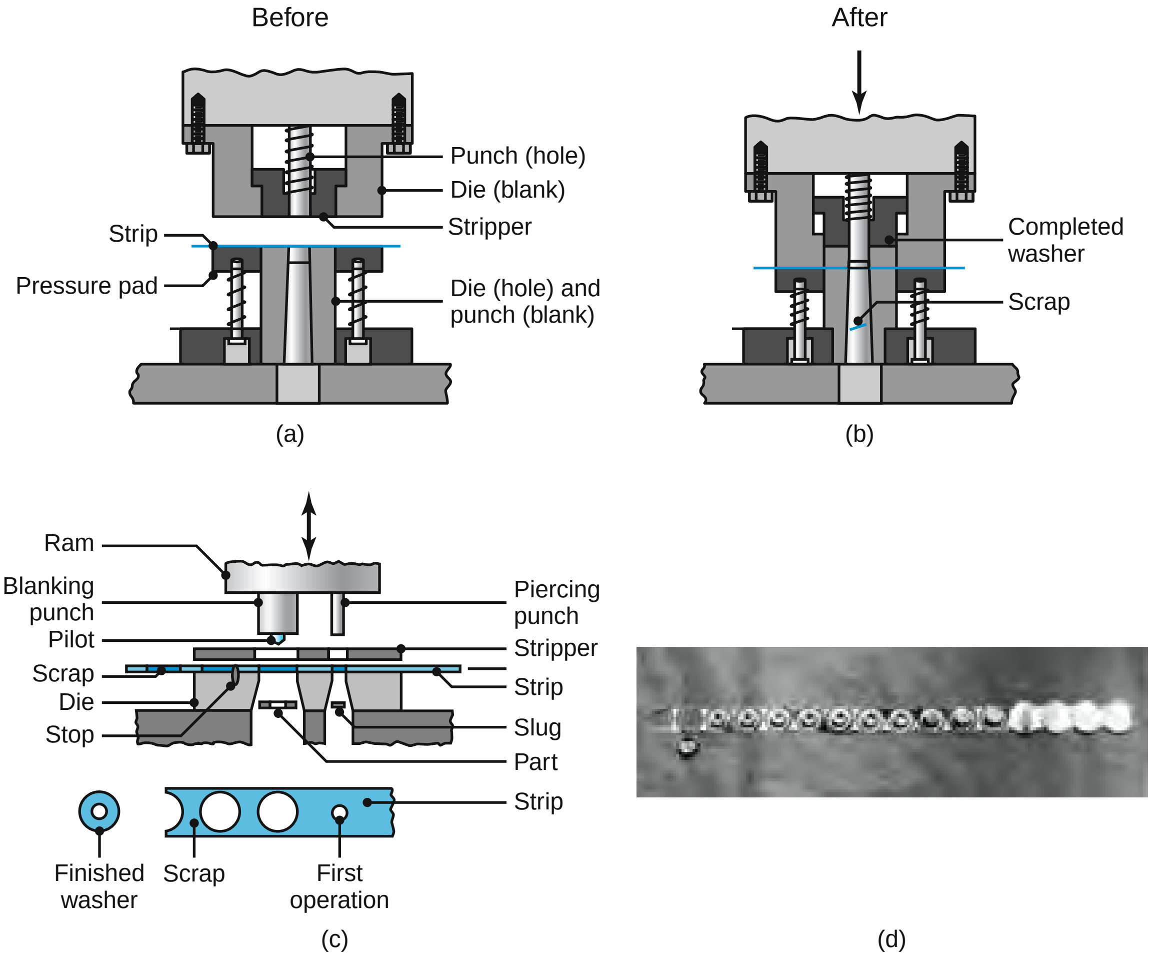


FIGURE 16.11 Schematic illustrations (a) before and (b) after blanking a common washer in a compound die. Note the separate movements of the die (for blanking) and the punch (for punching the hole in the washer). (c) Schematic illustration of making a washer in a progressive die. (d) Forming of the top piece of an aerosol spray can in a progressive die. Note that the part is attached to the strip until the last operation is completed.

Progressive Dies. Parts requiring multiple operations to produce can be made at high production rates in *progressive dies*. The sheet metal is fed through as a coil strip, and a different operation (such as punching, blanking, and notching) is performed at the same station of the machine with each stroke of a series of punches (Fig. 16.11c). An example of a part made in progressive dies is shown in Fig. 16.11d; the part is the small round piece that supports the plastic tip in spray cans.

Transfer Dies. In a *transfer-die* setup, the sheet metal undergoes different operations at different stations of the machine that are arranged along a straight line or a circular path. After each step in a station, the part is transferred to the next station for further operations.

Tool and Die Materials. Tool and die materials for shearing generally are tool steels and (for high production rates) carbides (see Table 5.7). Lubrication is important for reducing tool and die wear, thus improving edge quality.

16.2.4 Miscellaneous Methods of Cutting Sheet Metal

There are several other methods of cutting sheets and, particularly, plates:

- **Laser-beam cutting** is an important process (Section 26.7) typically used with computer-controlled equipment to cut a variety of shapes consistently, in various thicknesses, and without the use of any dies. Laser-beam cutting also can be combined with punching and shearing. These processes cover different and complementary ranges. Parts with certain features can be produced best by one process; some with other features can be produced best by the other process. Combination machines incorporating both capabilities have been designed and built. (See also Example 27.1.)
- **Water-jet cutting** is effective on many metallic as well as nonmetallic materials (Section 27.8).
- Cutting with a **band saw**; this method is a chip-removal process.
- **Friction sawing** involves a disk or blade that rubs against the sheet or plate at high surface speeds (Section 24.5).
- **Flame cutting** is another common method, particularly for thick plates; it is used widely in shipbuilding and on heavy structural component (Section 30.8).

16.3 Sheet-metal Characteristics and Formability

After a blank is cut from a larger sheet or coil, it is formed into various shapes by several processes described in the rest of this chapter. We will now briefly review those characteristics of sheet metals that have important effects on these forming operations, as outlined in Table 16.2.

TABLE 16.2

Important Metal Characteristics for Sheet-forming Operations

Characteristic	Importance
Elongation	Determines the capability of the sheet metal to stretch without necking and failure; high strain-hardening exponent (n) and strain-rate sensitivity exponent (m) are desirable
Yield-point elongation	Typically observed with mild-steel sheets (also called Lüder's bands or stretcher strains); results in depressions on the sheet surface; can be eliminated by temper rolling, but sheet must be formed within a certain time after rolling
Anisotropy (planar)	Exhibits different behavior in different planar directions, present in cold-rolled sheets because of preferred orientation or mechanical fibering, causes earing in deep drawing, can be reduced or eliminated by annealing but at lowered strength
Anisotropy (normal)	Determines thinning behavior of sheet metals during stretching, important in deep drawing
Grain size	Determines surface roughness on stretched sheet metal; the coarser the grain, the rougher is the appearance (like an orange peel); also affects material strength and ductility
Residual stresses	Typically caused by nonuniform deformation during forming, results in part distortion when sectioned, can lead to stress-corrosion cracking, reduced or eliminated by stress relieving
Springback	Due to elastic recovery of the plastically deformed sheet after unloading, causes distortion of part and loss of dimensional accuracy, can be controlled by techniques such as overbending and bottoming of the punch
Wrinkling	Caused by compressive stresses in the plane of the sheet; can be objectionable; depending on its extent, can be useful in imparting stiffness to parts by increasing their section modulus; can be controlled by proper tool and die design
Quality of sheared edges	Depends on process used; edges can be rough, not square, and contain cracks, residual stresses, and a work-hardened layer, which are all detrimental to the formability of the sheet; edge quality can be improved by fine blanking, reducing the clearance, shaving, and improvements in tool and die design and lubrication
Surface condition of sheet	Depends on sheet-rolling practice; important in sheet forming, as it can cause tearing and poor surface quality

Elongation. Sheet-metal-forming processes rarely involve simple uniaxial stretching like that in a tension test. However, observations from tensile testing are useful and necessary for understanding the behavior of metals in these operations. Recall from Section 2.2 that a specimen subjected to tension first undergoes **uniform elongation** and that when the load exceeds the ultimate tensile strength of the material, the specimen begins to neck and thus elongation is no longer uniform.

Because the material usually is being stretched in sheet forming, high uniform elongation is desirable for good formability. The true strain at which necking begins is numerically equal to the *strain-hardening exponent* (n) shown in Eq. (2.8). Thus, a high n value indicates large uniform elongation (see also Table 2.3). Necking may be *localized* or it may be *diffuse*, depending on the *strain-rate sensitivity* (m) of the material; this relationship is given in Eq. (2.9). The higher the value of m, the more diffuse the neck becomes. A diffuse neck is desirable in sheet-forming operations. In addition to uniform elongation and necking, the **total elongation** of the specimen (in terms of that for a 50-mm gage length) is also a significant factor in the formability of sheet metals.

Yield-point Elongation. Low-carbon steels and some aluminum–magnesium alloys exhibit a behavior called *yield-point elongation*: having both upper and lower yield points (Fig. 16.12a). This behavior results in **Lüder's bands** (also called *stretcher-strain marks* or *worms*) on the sheet (Fig. 16.12b)—elongated depressions on the surface of the sheet, such as can be found on the bottom of cans containing common household products (Fig. 16.12c). These marks may be objectionable in the final product, because coarseness on the surface degrades appearance and may cause difficulties in subsequent coating and painting operations.

The usual method of avoiding Lüder's bands is to eliminate or reduce yield-point elongation by reducing the thickness of the sheet 0.5 to 1.5% by cold rolling (**temper** or **skin rolling**). Because of strain aging, however, the yield-point elongation reappears after a few days at room temperature or after a few hours at higher temperatures. To prevent this undesirable occurrence, the material should be formed within a certain time limit (which depends on the type of the steel).

Anisotropy. An important factor that influences sheet-metal forming is *anisotropy* (*directionality*) of the sheet. Recall that anisotropy is acquired during the thermomechanical processing of the sheet and that there are two types of anisotropy: *crystallographic anisotropy* (preferred orientation of the grains) and *mechanical fibering*

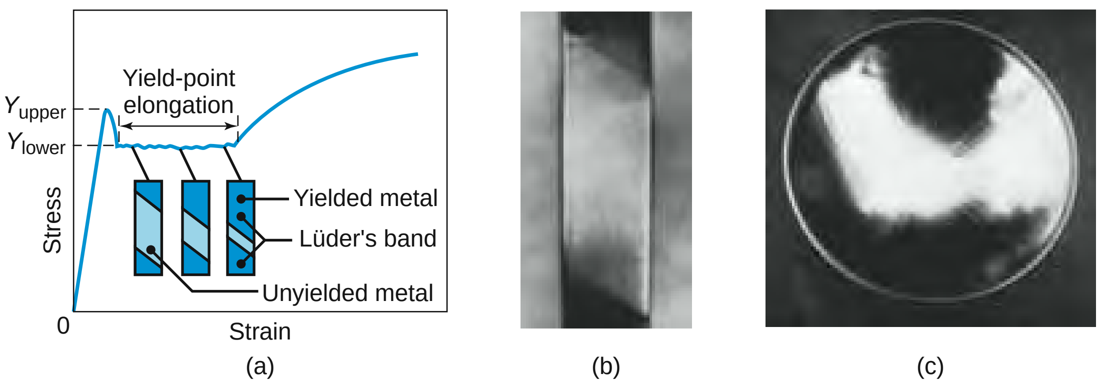


FIGURE 16.12 (a) Yield-point elongation in a sheet-metal specimen. (b) Lüder's bands in a low-carbon steel sheet. (c) Stretcher strains at the bottom of a steel can for household products. *Source*: (b) Courtesy of Caterpillar, Inc.

(alignment of impurities, inclusions, and voids throughout the thickness of the sheet). The relevance of this subject is discussed further in Section 16.4.

Grain Size. As described in Section 1.4, grain size affects mechanical properties and influences the surface appearance of the formed part (*orange peel*). The smaller the grain size, the stronger is the metal; the coarser the grain, the rougher is the surface appearance. An ASTM grain size of 7 or finer (Table 1.1) is preferred for general sheet-forming operations.

Dent Resistance of Sheet Metals. Dents commonly are found on cars, appliances, and office furniture. Dents usually are caused by dynamic forces from moving objects that hit the sheet metal. In typical automotive panels, for example, velocities at impact range up to 45 m/s (150 ft/s). Thus, it is the *dynamic yield stress* (yield stress under high rates of deformation), rather than the static yield stress, that is the significant strength parameter.

Dynamic forces tend to cause *localized* dents, whereas static forces tend to *diffuse* the dented area. This phenomenon may be demonstrated by trying to dent a piece of flat sheet metal, first by pushing a ball-peen hammer against it and then by striking it with the hammer. Note how localized the dent will be in the latter case. *Dent resistance* of sheet-metal parts has been found to (a) increase as the sheet thickness and its yield stress increase and (b) decrease as its elastic modulus and its overall panel stiffness increase. Consequently, panels rigidly held at their edges have lower dent resistance because of their higher stiffness.

16.4 Formability Tests for Sheet Metals

Sheet-metal formability is of great technological and economic interest, and it generally is defined as the ability of the sheet metal to undergo the desired shape change without failure, such as by necking, cracking, or tearing. As we shall see throughout the rest of this chapter, sheet metals (depending in part on geometry) may undergo two basic modes of deformation: (1) *stretching* and (2) *drawing*. There are important distinctions between these two modes, and different parameters are involved in determining formability under these different conditions. This section describes the methods that generally are used to predict formability.

Cupping Tests. The earliest tests developed to predict sheet-metal formability were cupping tests (Fig. 16.13a). In the *Erichsen test*, the sheet specimen is clamped between two circular, flat dies and a steel ball or round punch is forced into the sheet until a crack begins to appear on the stretched specimen. The *punch depth, d*, at which failure occurs is a measure of the formability of the sheet. Although this and similar tests are easy to perform, they do not simulate the exact conditions of actual forming operations and hence are not particularly reliable, especially for complex parts.

Forming-limit Diagrams. An important advance in testing the formability of sheet metals is the development of *forming-limit diagrams*, as shown in Fig. 16.14. A forming-limit diagram (FLD) for a particular metal is constructed by first marking the flat sheet with a grid pattern of circles (see Fig. 16.15), using chemical or photoprinting techniques. The blank then is stretched over a punch (Fig. 16.13a), and the deformation of the circles is observed and measured in regions where failure (*necking* and *tearing*) has occurred. Although the circles typically are 2.5 to 5 mm (0.1 to 0.2 in.) in diameter, for improved accuracy of measurement, they should be made as small as is practical.

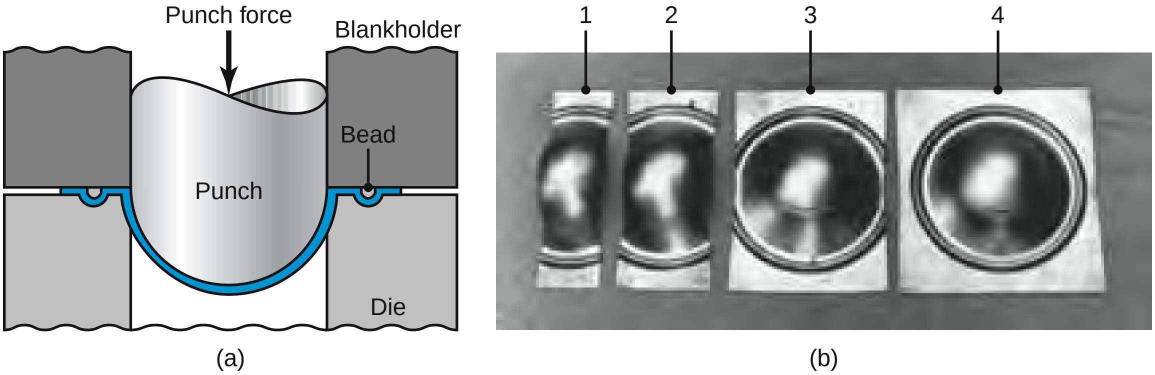


FIGURE 16.13 (a) A cupping test (the Erichsen test) to determine the formability of sheet metals. (b) Bulge-test results on steel sheets of various widths. The specimen farthest left is subjected to, basically, simple tension. The specimen that is farthest right is subjected to equal biaxial stretching. *Source*: Courtesy of Inland Steel Company.

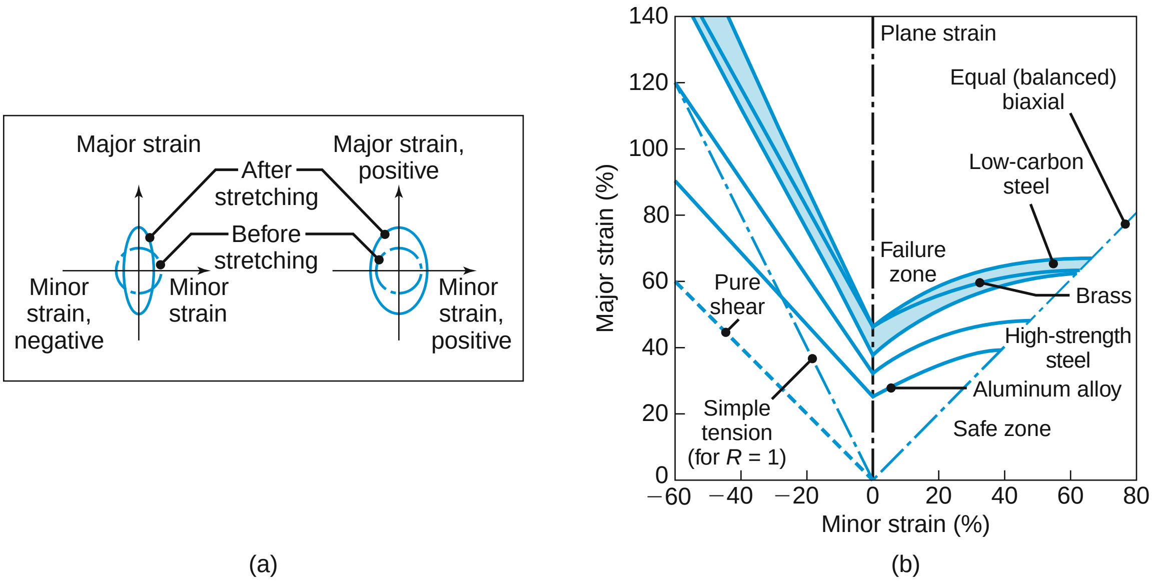


FIGURE 16.14 (a) Strains in deformed circular grid patterns. (b) Forming-limit diagrams (FLD) for various sheet metals. Although the major strain is always positive (stretching), the minor strain may be either positive or negative. R is the normal anisotropy of the sheet, as described in Section 16.4. *Source*: After S.S. Hecker and A.K. Ghosh.

In order to develop unequal stretching to simulate actual sheet-forming operations, the flat specimens are cut to varying widths (Fig. 16.13b) and then tested. Note that a square specimen (farthest right in the figure) produces *equal biaxial stretching* (such as that achieved in blowing up a spherical balloon), whereas a narrow specimen (farthest left in the figure) approaches the state of *uniaxial stretching* (that is, simple tension). After a series of such tests is performed on a particular sheet metal and at different widths, a forming-limit diagram is constructed showing the boundaries between *failure* and *safe* regions (Fig. 16.14b).

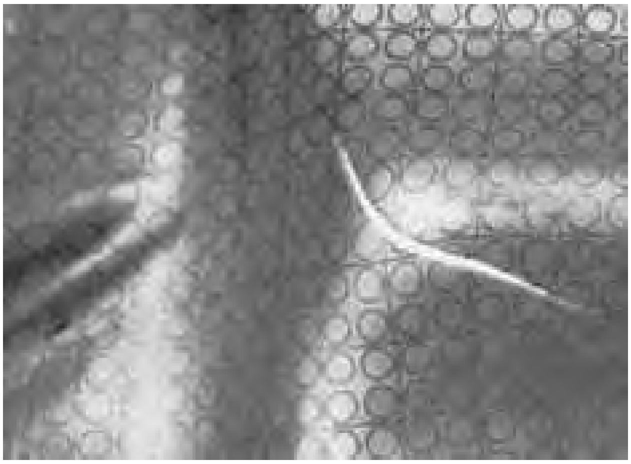


FIGURE 16.15 The deformation of the grid pattern and the tearing of sheet metal during forming. The major and minor axes of the circles are used to determine the coordinates on the forming-limit diagram in Fig. 16.14b. *Source*: S.P. Keeler.

In order to develop a forming-limit diagram, the major and minor engineering strains, as measured from the deformation of the original circles, are obtained. Note in Fig. 16.14a that the original circle has deformed into an ellipse. The *major axis* of the ellipse represents the major direction and magnitude of stretching. The major strain is the *engineering strain* in this direction and is always *positive*, because the sheet is being stretched. The *minor axis* of the ellipse represents the magnitude of the stretching or shrinking in the *transverse* direction.

Note that the minor strain can be either *positive* or *negative*. For example, if a circle is placed in the center of a tensile-test specimen and then stretched uniaxially (simple tension), the specimen becomes narrower as it is stretched (due to the Poisson effect), and thus the minor strain is negative. (This behavior can be demonstrated easily by stretching a rubber band and observing the dimensional changes it undergoes.) On the other hand, if we place a circle on a spherical rubber balloon and inflate it, the minor and major strains are both positive and equal in magnitude.

By comparing the surface areas of the original circle and the deformed circle on the formed sheet, we also can determine whether the thickness of the sheet has changed during deformation. Because the volume remains constant in plastic deformation, we know that if the area of the deformed circle is larger than the original circle, the sheet has become thinner. This phenomenon can be demonstrated easily by blowing up a balloon and noting that it becomes more translucent as it is stretched (because it is getting thinner).

The data thus obtained from different locations in each of the samples shown in Fig. 16.13b are then plotted as shown in Fig. 16.14b. The curves represent the boundaries between *failure zones* and *safe zones* for each type of metal, and as can be noted, the higher the curve, the better is the formability of that particular metal. As expected, different materials and conditions (such as cold worked or heat treated) have different forming-limit diagrams.

Taking the aluminum alloy in Fig. 16.14b as an example, if a circle in a particular location on the sheet has undergone major and minor strains of plus 20% and minus 10%, respectively, there would be no tear in that location of the specimen. On the other hand, if the major and minor strains were plus 80% and minus 40%, respectively, at another location, there would be a tear in that particular location of the specimen. An example of a formed sheet-metal part with a grid pattern is shown in Fig. 16.15. Note the deformation of the circular patterns in the vicinity of the tear on the formed sheet.

It is important to note in forming-limit diagrams that a compressive minor strain of, say, 20% is associated with a higher major strain than is a tensile (positive) minor strain of the same magnitude. In other words, it is desirable for the minor strain to be negative (that is, shrinking in the minor direction). In the forming of complex parts, special tooling can be designed to take advantage of the beneficial effect of negative minor strains on formability.

The effect of sheet thickness on forming-limit diagrams is to raise the curves in Fig. 16.14b. The thicker the sheet, the higher its formability curve, and thus the more formable the sheet is. On the other hand, in actual forming operations, a thick blank may not bend as easily around small radii without cracking (as described in Section 16.5 on bending). Friction and lubrication at the interface between the punch and the sheet metal are also important factors in the test results. With well-lubricated interfaces, the strains in the sheet are distributed more uniformly over the punch. Also, as expected, and depending on the material and its notch sensitivity, surface scratches, deep gouges, and blemishes can reduce formability significantly and thereby lead to premature tearing and failure of the part.

16.5 Bending Sheets, Plates, and Tubes

Bending is one of the most common industrial forming operations. We merely have to look at an automobile body, appliance, paper clip, or file cabinet to appreciate how many parts are shaped by bending. Furthermore, bending also imparts stiffness to the part by increasing its moment of inertia. Note, for example, how corrugations, flanges, beads, and seams improve the stiffness of structures without adding any weight. As a specific example, observe the diametral stiffness of a metal can with and without circumferential beads (see also *beading*).

The terminology used in the bending of a sheet or plate is shown in Fig. 16.16. Note that the outer fibers of the material are in tension, while the inner fibers are in compression. Because of the Poisson effect, the width of the part (*bend length*, L) has become smaller in the outer region and larger in the inner region than the original width (as can be seen in Fig. 16.17c). This phenomenon may be observed easily by bending a rectangular rubber eraser and observing the changes in its shape.

As shown in Fig. 16.16, the **bend allowance,** L_b, is the length of the *neutral axis* in the bend; it is used to determine the length of the blank for a part to be bent. The position of the neutral axis,

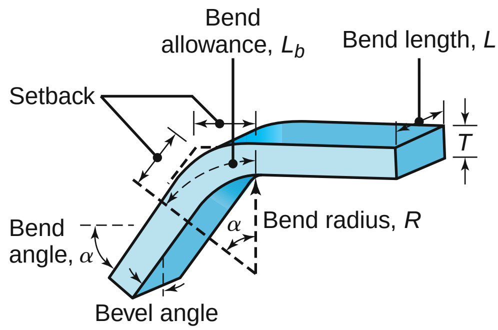


FIGURE 16.16 Bending terminology. Note that the bend radius is measured to the inner surface of the bent part.

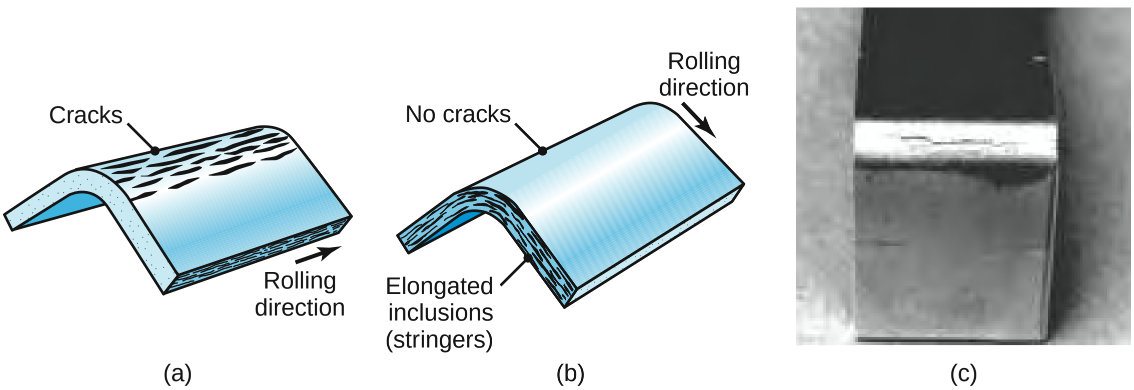


FIGURE 16.17 (a) and (b) The effect of elongated inclusions (stringers) on cracking as a function of the direction of bending with respect to the original rolling direction of the sheet. (c) Cracks on the outer surface of an aluminum strip bent to an angle of 90°. Note also the narrowing of the top surface in the bend area (due to the Poisson effect).

TABLE 16.3

Minimum Bend Radius for Various Metals at Room Temperature

	Condition	
Material	Soft	Hard
Aluminum alloys	0	$6T$
Beryllium copper	0	$4T$
Brass (low-leaded)	0	$2T$
Magnesium	$5T$	$13T$
Steels		
Austenitic stainless	$0.5T$	$6T$
Low-carbon, low-alloy, and HSLA	$0.5T$	$4T$
Titanium	$0.7T$	$3T$
Titanium alloys	$2.6T$	$4T$

however, depends on the radius and the bend angle (as described in texts on mechanics of materials). An approximate formula for the bend allowance is

$$L_b = \alpha(R + kT), \tag{16.2}$$

where α is the bend angle (in radians), T is the sheet thickness, R is the bend radius, and k is a constant. In practice, k values typically range from 0.33 (for $R < 2T$) to 0.5 (for $R > 2T$). Note that for the ideal case, the neutral axis is at the center of the sheet thickness, $k = 0.5$, and, hence,

$$L_b = \alpha\left[R + \left(\frac{T}{2}\right)\right]. \tag{16.3}$$

Minimum Bend Radius. The radius at which a crack first appears at the outer fibers of a sheet being bent is referred to as the *minimum bend radius*. It can be shown that the engineering strain on the outer and inner fibers of a sheet during bending is given by the expression

$$e = \frac{1}{(2R/T) + 1}. \tag{16.4}$$

Thus, as R/T decreases (that is, as the ratio of the bend radius to the thickness becomes smaller), the tensile strain at the outer fiber increases and the material eventually develops cracks (Fig. 16.17). The bend radius usually is expressed (reciprocally) in terms of the thickness, such as $2T$, $3T$, $4T$, and so on (see Table 16.3). Thus, a $3T$ minimum bend radius indicates that the *smallest radius* to which the sheet can be bent without cracking is three times its thickness.

There is an inverse relationship between *bendability* and the tensile reduction of the area of the material (Fig. 16.18). The *minimum bend radius, R*, is, approximately,

$$R = T\left(\frac{50}{r} - 1\right), \tag{16.5}$$

where r is the tensile reduction of area of the sheet metal. Thus, for $r = 50$, the minimum bend radius is zero; that is, the sheet can be folded over itself (see *hemming*, Fig. 16.23) in much the same way as a piece of paper is folded. To increase the bendability of metals, we may increase their tensile reduction of area either by heating or by bending in a high-pressure environment (which improves the ductility of the material;

see *hydrostatic stress*, Section 2.2.8). Bendability also depends on the *edge condition* of the sheet. Since rough edges are points of stress concentration, bendability decreases as edge roughness increases.

Another significant factor in edge cracking is the amount, shape, and hardness of *inclusions* present in the sheet metal and the amount of cold working that the edges undergo during shearing. Because of their pointed shape, inclusions in the form of stringers are more detrimental than globular-shaped inclusions (see also Fig. 2.23). The resistance to edge cracking during bending can be improved greatly by removing the cold-worked regions by shaving or machining the edges of the part (see Fig. 16.9) or by annealing it to improve its ductility.

Anisotropy of the sheet is another important factor in bendability. Cold rolling results in anisotropy by *preferred orientation* or by *mechanical fibering* due to the alignment of any impurities, inclusions, and voids that may be present, as shown in Fig. 1.13. Prior to laying out or nesting (see Fig. 16.55) blanks for subsequent bending, caution should be exercised to cut in the proper direction from a rolled sheet; however, this choice may not always be possible in practice.

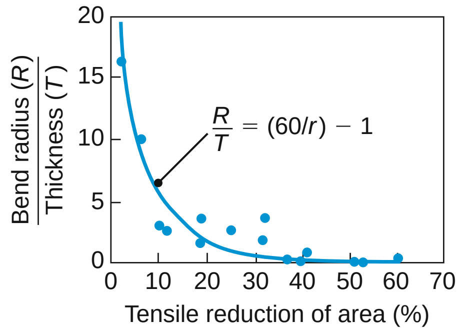


FIGURE 16.18 Relationship between R/T and tensile reduction of area for sheet metals. Note that sheet metal with a 50% tensile reduction of area can be bent over itself in a process like the folding of a piece of paper without cracking. *Source*: After J. Datsko and C.T. Yang.

Springback. Because all materials have a finite modulus of elasticity, plastic deformation always is followed by some elastic recovery when the load is removed (see Fig. 2.3). In bending, this recovery is called *springback*, which can be observed easily by bending and then releasing a piece of sheet metal or wire. Springback occurs not only in flat sheets and plates, but also in solid or hollow bars and tubes of any cross section. As noted in Fig. 16.19, the final bend angle after springback is smaller than the angle to which the part was bent, and the final bend radius is larger than before springback occurs.

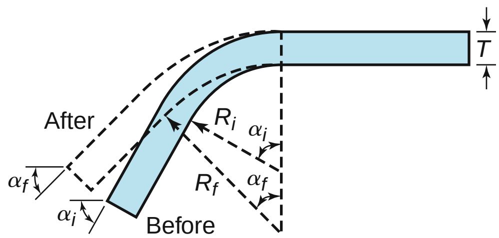


FIGURE 16.19 Springback in bending. The part tends to recover elastically after bending, and its bend radius becomes larger. Under certain conditions, it is possible for the final bend angle to be smaller than the original angle (negative springback).

Springback can be calculated approximately in terms of the radii R_i and R_f (Fig. 16.19) as

$$\frac{R_i}{R_f} = 4\left(\frac{R_i Y}{ET}\right)^3 - 3\left(\frac{R_i Y}{ET}\right) + 1. \qquad (16.6)$$

Note from this formula that springback increases (a) as the R/T ratio and the yield stress, Y, of the material increase and (b) as the elastic modulus, E, decreases.

In V-die bending (Figs. 16.20 and 16.21), it is possible for the material to also exhibit *negative springback*. This condition is caused by the nature of the deformation occurring just as the punch completes the bending operation at the end of the stroke. Negative springback does not occur in *air bending*, shown in Fig. 16.22a (also called *free bending*), because of the absence of constraints that a V-die imposes on the bend area.

Compensation for Springback. Springback in forming operations usually is compensated for by *overbending* the part (Fig. 16.20a and b). Several trials may be necessary to obtain the desired results. Another method is to *coin* the bend area by subjecting it to highly localized compressive stresses between the tip of the punch and the die surface (Fig. 16.20c and d)—a technique known as *bottoming* the punch. Another method is *stretch bending*, in which the part is subjected to tension while being bent (see also *stretch forming*, Section 16.6).

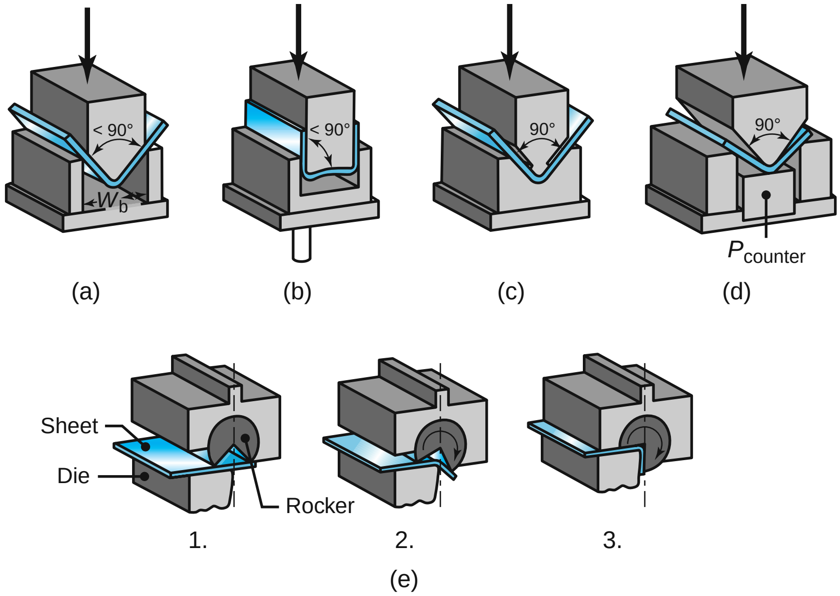


FIGURE 16.20 Methods of reducing or eliminating springback in bending operations.

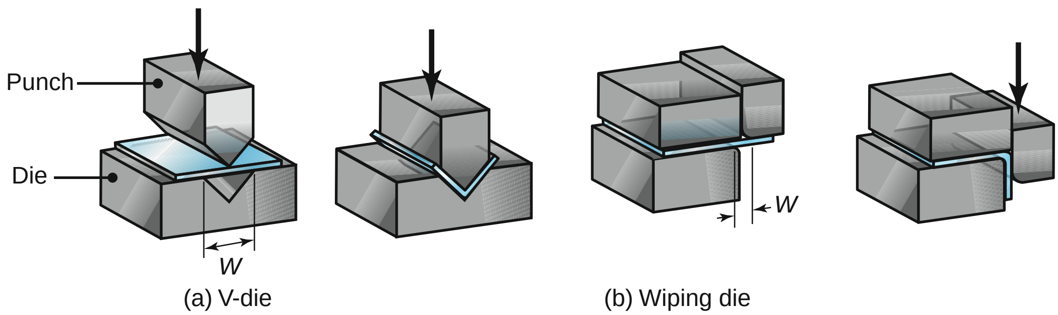


FIGURE 16.21 Common die-bending operations showing the die-opening dimension, W, used in calculating bending forces.

Bending Force. The bending force for sheets and plates can be estimated by assuming that the process is one of simple bending of a rectangular beam, as described in texts on mechanics of solids. Thus, the bending force is a function of the strength of the material, the length, L, of the bend, the thickness, T, of the sheet, and the die opening, W. (W is shown in Fig. 16.21.) Excluding friction, the *maximum bending force*, P, is

$$P = \frac{kYLT^2}{W}, \tag{16.7}$$

where the factor k ranges from about 0.3 for a wiping die, to about 0.7 for a U-die, to about 1.3 for a V-die and Y is the yield stress of the material.

For a V-die, Eq. (16.7) is often modified as

$$P = \frac{(\text{UTS})LT^2}{W}, \tag{16.8}$$

where UTS is the ultimate tensile strength of the material. This equation applies well to situations in which the punch-tip radius and the sheet thickness are relatively small compared to the die opening, W.

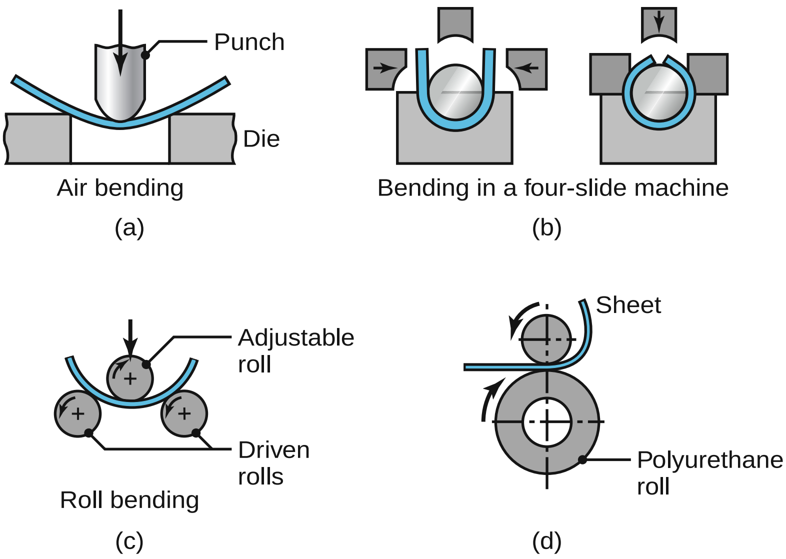


FIGURE 16.22 Examples of various bending operations.

The force in die bending varies throughout the bending cycle. It increases from zero to a maximum, and it may even decrease as the bend is completed. The force then increases sharply as the punch reaches the bottom of its stroke and the part touches the bottom of the die. In air bending (Fig. 16.22a), however, the force does not increase again after it begins to decrease, as it has no resistance to its free movement downward.

16.6 Miscellaneous Bending and Related Operations

Press-brake Forming. Sheet metal or plate can be bent easily with simple fixtures using a press. Sheets or narrow strips that are 7 m (20 ft) or even longer usually are bent in a *press brake* (Fig. 16.23). The machine utilizes long dies in a mechanical or hydraulic press and is particularly suitable for small production runs. As can be seen in Fig. 16.23, the tooling is simple, their motions are only up and down, and they easily are adaptable to a wide variety of shapes. Also, the process can be automated easily for low-cost, high-production runs. *Die materials* for press brakes range from hardwood (for low-strength materials and small-production runs) to carbides for strong and abrasive sheet materials and also are chosen to improve die life. For most applications, however, carbon-steel or gray-iron dies generally are used.

Bending in a Four-slide Machine. Bending relatively short pieces can be done on a machine such as that shown in Fig. 16.22b. In these machines, the lateral movements of the dies are controlled and synchronized with the vertical die movement to form the part into desired shapes. This process is useful in making seamed tubing and conduits, bushings, fasteners, and various machinery components.

Roll Bending. In this process (Fig. 16.22c), plates are bent using a set of rolls. By adjusting the distance between the three rolls, various curvatures can be obtained. This process is flexible and is used widely for bending plates for applications such as boilers, cylindrical pressure vessels, and various curved structural members. Figure 16.22d

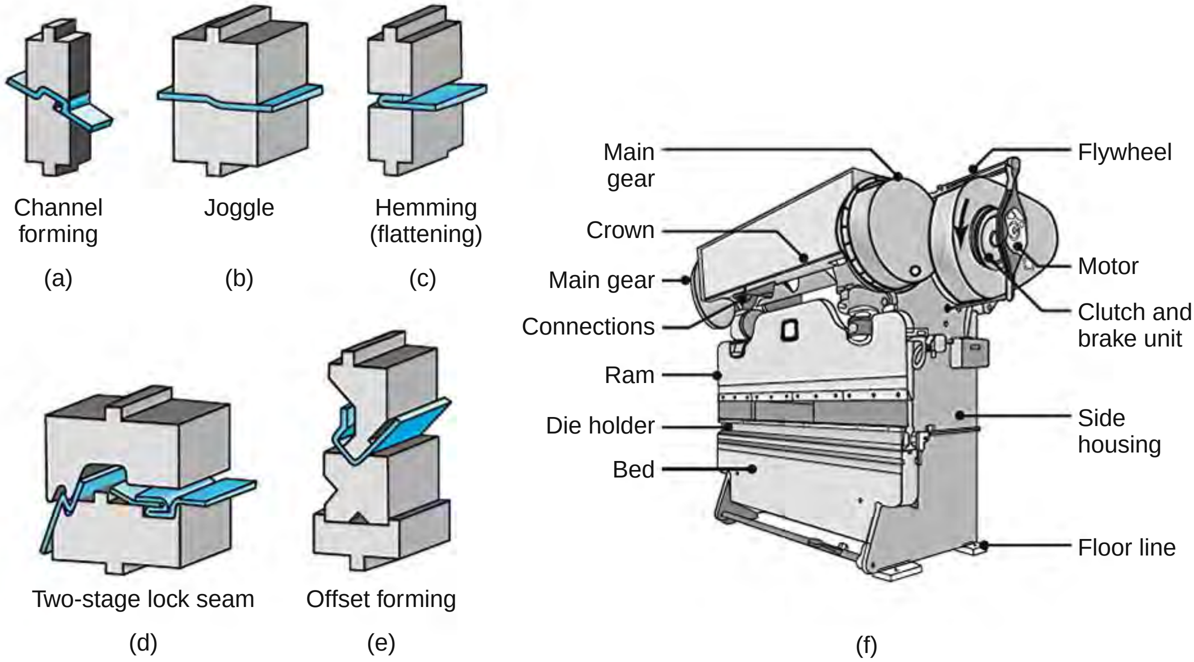


FIGURE 16.23 (a) through (e) Schematic illustrations of various bending operations in a press brake. (f) Schematic illustration of a press brake. *Source*: Courtesy of Verson Allsteel Company.

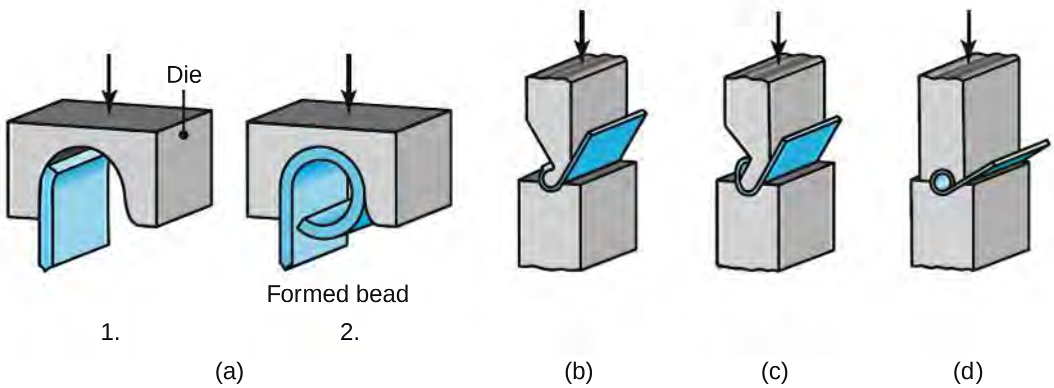


FIGURE 16.24 (a) Bead forming with a single die. (b) through (d) Bead forming with two dies in a press brake.

shows the bending of a strip with a compliant roll made of polyurethane, which conforms to the shape of the strip as the hard upper roll presses upon it.

Beading. In *beading*, the periphery of the sheet metal is bent into the cavity of a die (Fig. 16.24). The bead imparts stiffness to the part by increasing the moment of inertia of that section. Also, beads improve the appearance of the part and eliminate exposed sharp edges that can be hazardous.

Flanging. This is a process of bending the edges of sheet metals, usually to 90°. In **shrink flanging** (Fig. 16.25a), the flange is subjected to compressive hoop stresses that, if excessive, can cause the flange periphery to wrinkle. The wrinkling tendency

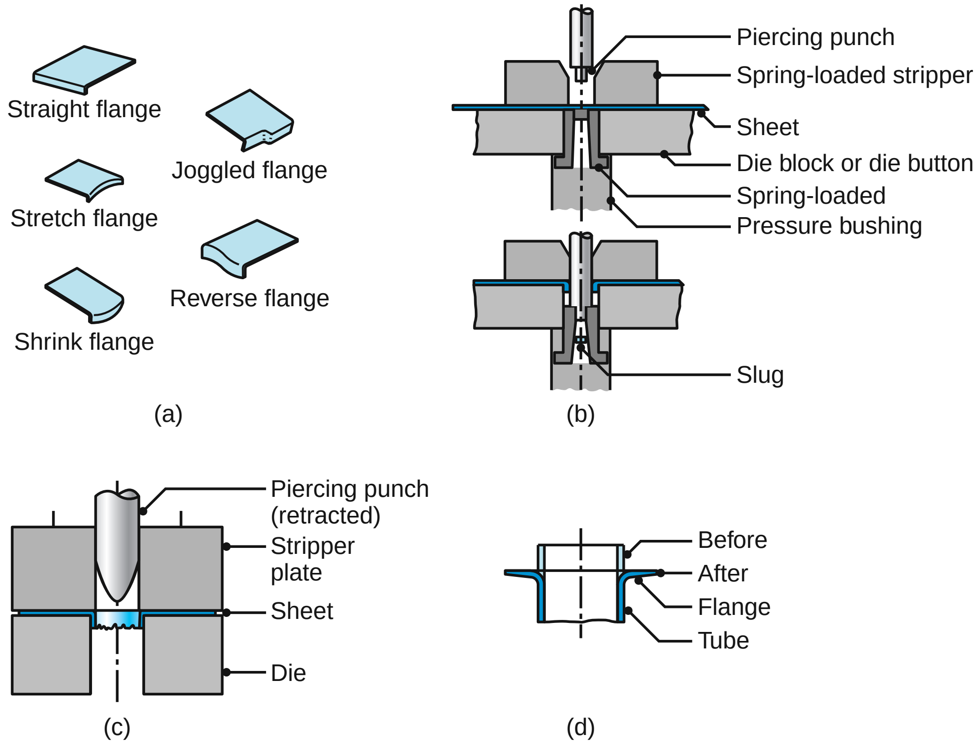


FIGURE 16.25 Various flanging operations. (a) Flanges on flat sheet. (b) Dimpling. (c) The piercing of sheet metal to form a flange. In this operation, a hole does not have to be prepunched before the punch descends. Note, however, the rough edges along the circumference of the flange. (d) The flanging of a tube. Note the thinning of the edges of the flange.

increases with decreasing radius of curvature of the flange. In **stretch flanging**, the flange periphery is subjected to tensile stresses that, if excessive, can lead to cracking along the periphery.

Roll Forming. This process, which is also called *contour-roll forming* or *cold-roll forming*, is used for forming continuous lengths of sheet metal and for large production runs. As it passes through a set of rolls, the metal strip is bent in consecutive stages (Fig. 16.26). The formed strip is then sheared into specific lengths and stacked continuously.

Typical roll-formed products are panels, door and picture frames, channels, gutters, siding, and pipes and tubing with lock seams (see Section 32.5). The length of the part is limited only by the amount of material supplied to the rolls from the coiled stock. Sheet thickness usually ranges from about 0.125 to 20 mm (0.005 to 0.75 in.). Forming speeds are generally below 1.5 m/s (300 ft/min), although they can be much higher for special applications.

The design and sequencing of the rolls (which usually are mechanically driven) require considerable experience. Dimensional tolerances and springback, as well as tearing and buckling of the strip, have to be considered. The rolls generally are made of carbon steel or of gray iron, and they may be chromium plated for a better surface finish of the formed product and for better wear resistance of the rolls. Lubricants may be used to reduce roll wear, to improve surface finish, and to cool the rolls and the sheet being formed.

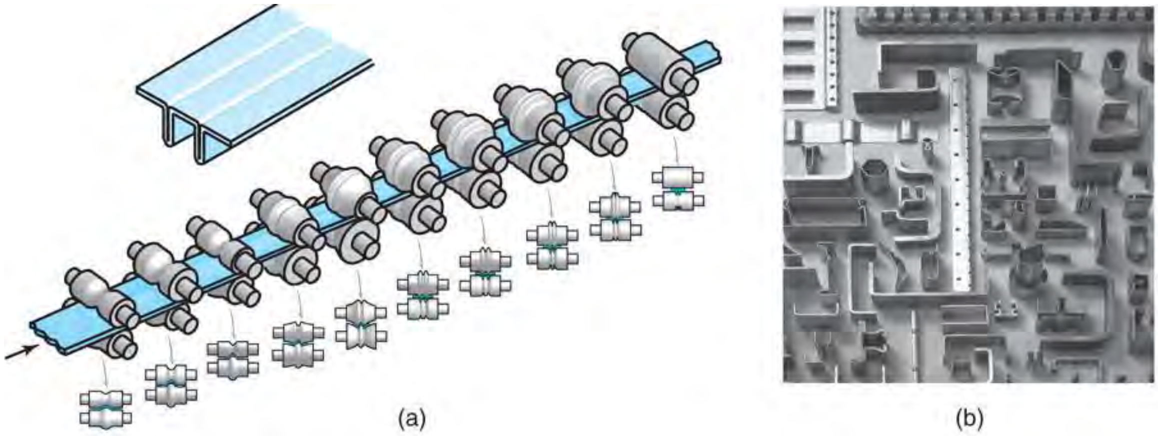


FIGURE 16.26 (a) Schematic illustration of the roll-forming process. (b) Examples of roll-formed cross sections. *Source*: (b) Courtesy of Sharon Custom Metal Forming, Inc.

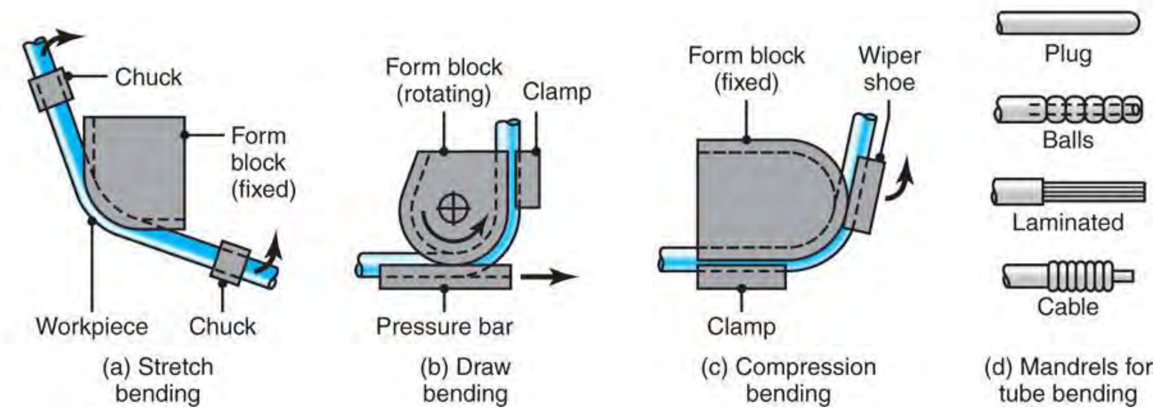


FIGURE 16.27 Methods of bending tubes. Internal mandrels or filling of tubes with particulate materials such as sand are often necessary to prevent collapse of the tubes during bending. Tubes also can be bent by a technique in which a stiff, helical tension spring is slipped over the tube. The clearance between the outer diameter of the tube and the inner diameter of the spring is small; thus, the tube cannot kink and the bend is uniform.

Tube Bending and Forming. Bending and forming tubes and other hollow sections requires special tooling because of the tendency for buckling and folding, as one notes when trying to bend a piece of copper tubing or even a plastic soda straw. The oldest method of bending a tube or pipe is to first pack its inside with loose particles (commonly sand) and then bend it into a suitable fixture. The function of the filler is to prevent the tube from buckling inward. After the tube has been bent, the sand is shaken out. Tubes also can be plugged with various flexible internal mandrels (Fig. 16.27) for the same purpose as the sand. Note that (because of its lower tendency for buckling) a relatively thick tube to be formed to a large bend radius can be bent safely without the use of fillers or plugs. (See also *tube hydroforming*, Section 16.8.)

Dimpling, Piercing, and Flaring. In *dimpling* (Fig. 16.25b), a hole first is punched and then expanded into a flange. Flanges also may be produced by *piercing* with a shaped punch (Fig. 16.25c). Tube ends can be flanged by a similar process (Fig. 16.25d). When the bend angle is less than 90° (as in fittings with conical ends), the process is called *flaring*. The condition of the edges (see Fig. 16.3) is important in these operations. Stretching the material causes high tensile stresses along the periphery (tensile hoop stresses), which can lead to cracking and tearing of the flange.

As the ratio of flange diameter to hole diameter increases, the strains increase proportionately. Depending on the roughness of the edge, there will be a tendency for cracking along the outer periphery of the flange. To reduce this possibility, sheared or punched edges may be shaved off with a sharp tool (see Fig. 16.9) to improve the surface finish of the edge.

Hemming and Seaming. In the *hemming* process (also called *flattening*), the edge of the sheet is folded over itself (Fig. 16.23c). Hemming increases the stiffness of the part, improves its appearance, and eliminates sharp edges. *Seaming* involves joining two edges of sheet metal by hemming (Fig. 16.23d). Double seams are made by a similar process using specially shaped rollers for watertight and airtight joints, such as are needed in food and beverage containers.

Bulging. This process involves placing a tubular, conical, or curvilinear part into a split-female die and then expanding the part, usually with a polyurethane plug (Fig. 16.28a). The punch is then retracted, the plug returns to its original shape (by total elastic recovery), and the formed part is removed by opening the split dies. Typical products made are coffee or water pitchers, beer barrels, and beads on oil drums. For parts with complex shapes, the plug (instead of being cylindrical) may be shaped in order to apply higher pressures at critical regions of the part. The major advantages of using polyurethane plugs is that they are highly resistant to abrasion and wear; furthermore, they do not damage the surface finish of the part being formed.

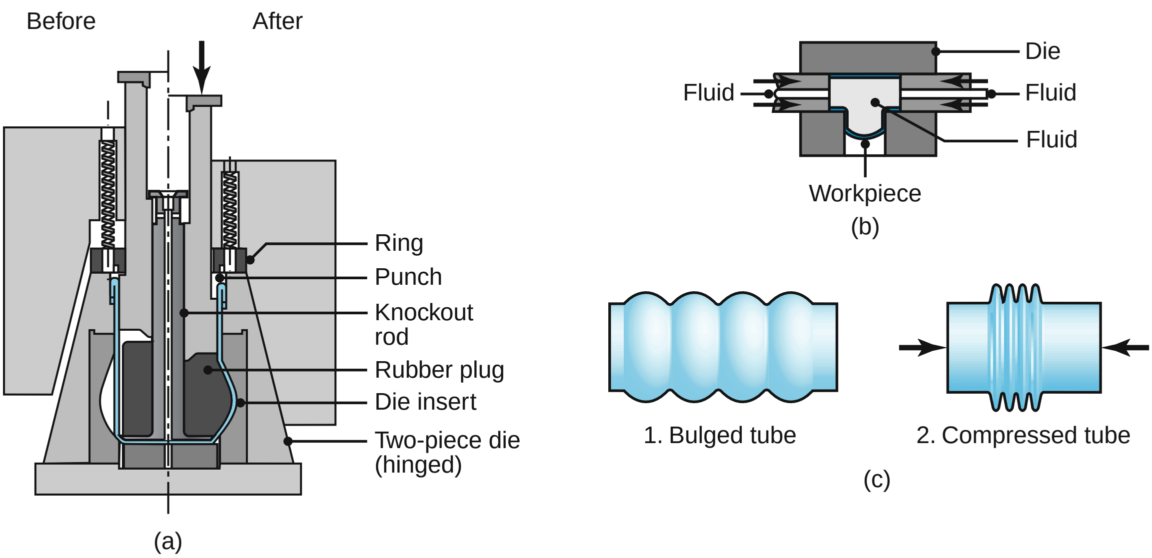


FIGURE 16.28 (a) The bulging of a tubular part with a flexible plug. Water pitchers can be made by this method. (b) Production of fittings for plumbing by expanding tubular blanks under internal pressure. The bottom of the piece is then punched out to produce a "T." *Source*: After J.A. Schey. (c) Steps in manufacturing bellows.

Segmented Dies. These dies consist of individual segments that are placed inside the part to be formed and expanded mechanically in a generally radial direction. They are then retracted to remove the formed part. Segmented dies are relatively inexpensive, and they can be used for large production runs.

Stretch Forming. In *stretch forming*, the sheet metal is clamped along its edges and then stretched over a male die (*form block* or *form punch*). The die moves upward, downward, or sideways, depending on the particular design of the machine (Fig. 16.29). Stretch forming is used primarily to make aircraft wing-skin panels, fuselages, and boat hulls. Aluminum skins for the Boeing 767 and 757 aircraft, for example, are made by stretch forming—with a tensile force of 9 MN (2 million lb). The rectangular sheets are 12 m × 2.5 m × 6.4 mm (40 ft × 8.3 ft × 0.25 in.). Although this process generally is used for low-volume production, it is versatile and economical, particularly for the aerospace industry.

In most operations, the blank is a rectangular sheet clamped along its narrower edges and stretched lengthwise, thus allowing the material to shrink in width. Controlling the amount of stretching is important in order to prevent tearing. Stretch forming cannot produce parts with sharp contours or with reentrant corners (depressions on the surface of the die). Various accessory equipment can be used in conjunction with stretch forming, including further forming with both male and female dies while the part is under tension. Dies for stretch forming generally are made of zinc alloys, steel, plastics, or wood. Most applications require little or no lubrication.

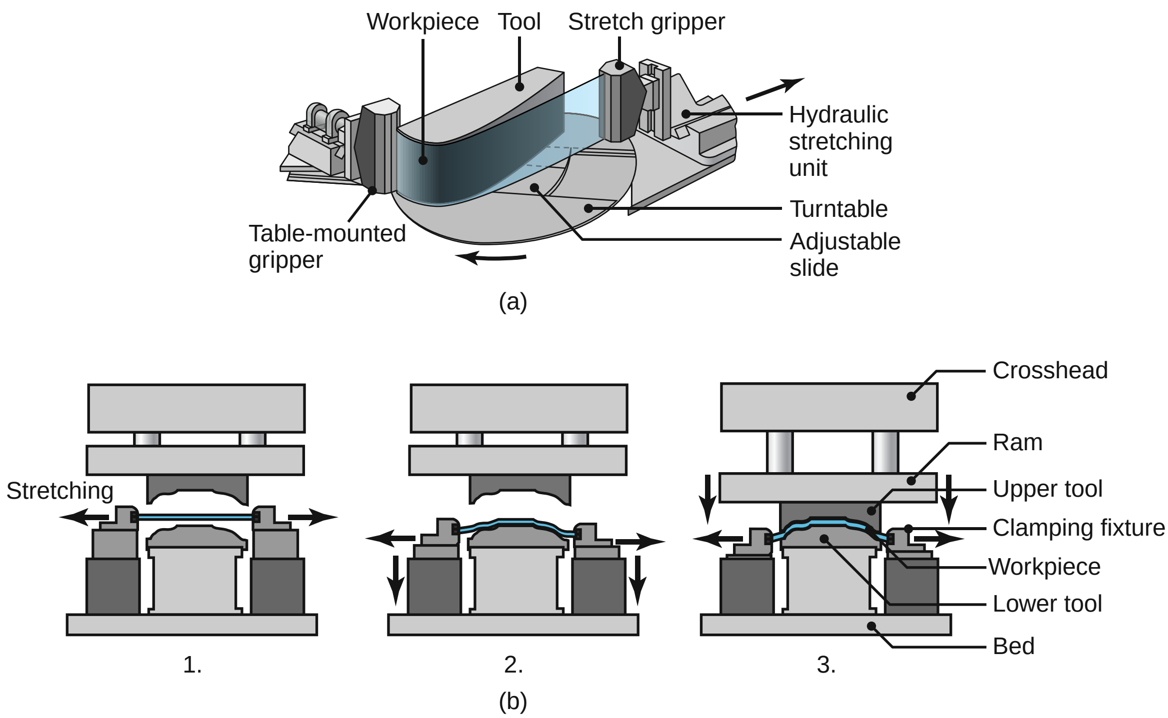


FIGURE 16.29 Schematic illustration of a stretch-forming process. Aluminum skins for aircraft can be made by this method. *Source*: (a) Courtesy of Cyril Bath Co.

16.7 Deep Drawing

Numerous parts made of sheet metal are cylindrical or box shaped, such as pots and pans, all types of containers for food and beverages (Fig. 16.30), stainless-steel kitchen sinks, canisters, and automotive fuel tanks. Such parts usually are made by a process in which a punch forces a flat sheet-metal blank into a die cavity (Fig. 16.31a). Although the process generally is called *deep drawing* (because of its capability for producing deep parts), it also is used to make parts that are shallow or have moderate depth. It is one of the most important metalworking processes because of its widespread use.

In the basic deep-drawing process, a round sheet-metal blank is placed over a circular die opening and is held in place with a **blankholder**, or *hold-down ring* (Fig. 16.31b). The punch travels downward and forces the blank into the die cavity, forming a cup. The important variables in deep drawing are the properties of the sheet metal, the ratio of blank diameter, D_o; the punch diameter, D_p; the clearance, c,

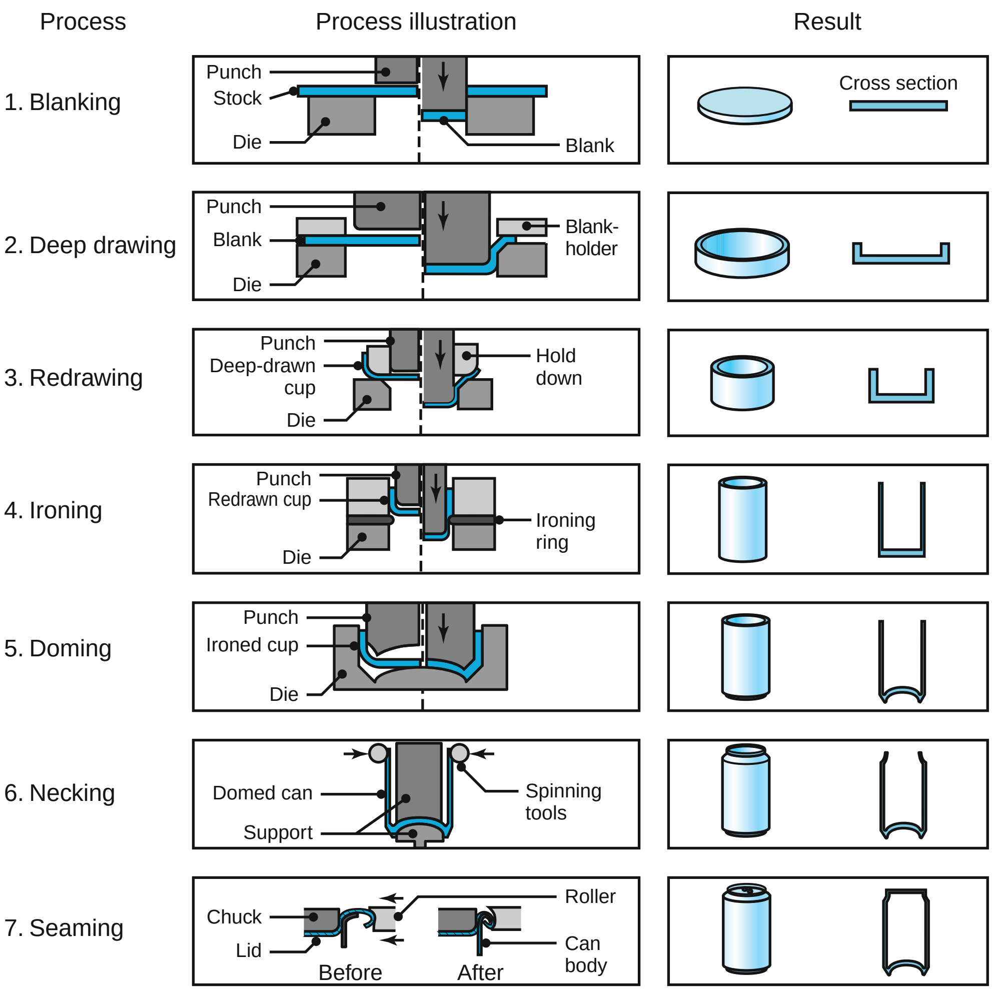


FIGURE 16.30 The metal-forming processes involved in manufacturing a two-piece aluminum beverage can.

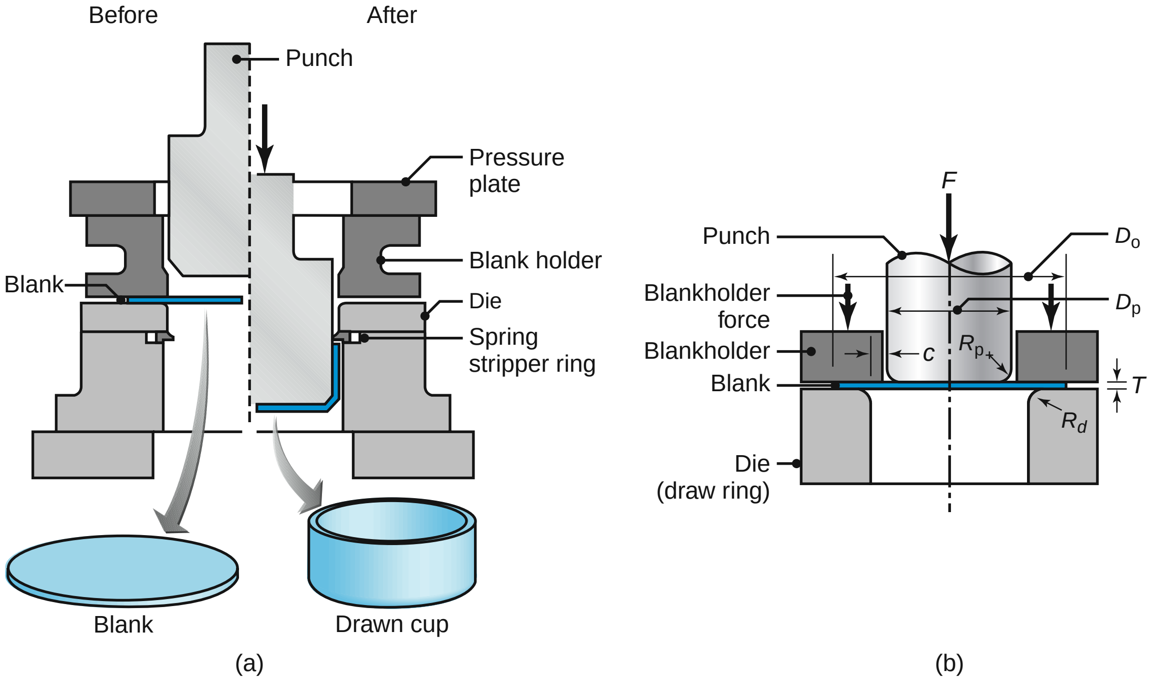


FIGURE 16.31 (a) Schematic illustration of the deep-drawing process on a circular sheet-metal blank. The stripper ring facilitates the removal of the formed cup from the punch. (b) Process variables in deep drawing. Except for the punch force, F, all the parameters indicated in the figure are independent variables.

between punch and die; the punch radius, R_p; the die-corner radius, R_d; the blank-holder force; and friction and lubrication between all contacting surfaces.

During the drawing operation, the movement of the blank into the die cavity induces compressive circumferential (hoop) stresses in the flange, which tend to cause the flange to *wrinkle* during drawing. This phenomenon can be demonstrated simply by trying to force a circular piece of paper into a round cavity, such as a drinking glass. Wrinkling can be reduced or eliminated if a blankholder is loaded by a certain force. In order to improve performance, the magnitude of this force can be controlled as a function of punch travel.

Because of the many variables involved, the *punch force*, F, is difficult to calculate directly. It has been shown, however, that the *maximum punch force*, F_{max}, can be estimated from the formula

$$F_{max} = \pi D_p T(\text{UTS})\left[\left(\frac{D_o}{D_p}\right) - 0.7\right], \tag{16.9}$$

where the nomenclature is the same as that in Fig. 16.31b. It can be seen that the force increases with increasing blank diameter, thickness, strength, and the ratio (D_o/D_p). The wall of the cup is subjected principally to a longitudinal (vertical) tensile stress due to the punch force. Elongation under this stress causes the cup wall to become thinner and, if excessive, can cause *tearing* of the cup.

16.7.1 Deep Drawability

In a deep-drawing operation, failure generally results from the *thinning* of the cup wall under high longitudinal tensile stresses. If we follow the movement of the material as it flows into the die cavity, it can be seen that the sheet metal (a) must be capable of undergoing a reduction in width due to a reduction in diameter and (b) must also resist thinning under the longitudinal tensile stresses in the cup wall. *Deep drawability* generally is expressed by the **limiting drawing ratio** (LDR) as

$$\text{LDR} = \frac{\text{Maximum blank diameter}}{\text{Punch diameter}} = \frac{D_o}{D_p}. \qquad (16.10)$$

Whether a sheet metal can be deep drawn successfully into a round cup-shaped part has been found to be a function of the **normal anisotropy**, R (also called *plastic anisotropy*), of the sheet metal. Normal anisotropy is defined in terms of the true strains that the specimen undergoes in tension (Fig. 16.32):

$$R = \frac{\text{Width strain}}{\text{Thickness strain}} = \frac{\varepsilon_w}{\varepsilon_t}. \qquad (16.11)$$

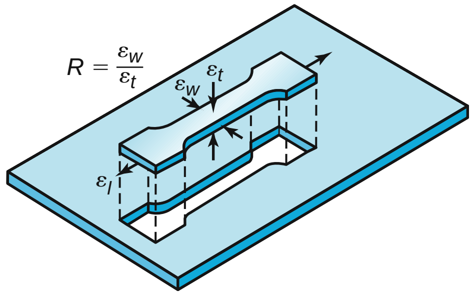


FIGURE 16.32 Strains on a tensile-test specimen removed from a piece of sheet metal. These strains are used in determining the normal and planar anisotropy of the sheet metal.

In order to determine the magnitude of R, a tensile-test specimen is first prepared and subjected to an elongation of 15 to 20%. The true strains that the sheet undergoes are calculated in the manner discussed in Section 2.2. Because cold-rolled sheets generally have anisotropy in their *planar* direction, the R value of a specimen cut from a rolled sheet will depend on its orientation with respect to the rolling direction of the sheet. For this condition, an average value, R_{avg}, is calculated from the equation

$$R_{avg} = \frac{R_0 + 2R_{45} + R_{90}}{4}, \qquad (16.12)$$

where the subscripts are the angles with respect to the rolling direction of the sheet. Some typical R_{avg} values are given in Table 16.4.

The experimentally determined relationship between R_{avg} and the limiting drawing ratio is shown in Fig. 16.33. It has been established that no other mechanical property of sheet metal shows as consistent a relationship to LDR as does R_{avg}. Thus, by using a simple tensile-test result and obtaining the normal anisotropy of the sheet metal, the limiting drawing ratio of a material can be determined.

Earing. In deep drawing, the edges of cups may become wavy—a phenomenon called *earing* (Fig. 16.34). Ears are objectionable on deep-drawn cups because they have to be trimmed off, as they serve no useful purpose and interfere with further processing of the cup, resulting in scrap. Earing is caused by the **planar anisotropy**

TABLE 16.4

Typical Ranges of Average Normal Anisotropy, R_{avg}, for Various Sheet Metals

Zinc alloys	0.4–0.6
Hot-rolled steel	0.8–1.0
Cold-rolled, rimmed steel	1.0–1.4
Cold-rolled, aluminum-killed steel	1.4–1.8
Aluminum alloys	0.6–0.8
Copper and brass	0.6–0.9
Titanium alloys (α)	3.0–5.0
Stainless steels	0.9–1.2
High-strength, low-alloy steels	0.9–1.2

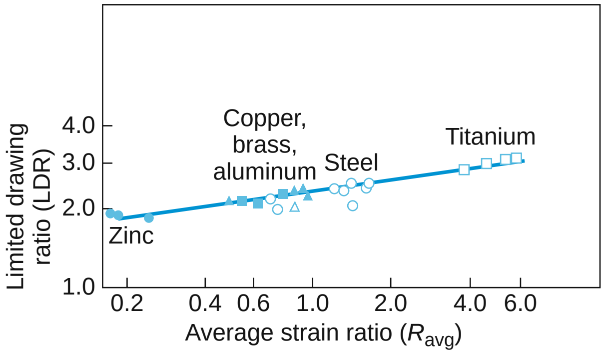


FIGURE 16.33 The relationship between average normal anisotropy and the limiting drawing ratio for various sheet metals. *Source*: After M. Atkinson.

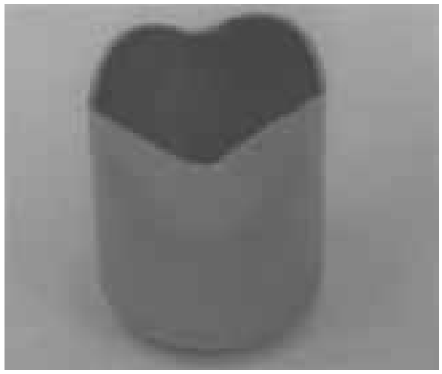


FIGURE 16.34 Earing in a drawn steel cup, caused by the planar anisotropy of the sheet metal.

of the sheet, and the number of ears produced may be two, four, or eight, depending on the processing history and microstructure of the sheet. If the sheet is stronger in the rolling direction than transverse to the rolling direction and the strength varies uniformly with respect to orientation, then two ears will form. If the sheet has high strength at different orientations, then more ears will form.

The planar anisotropy of the sheet is indicated by ΔR. It is defined in terms of directional R values from the equation

$$\Delta R = \frac{R_0 - 2R_{45} + R_{90}}{2}. \tag{16.13}$$

When $\Delta R = 0$, no ears form. The height of the ears increases as ΔR increases.

It can be seen that deep drawability is enhanced by a high R_{avg} value and a low ΔR. Generally, however, sheet metals with high R_{avg} also have high ΔR values. Sheet-metal textures are being developed continually to improve drawability by controlling the type of alloying elements in the material as well as various processing parameters during rolling of the sheet.

16.7.2 Deep-drawing Practice

Certain guidelines have been established for successful deep-drawing practice. The blankholder pressure is chosen generally as 0.7 to 1.0% of the sum of the yield strength and the ultimate tensile strength of the sheet metal. Too high a blankholder force increases the punch force and causes the cup wall to tear. On the other hand, if the blankholder force is too low, wrinkling will occur.

Clearances are usually 7 to 14% greater than sheet thickness. If the clearance is too small, the blank may be pierced or sheared by the punch. The corner radii of the punch and of the die are also important parameters. If they are too small, they can cause fracture at the corners; if they are too large, the cup wall may wrinkle—a phenomenon called *puckering*.

Draw beads (Fig. 16.35) often are necessary to control the flow of the blank into the die cavity. Beads restrict the free flow of the sheet metal by bending and unbending it during the drawing cycle, thereby increasing the force required to pull the sheet into the die cavity. This phenomenon can be demonstrated simply by placing a strip of paper or aluminum foil through one's fingers in an arrangement similar to that shown in Fig. 13.35a. Note that a certain force is now required to pull the strip

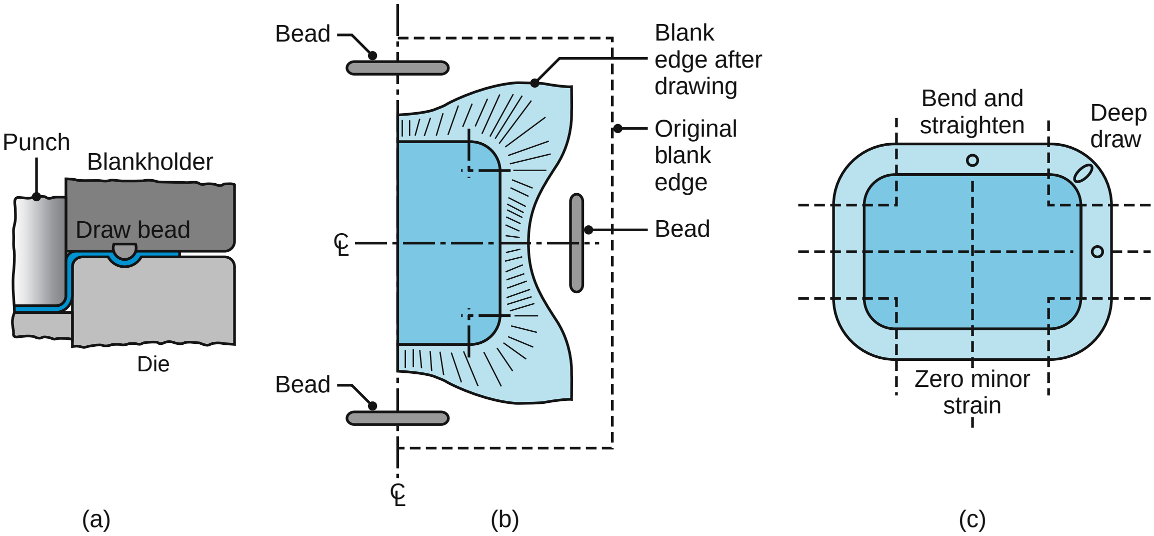


FIGURE 16.35 (a) Schematic illustration of a draw bead. (b) Metal flow during the drawing of a box-shaped part while using beads to control the movement of the material. (c) Deformation of circular grids in the flange in deep drawing.

through your fingers. Draw beads also help to reduce the required blankholder forces, because the beaded sheet has a higher stiffness (due to its higher moment of inertia) and, hence, a lower tendency to wrinkle. Draw-bead diameters may range from 13 to 20 mm (0.50 to 0.75 in.)—the latter applicable to large stampings, such as automotive panels.

Draw beads also are useful in drawing *box-shaped* and *nonsymmetric* parts, because they can present significant difficulties in practice (Fig. 16.35b and c). Note in Fig. 16.35c, for example, that various regions of the part undergo different types of deformation during drawing. (Recall also the fundamental principle that the material flows in the direction of least resistance.)

In order to avoid tearing of the sheet metal during forming, it often is necessary to incorporate the following factors:

- Proper design and location of draw beads
- Large die radii
- Effective lubrication
- Proper blank size and shape
- The cutting off of corners of square or rectangular blanks at 45° to reduce tensile stresses developed during drawing
- The use of blanks free of internal and external defects.

Ironing. Note in Fig. 16.31 that if the clearance between the punch and the die is sufficiently large, the drawn cup will have thicker walls at its rim than at its base. The reason for this is that the cup rim consists of material from the outer diameter of the blank; hence, it has been reduced in diameter more (and thus becomes thicker) than the material constituting the rest of the cup wall. As a result, the cup will develop a nonuniform wall thickness. The thickness of the cup wall can be controlled by a process called *ironing*, in which a drawn cup is pushed through one or more ironing rings (see Fig. 16.30). The clearance between the ironing rings and the punch is less than the cup wall thickness, so the cup after ironing has essentially a

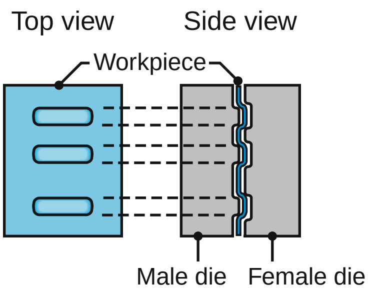


FIGURE 16.36 An embossing operation with two dies. Letters, numbers, and designs on sheet-metal parts can be produced by this process.

constant wall thickness (that is equal to the clearance, except for some small elastic recovery). Aluminum beverage cans, for example, typically undergo two or three ironing operations in one stroke in which the drawn cup is pushed through a set of ironing rings.

Redrawing. Containers that are too difficult to draw in one operation generally undergo *redrawing* (see Fig. 16.30). Because of the volume constancy of the metal, the cup becomes longer as it is redrawn to smaller diameters. In *reverse redrawing*, the cup is placed upside down in the die and thus is subjected to bending in the direction opposite to its original configuration.

Drawing without Blankholder. Deep drawing also may be carried out successfully without a blankholder, provided that the sheet metal is sufficiently thick to prevent wrinkling. A typical range of the diameter is

$$D_o - D_p < 5T, \tag{16.14}$$

where T is the sheet thickness. The dies are contoured specially for this operation.

Embossing. This is an operation consisting of shallow or moderate draws made with male and female matching shallow dies (Fig. 16.36). Embossing is used principally for the stiffening of flat sheet-metal panels and for purposes of decorating, numbering, and lettering, such as letters on the lids of aluminum beverage cans.

Tooling and Equipment for Drawing. The most common tool and die materials for deep drawing are tool steels and cast irons and include dies produced from ductile-iron castings made by the lost-foam process. Other materials, such as carbides and plastics, also may be used (see Table 5.7). Die-manufacturing methods are described in detail in Section 14.7. Because of the generally axisymmetric shape of the punch and die components (such as for making cylindrical cans and containers), they can be manufactured on equipment such as high-speed machining on computer-controlled lathes.

The equipment for deep drawing is usually a *double-action hydraulic press* or a *mechanical press*, the latter generally being favored because of its higher operating speed. In the double-action hydraulic press, the punch and the blankholder are controlled independently. Punch speeds generally range between 0.1 and 0.3 m/s (20 and 60 ft/min).

CASE STUDY 16.1 Manufacturing of Food and Beverage Cans

Can manufacturing is a major and competitive industry worldwide, with approximately 100 billion beverage cans and 30 billion food cans produced each year in the United States alone. These containers are strong and lightweight (typically weighing less than 0.5 oz), and they are under an internal pressure of 90 psi—reliably and without leakage of their contents. There are stringent requirements for the surface finish of the can, since brightly decorated and shiny cans are preferred over dull-looking containers. Considering all of these features, metal cans are very inexpensive. Can makers charge approximately $40 per 1000 cans, or about 4 cents per can. Thus, the cost of empty cans alone in a six-pack is 24 cents, which also indicates the importance of recycling cans.

Food and beverage cans may be produced in a number of ways, the most common ones being two-piece and three-piece cans. Two-piece cans consist of the can body and the lid (Fig. 16.37a). The body is made of one piece that has been drawn and ironed—hence the industry practice of referring to this style as D&I (drawn and ironed) cans. Three-piece cans are produced by attaching a lid and a bottom to a sheet-metal cylindrical body.

Drawn and ironed can bodies are produced from a number of alloys, but the most common are

FIGURE 16.37 (a) Aluminum beverage cans. Note the excellent surface finish. (b) Detail of the can lid, showing the integral rivet and scored edges for the pop-top.

3004-H19 aluminum (see Section 6.2) and electrolytic tin-plated ASTM A623 steel. Aluminum lids are used for both steel and aluminum cans and are produced from 5182-H19 or 5182-H48. The lid presents a demanding set of design requirements, as can be appreciated by reviewing Fig. 16.37b. Not only must the can lid be scored easily (curved grooves around the tab), but an integral rivet is formed and headed in the lid to hold the tab in place. Aluminum alloy 5182 has the unique characteristics of having sufficient formability to enable forming of the integral rivet without cracking and has the ability to be scored. The lids basically are stamped from 5182 aluminum sheet, the pop-top is scored, and a plastic seal is placed around the periphery of the lid. This polymer layer seals the can's contents after the lid is seamed to the can body, as described next.

The traditional method of manufacturing the can bodies is shown in Fig. 16.30. The process starts with 5.5-in.-diameter blanks produced from rolled sheet stock. These blanks are (a) deep drawn to a diameter of around 3.5 in., (b) redrawn to the final diameter of around 2.6 in., (c) ironed through two or three ironing rings in one pass, and (d) domed for the can bottom. The deep-drawing and ironing operations are performed in a special type of press that typically produces cans at speeds over 400 strokes per minute. Following this series of operations, a number of additional processes take place.

Necking of the can body is performed either through spinning (Section 16.9) or by die necking (a forming operation similar to that shown in Fig. 15.19a, where a thin-walled tubular part is pushed into the die), and it is then spin-flanged. The reason for necking the can top is that the 5182 aluminum used for the lid is relatively expensive. Thus, by tapering the top of the can, a smaller volume of material is needed, thereby reducing the cost. Also, it should be noted that the cost of a can often is calculated to millionths of a dollar hence any design feature that reduces its cost will be exploited by this competitive industry.

Source: Courtesy of J.E. Wang, Texas A&M University.

16.8 Rubber Forming and Hydroforming

In the processes described in the preceding sections, it has been noted that the dies generally are made of solid materials, such as steels and carbides. However, in *rubber forming* (also known as the *Guerin process*), one of the dies in a set is made of a flexible material, typically a polyurethane membrane. Polyurethanes are used widely because of their abrasion resistance, fatigue life, and resistance to cutting or tearing.

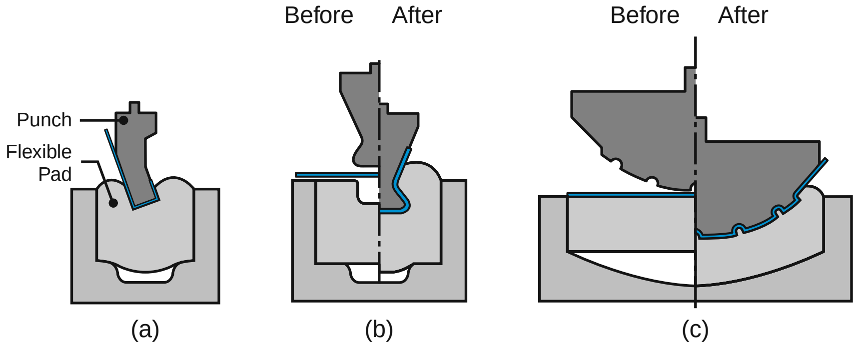


FIGURE 16.38 Examples of the bending and embossing of sheet metal with a metal punch and with a flexible pad serving as the female die. *Source*: Courtesy of Polyurethane Products Corporation.

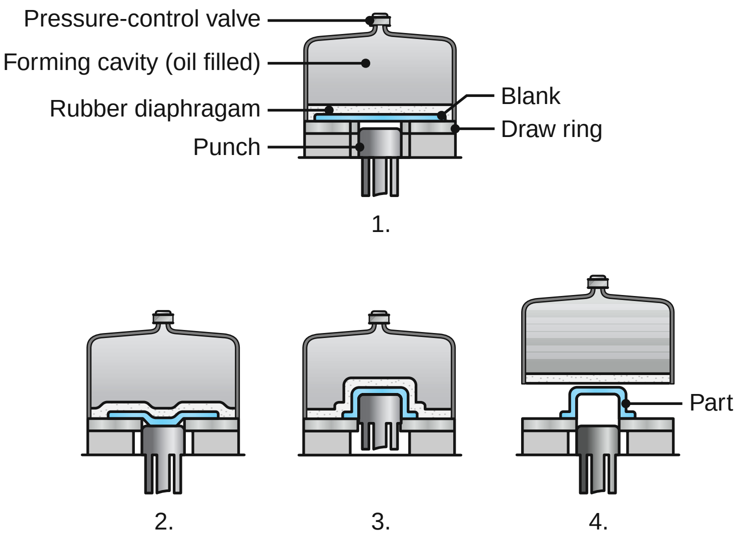


FIGURE 16.39 The hydroform (or fluid-forming) process. Note that, in contrast to the ordinary deep-drawing process, the pressure in the dome forces the cup walls against the punch. The cup travels with the punch; in this way, deep drawability is improved.

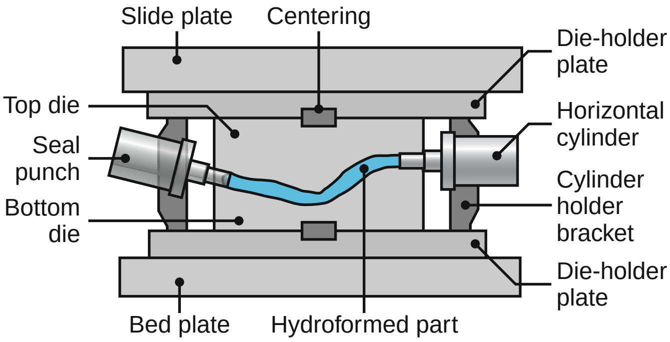
In the bending and embossing of sheet metal by this process, the female die is replaced with a rubber pad (Fig. 16.38). Note that the outer surface of the sheet is protected from damage or scratches, because it is not in contact with a hard metal surface during forming. Pressures in rubber forming are typically on the order of 10 MPa (1500 psi).

In the **hydroform**, or *fluid-forming process* (Fig. 16.39), the pressure over the rubber membrane is controlled throughout the forming cycle with a maximum pressure of up to 100 MPa (15,000 psi). This procedure allows close control of the part during forming and prevents wrinkling or tearing. Deeper draws are obtained than in conventional deep drawing, because the pressure around the rubber membrane forces the cup against the punch. As a result, the friction at the punch–cup interface increases, which then reduces the longitudinal tensile stresses in the cup and thus delays fracture.

The control of frictional conditions in rubber forming as well as other sheet-forming operations can be a critical factor in making parts successfully. The use of proper lubricants and their application methods is also important.

In *tube hydroforming* (Fig. 16.40), metal tubing is formed in a die and pressurized internally by a fluid, usually water. This process, which now is being applied more widely, can form simple tubes as well as various intricate hollow shapes (Fig. 16.40b). Parts made by the process include automotive-exhaust and tubular structural components.

When selected properly, rubber-forming and hydroforming processes have the advantages of (a) the capability to form complex shapes, (b) forming parts with laminated sheets of various materials and coatings, (c) flexibility and ease of operation, (d) the avoidance of damage to the surfaces of the sheet, (e) low die wear, and (f) low tooling cost.



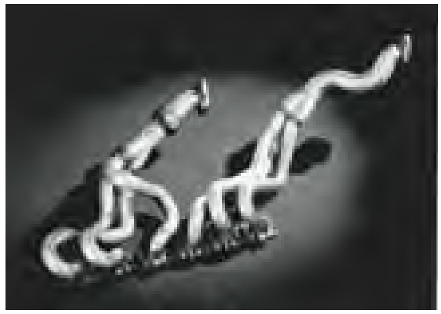


FIGURE 16.40 (a) Schematic illustration of the tube-hydroforming process. (b) Example of tube-hydroformed parts. Automotive-exhaust and structural components, bicycle frames, and hydraulic and pneumatic fittings are produced through tube hydroforming. *Source*: Courtesy of Schuler GmBH.

CASE STUDY 16.2 Tube Hydroforming of an Automotive Radiator Closure

The conventional assembly used to support an automotive radiator, or radiator closure, is constructed through the stamping of components that are subsequently welded together. To simplify the design and to achieve weight savings, a hydroformed assembly was designed, as shown in Fig. 16.41. Note that the design uses varying cross sections, an important design feature to reduce weight and to provide surfaces to facilitate assembly and mounting of the radiator.

Tube hydroforming is a versatile process that is capable of producing complex shapes. A typical tube hydroforming processing sequence consists of the following steps:

1. Bending of tube to the desired configuration
2. Tube hydroforming to achieve the desired shape
3. Finishing operations, such as end shearing and inspection
4. Assembly, including welding of components.

The sequence of operations on one of the tube components of the closure is shown in Fig. 16.42.

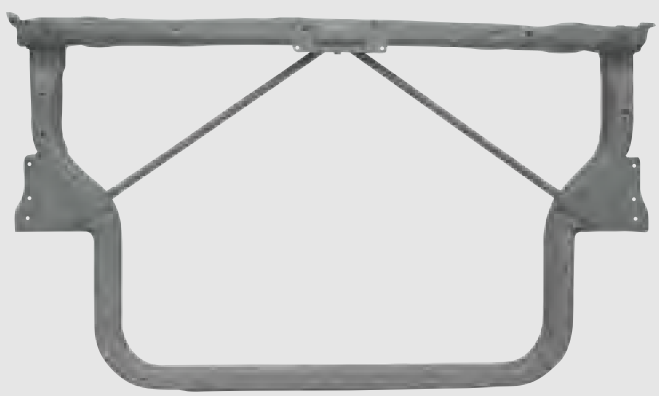


FIGURE 16.41 Hydroformed automotive radiator closure.

(*continued*)

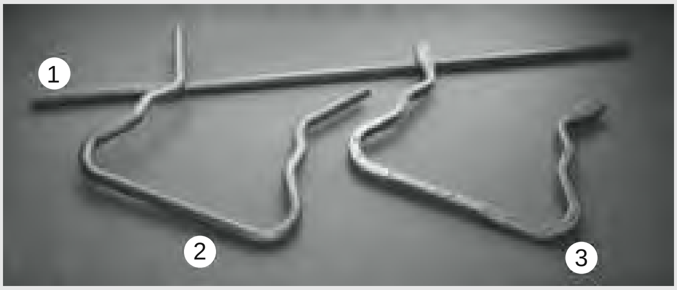


FIGURE 16.42 Sequence of operations in producing a tube-hydroformed component: (1) tube as cut to length; (2) after bending; (3) after hydroforming.

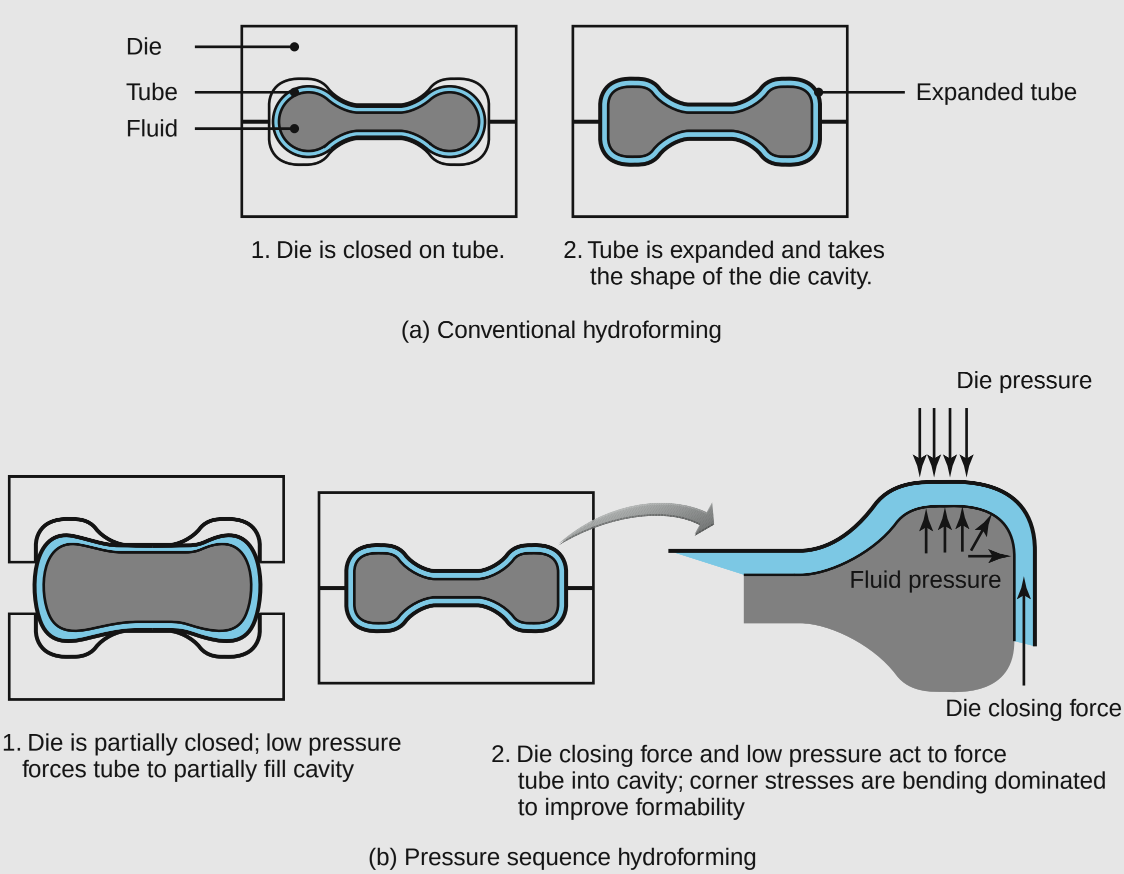


FIGURE 16.43 Schematic illustration of expansion of a tube to a desired cross section through (a) conventional hydroforming and (b) pressure sequence hydroforming.

The tube, constructed of steel with a 300 MPa yield strength, is bent to shape (see Fig. 16.27). The bent tube is then placed in a hydroforming press and end caps are attached.

Conventional hydroforming involves closing the die onto the tube, followed by internal pressurization to force the tube to the desired shape. Figure 16.43a shows a typical cross section. Note that as the tube is

FIGURE 16.44 View of the tube-hydroforming press, with bent tube in place in the forming die.

expanded, there is significant wall thinning, especially at the corners, because of friction at the tube–die interface. The pressure sequence hydroforming process is therefore used on this part, as shown in Fig. 16.43b. In this approach, a first pressure stage (prepressure stage) is applied as the die is closing, causing the tube to partially fill the die cavity and form the cross-sectional corners. After the die is completely closed, the internal pressure is increased to lock in the form and provide support for hole piercing. This sequence has the benefit of forming the sharp corners in the cross section by bending, as opposed to pure stretching in conventional hydroforming. The resulting wall thickness is much more uniform, producing a more structurally sound component. Figure 16.44 shows a part being hydroformed.

The assembly shown has 76 holes that are pierced inside the hydroforming die. The ends are then sheared to length. The 10 components in the hydroformed closure are then assembled through robotic gas-metal arc welding (see Section 30.4.3) and with threaded fasteners to aid in serviceability.

Compared to the original stamped design, the hydroformed design has four fewer components, uses only 20 welds as opposed to 174 for the stamped design, and weighs 10.5 kg (23 lb) versus 14.1 kg (31.1 lb). Furthermore, the stiffness of the enclosure is increased by as much as 150% in some directions. In addition, the cooling system surface area is increased by 43% in the new design.

Source: Courtesy of B. Longhouse, Vari-Form, Inc.

16.9 Spinning

Spinning is a process that involves the forming of axisymmetric parts over a mandrel by the use of various tools and rollers—a process is similar to that of forming clay on a potter's wheel.

Conventional Spinning. In *conventional spinning*, a circular blank of flat or preformed sheet metal is placed and held against a mandrel and rotated while a rigid tool deforms and shapes the material over the mandrel (Fig. 16.45a). The tool may be activated either manually or (for higher production rates) by computer-controlled mechanisms. The process typically involves a sequence of passes, and it requires considerable skill. Conventional spinning is suitable particularly for conical and

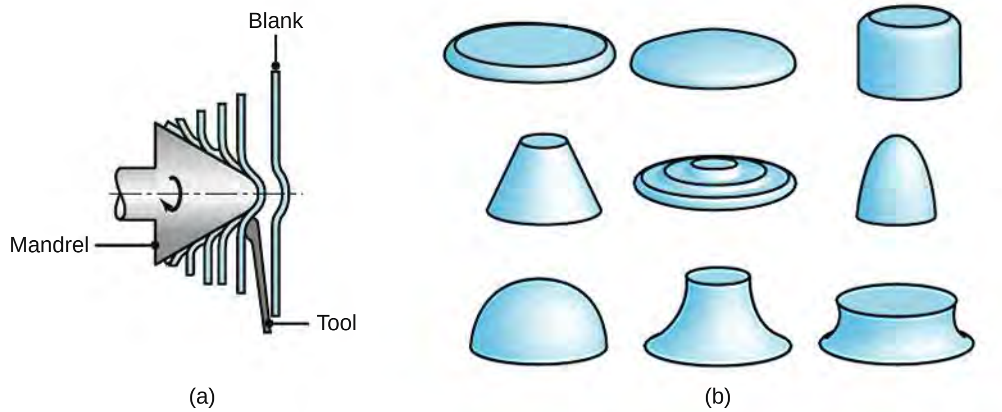


FIGURE 16.45 (a) Schematic illustration of the conventional spinning process. (b) Types of parts conventionally spun. All parts are axisymmetric.

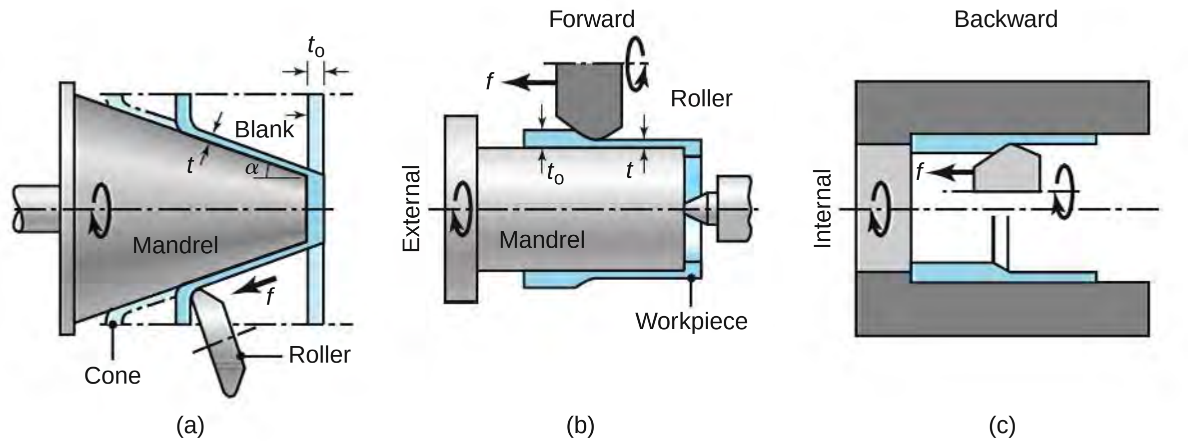


FIGURE 16.46 (a) Schematic illustration of the shear-spinning process for making conical parts. The mandrel can be shaped so that curvilinear parts can be spun. (b) and (c) Schematic illustrations of the tube-spinning process.

curvilinear shapes (Fig. 16.45b), which otherwise would be difficult or uneconomical to produce. Part diameters range up to 6 m (20 ft). Although most spinning is performed at room temperature, thick parts and metals with high strength or low ductility require spinning at elevated temperatures.

Shear Spinning. Also known as *power spinning*, *flow turning*, *hydrospinning*, and *spin forging*, this operation produces an axisymmetric conical or curvilinear shape, reducing the sheet's thickness while maintaining its maximum (blank) diameter (Fig. 16.46a). A single forming roller can be used, but two rollers are preferable in order to balance the forces acting on the mandrel. Typical parts made are rocket motor casings and missile nose cones. Parts up to 3 m (10 ft) in diameter can be formed by shear spinning. This operation wastes little material, and it can be completed in a relatively short time—in some cases in as little as a few seconds. Various shapes can be spun with fairly simple tooling, which generally is made of tool steel.

The *spinnability* of a metal in this process generally is defined as the maximum reduction in thickness to which a part can be subjected by spinning without fracture.

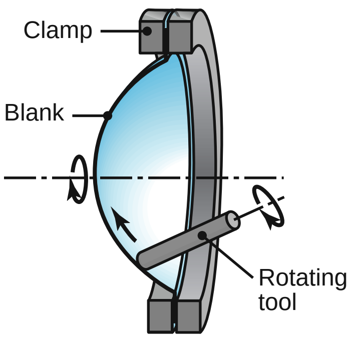
Spinnability is found to be related to the tensile reduction of area of the material, just as is bendability (see Fig. 16.18). Thus, if a metal has a tensile reduction of area of 50% or higher, its thickness can be reduced by as much as 80% in just one spinning pass. For metals with low ductility, the operation is carried out at elevated temperatures by heating the blank in a furnace and transferring it rapidly to the mandrel.

Tube Spinning. In *tube spinning*, the thickness of hollow, cylindrical blanks is reduced or shaped by spinning them on a solid, round mandrel using rollers (Fig. 16.46). The reduction in wall thickness results in a longer tube. This operation may be carried out externally or internally; thus, various external and internal profiles can be produced from cylindrical blanks with constant wall thickness. The parts may be spun *forward* or *backward*; this nomenclature is similar to that of direct and indirect extrusion, as described in Section 15.2. The maximum thickness reduction per pass in tube spinning is related to the tensile reduction of area of the material, as it is in shear spinning. Tube spinning can be used to make rocket, missile, and jet-engine parts, pressure vessels, and automotive components, such as car and truck wheels.

Incremental Forming. *Incremental forming* is a term applied to a class of processes that are related to conventional metal spinning. The simplest version is *incremental stretch expanding*, shown in Fig. 16.47, wherein a rotating blank is deformed by a steel rod with a smooth hemispherical tip to produce axisymmetric parts. No special tooling or mandrel is used, and the motion of the rod determines the final part shape in one or more passes. The strain distribution within the workpiece depends on the tool path across the part profile, and proper lubrication is essential.

CNC incremental forming uses a CNC machine tool (see Section 37.3) that is programmed to follow contours at different depths across the sheet-metal surface. In this arrangement, the blank is clamped and is stationary, and the tool rotates to assist forming. Tool paths are calculated in a manner similar to machining (Part IV), using a CAD model of the desired shape as the starting point (see Fig. 20.2). Figure 16.47b depicts an example of a part that has been produced by CNC incremental forming. Note that the part does not have to be axisymmetric.

The main advantages of incremental forming are low tooling costs and high flexibility in the shapes that can be produced. CNC incremental forming has been



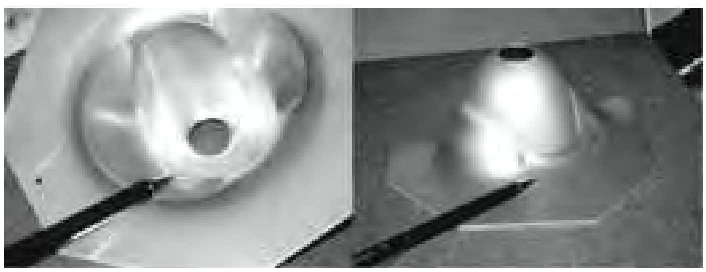


FIGURE 16.47 (a) Illustration of an incremental-forming operation. Note that no mandrel is used and that the final part shape depends on the path of the rotating tool. (b) An automotive headlight reflector produced through CNC incremental forming. Note that the part does not have to be axisymmetric. *Source*: After J. Jeswiet, Queen's University, Ontario.

used for rapid prototyping of sheet-metal parts because the lead times associated with hard tooling are not necessary. The main drawbacks to incremental forming include low production rates and limitations on materials that can be formed.

16.10 Superplastic Forming

The superplastic behavior of certain metals and alloys was described in Section 2.2.7, where tensile elongations on the order of 2000% were obtained within certain temperature ranges. Common examples of such materials are zinc–aluminum and titanium alloys, which have very fine grains—typically less than 10 to 15 μm (see Table 1.1). Superplastic alloys can be formed into complex shapes by *superplastic forming*—a process that employs common metalworking techniques—as well as by polymer-processing techniques (such as thermoforming, vacuum forming, and blow molding, to be described in Chapter 19). The behavior of the material in superplastic forming is similar to that of bubble gum or hot glass, which, when blown, expands many times its original diameter before it bursts.

Superplastic alloys, particularly Zn-22Al and Ti-6Al-4V, also can be formed by bulk-deformation processes, including closed-die forging, coining, hubbing, and extrusion. Commonly used die materials in superplastic forming are low-alloy steels, cast tool steels, ceramics, graphite, and plaster of paris. Selection depends on the forming temperature and the strength of the superplastic alloy.

The very high ductility and relatively low strength of superplastic alloys offer the following advantages:

- Complex shapes can be formed out of one piece, with fine detail, close tolerances, and elimination of secondary operations
- Weight and material savings can be realized because of the good formability of the materials
- Little or no residual stresses develop in the formed parts
- Because of the low strength of the material at forming temperatures, the tooling can be made of materials that have lower strength than those in other metalworking processes; hence, tooling costs are lower.

On the other hand, superplastic forming has the following limitations:

- The material must not be superplastic at service temperatures; otherwise the part will undergo shape changes
- Because of the high strain-rate sensitivity of the superplastic material, it must be formed at sufficiently low strain rates, typically 10^{-4} to 10^{-2}/s. Forming times range anywhere from a few seconds to several hours; thus, cycle times are much longer than those of conventional forming processes. Consequently, superplastic forming is a batch-forming process.

Diffusion Bonding/Superplastic Forming. Fabricating complex sheet-metal structures by combining *diffusion bonding* with *superplastic forming* (SPF/DB) is an important process, particularly in the aerospace industry. Typical structures made are shown in Fig. 16.48, in which flat sheets are diffusion bonded (see Section 31.7) and formed. In this process, selected locations of the sheets are first diffusion bonded while the rest remains unbonded, using a layer of material (*stop-off*) to prevent bonding. The structure is then expanded in a mold, typically by using pressurized

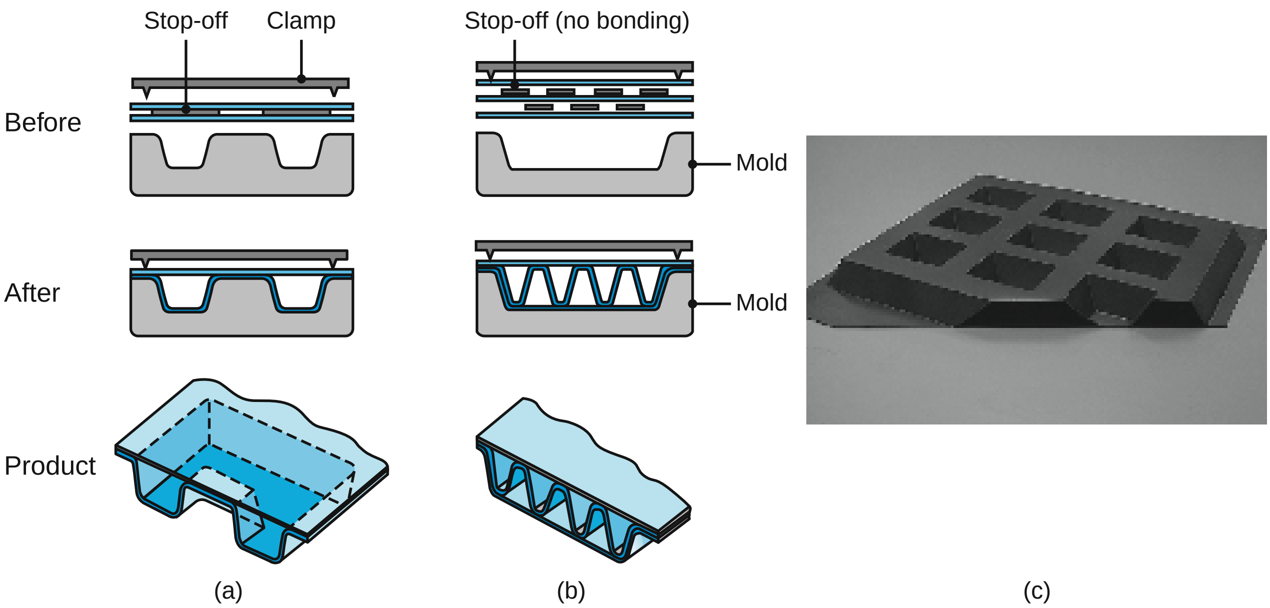


FIGURE 16.48 Types of structures made by superplastic forming and diffusion bonding of sheet metals. Such structures have a high stiffness-to-weight ratio. *Source*: (a) and (b) Courtesy of Rockwell International Corp., (c) Courtesy of Triumph Group, Inc.

neutral (argon) gas, thus taking the shape of the mold. These structures have high stiffness-to-weight ratios because they are thin, and by design, they have high section moduli. This important feature makes SPF/DB particularly attractive in aircraft and aerospace applications.

The SPF/DB process improves productivity by eliminating mechanical fasteners, and it produces parts with good dimensional accuracy and low residual stresses. The technology is well advanced for titanium structures for aerospace applications. In addition to various aluminum alloys being developed using this technique, other metals for superplastic forming include various nickel alloys.

16.11 Specialized Forming Processes

Although not as commonly used as the other processes covered thus far, several other sheet-forming processes are used for specialized applications.

Explosive Forming. Explosives generally are used for demolition in construction, in road building, and for many destructive purposes. However, controlling their quantity and shape makes it possible to use explosives as a source of energy for sheet-metal forming. In *explosive forming*, first utilized to form metals in the early 1900s, the sheet-metal blank is clamped over a die and the entire assembly is lowered into a tank filled with water (Fig. 16.49a). The air in the die cavity is then evacuated, an explosive charge is placed at a certain height, and the charge is detonated.

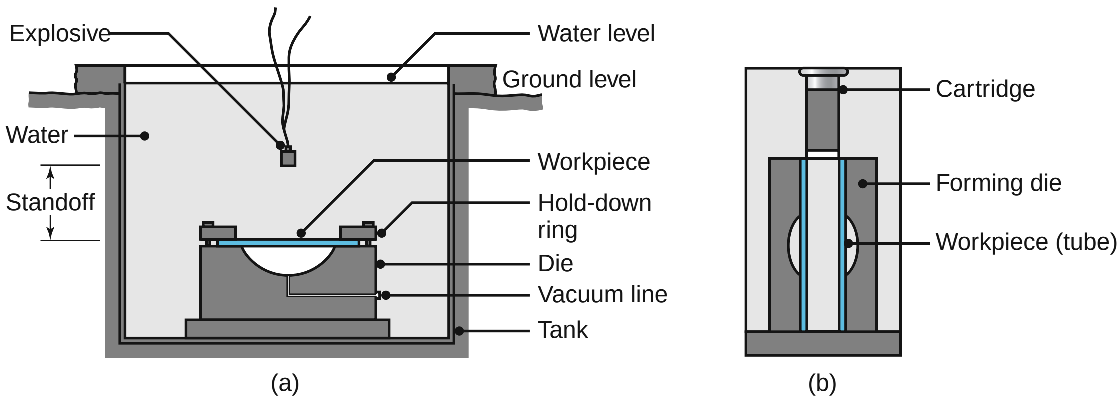


FIGURE 16.49 (a) Schematic illustration of the explosive-forming process. (b) Illustration of the confined method of the explosive bulging of tubes.

The explosive generates a shock wave with a pressure that is sufficient to form sheet metals. The *peak pressure*, *p*, generated in water is given by the expression

$$p = K\left(\frac{\sqrt[3]{W}}{R}\right)^a, \tag{16.15}$$

where p is in psi, K is a constant that depends on the type of explosive, such as 21,600 for TNT (trinitrotoluene), W is the weight of the explosive in pounds, R is the distance of the explosive from the sheet-metal surface (called the *standoff*) in feet, and a is a constant, generally taken to be 1.15.

A variety of shapes can be formed through explosive forming, provided that the material is ductile at the high rates of deformation characteristic of this process (see Table 2.4). The process is versatile, as there is virtually no limit to the size of the sheet or plate. It is suitable particularly for low-quantity production runs of large parts, such as those used in aerospace applications. Steel plates 25 mm (1 in.) thick and 3.6 m (12 ft) in diameter have been formed by this method, as have tubes with wall thicknesses as much as 25 mm (1 in.). The explosive-forming method also can be used at a much smaller scale, as shown in Fig. 16.49b. In this case, a *cartridge* (canned explosive) is used as the source of energy. The process can be useful in the bulging and expanding of thin-walled tubes for specialized applications.

The mechanical properties of parts made by explosive forming are basically similar to those of others made by conventional forming methods. Depending on the number of parts to be produced, dies may be made of aluminum alloys, steel, ductile iron, zinc alloys, reinforced concrete, wood, plastics, or composite materials.

Electromagnetically Assisted Forming. In *electromagnetically assisted forming*, also called *magnetic-pulse forming*, the energy stored in a capacitor bank is discharged rapidly through a magnetic coil. In a typical example, a ring-shaped coil is placed over a tubular workpiece. The tube is then collapsed by magnetic forces over a solid piece, thus making the assembly an integral part (Fig. 16.50).

The mechanics of this process is based on the fact that a magnetic field produced by the coil (Fig. 16.50a) crosses the metal tube (which is an electrical conductor) and generates *eddy currents* in the tube. In turn, these currents produce their own magnetic field. The forces produced by the two magnetic fields oppose each other. The repelling force generated between the coil and the tube then collapses the

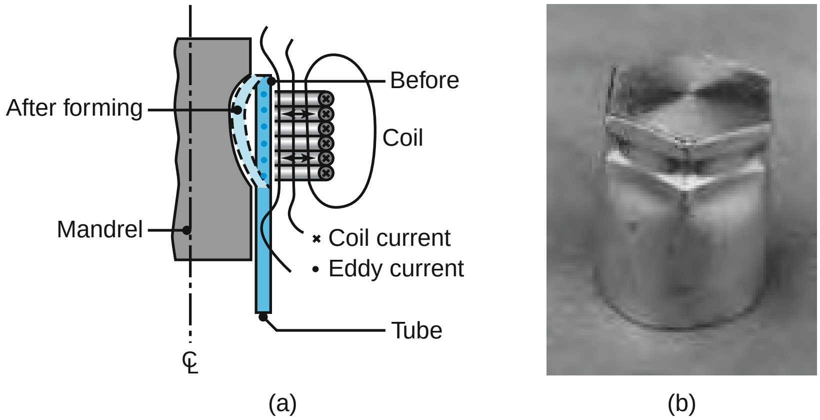


FIGURE 16.50 (a) Schematic illustration of the magnetic-pulse-forming process used to form a tube over a plug. (b) Aluminum tube collapsed over a hexagonal plug by the magnetic-pulse-forming process.

tube over the inner piece. The higher the electrical conductivity of the workpiece, the higher the magnetic forces. It is not necessary for the workpiece material to have magnetic properties.

It has been shown that the basic advantages of this process is that the formability of the material is increased, dimensional accuracy is improved, and springback and wrinkling are reduced. Magnetic coil design is an important consideration for the success of the operation. Flat magnetic coils also can be made for use in operations such as embossing and shallow drawing of sheet metals. The process has been found to be particularly effective for aluminum alloys. First used in the 1960s, electromagnetically assisted forming is now applied to (a) collapsing thin-walled tubes over rods, cables, and plugs; (b) compression-crimp sealing of automotive oil filter canisters; (c) specialized sheet-forming operations; (d) bulging and flaring operations; and (e) swaging end fittings onto torque tubes for the Boeing 777 aircraft.

Peen Forming. Peen forming is used to produce curvatures on thin sheet metals by *shot peening* (see Section 34.2) one surface of the sheet. As a result, the surface of the sheet is subjected to compressive stresses, which tend to expand the surface layer. Because the material below the peened surface remains rigid, the surface expansion causes the sheet to develop a curvature. The process also induces compressive surface residual stresses, which improve the fatigue strength of the sheet.

Peening is done with cast-iron or steel shot discharged either from a rotating wheel or by an air blast from a nozzle. Peen forming is used by the aircraft industry to generate smooth and complex curvatures on aircraft wing skins. Cast-steel shot about 2.5 mm (0.1 in.) in diameter, traveling at speeds of 60 m/s (200 ft/s), have been used to form wing panels 25 m (80 ft) long. For heavy sections, shot diameters as large as 6 mm (1/4 in.) may be used. The peen-forming process also is used for straightening twisted or bent parts, including out-of-round rings to make them round.

Laser Forming. This process involves the application of laser beams as a heat source in specific regions of the sheet metal. The steep thermal gradients developed through the thickness of the sheet produce thermal stresses, which are sufficiently high to cause localized plastic deformation of the sheet. With this method, a sheet, for example, can be bent permanently without using dies. In **laser-assisted forming,**

the laser acts as a localized heat source, thus reducing the strength of the sheet metal at specific locations, improving formability, and increasing process flexibility. Applications include straightening, bending, embossing, and forming of complex tubular or flat components.

Microforming. This is a more recent development and describes a family of processes that are used to produce very small metallic parts and components. Examples of *minitaturized products* include a wristwatch with an integrated digital camera and one gigabyte of a computer storage component. Typical components made by microforming include small shafts for micromotors, springs, screws, and a variety of cold-headed, extruded, bent, embossed, coined, punched, or deep-drawn parts. Dimensions are typically in the submillimeter range, and weights are on the order of milligrams.

Electrohydraulic Forming. Also called *underwater spark* or *electric-discharge forming*, the source of energy in this forming process is a spark between electrodes that are connected with a short, thin wire. The rapid discharge of the energy from a capacitor bank through the wire generates a shock wave, similar to those created by explosives. The energy levels are lower than those in explosive forming, being typically a few kJ. The pressure developed in the water medium is sufficiently high to form the part. Electrohydraulic forming is a batch process and can be used in making various small parts.

Gas Mixtures. As an energy source in this process, a gas mixture in a closed container is ignited. The pressure generated is sufficiently high to form sheet-metal parts. Although not often used in practice, the principle of this process is similar to that used for the generation of pressure in an internal combustion engine.

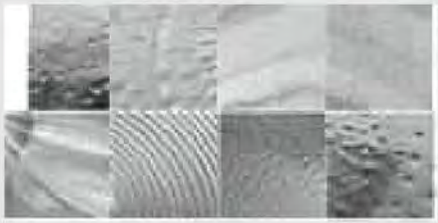
Liquefied Gases. Liquefied gases (such as liquid nitrogen) also have been used to develop pressures sufficiently high to form sheet metals. When allowed to reach room temperature in a closed container, liquefied nitrogen becomes gaseous and expands, developing the necessary pressure. Although not used in practice, the process is capable of forming relatively shallow parts.

CASE STUDY 16.3 Cymbal Manufacture

Cymbals (Fig. 16.51a) are an essential percussion instrument for all forms of music. Modern drum-set cymbals cover a wide variety of sounds—from deep, dark, and warm to bright, high-pitched, and cutting. Some cymbals sound musical, while others are "trashy." A wide variety of sizes, shapes, weights, hammerings, and surface finishes (Fig. 16.51b) is available to achieve the desired performance.

Cymbals are produced from metals—such as B20 bronze (80% Cu–20% Sn with a trace of silver), B8 bronze (92% Cu–8% Sn), nickel–silver alloy, and brass—by various methods of processing. The manufacturing sequence for producing B20 bronze cymbals is shown in Fig. 16.52. The metal is first cast into mushroom-shaped ingots and then cooled by ambient temperature. It then is rolled successively (up to 14 times), with water cooling the metal with each pass through the rolling mill. Special care is taken to roll the bronze at a different angle with each pass, to minimize anisotropy, impart preferred grain orientation, and develop an even, round shape. The as-rolled blanks are then reheated and stretch formed (pressed) into the cup or bell shape that determines the cymbal's overtones. The cymbals then are center drilled or punched to create hang holes and trimmed on a rotary shear to approximate final diameters. This operation is followed by another stretch-forming step to achieve the characteristic

(a)



(b)

FIGURE 16.51 (a) A selection of common cymbals. (b) Detailed view of different surface textures and finishes of cymbals. *Source*: Courtesy of W. Blanchard, Sabian Ltd.

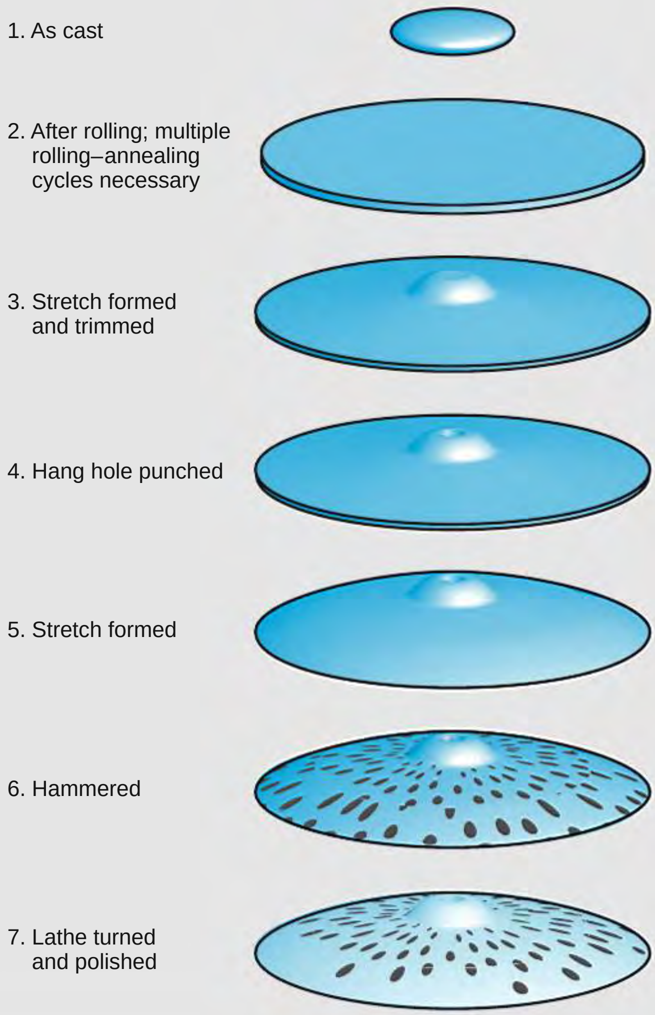
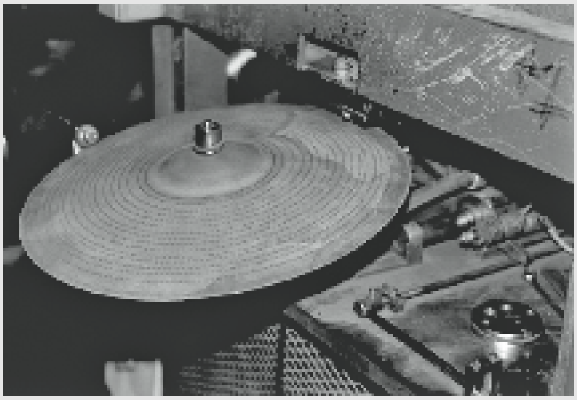


FIGURE 16.52 Manufacturing sequence for the production of cymbals. *Source*: Courtesy of W. Blanchard, Sabian Ltd.

(*continued*)



(a)

(b)

FIGURE 16.53 Hammering of cymbals. (a) Automated hammering on a peening machine; (b) hand hammering of cymbals. *Source*: Courtesy of W. Blanchard, Sabian Ltd.

"Turkish dish" form that controls the cymbal's pitch.

Automatic peen-forming is done on machinery without templates, since the cymbals have already been pressed into shape, but the pattern is controllable and uniform. The size and pattern of the peening operations depend on the desired response, such as tone, sound, response, and pitch of the cymbal. The cymbals are then hammered to impart a distinctive character to each instrument. Hammering can be done in automatic peen-forming machines (Fig. 16.53a) or by hand (Fig. 16.53b). Hand hammering involves placing the bronze blank on a steel anvil, where the cymbals then are struck manually by hand hammers.

A number of finishing operations are performed on the cymbals. These can involve merely the cleaning and printing of identifying information, as some musicians prefer the natural surface appearance and sound of formed, hot-rolled bronze. More commonly, the cymbals are lathe turned (without any machining fluid) in order to remove the oxide surface and reduce the thickness of the cymbal to create the desired weight and sound. As a result of this process, the surface finish becomes lustrous and, in some cases, develops a favorable microstructure. Some cymbals are polished to a glossy "brilliant finish." In many cases, the surface indentations from peening persist after finishing; this is recognized as an essential performance feature of the cymbal, and it is also an aesthetic feature that is appreciated by musicians. Various surface finishes associated with modern cymbals are shown in Fig. 16.51b.

Source: Courtesy of W. Blanchard, Sabian Ltd.

16.12 Manufacturing of Metal Honeycomb Structures

A *honeycomb structure* consists basically of a core of honeycomb or other corrugated shapes bonded to two thin outer skins (Fig. 16.54). The most common example of such a structure is corrugated cardboard, which has a high stiffness-to-weight ratio and is used extensively in packaging for shipping consumer and industrial goods.

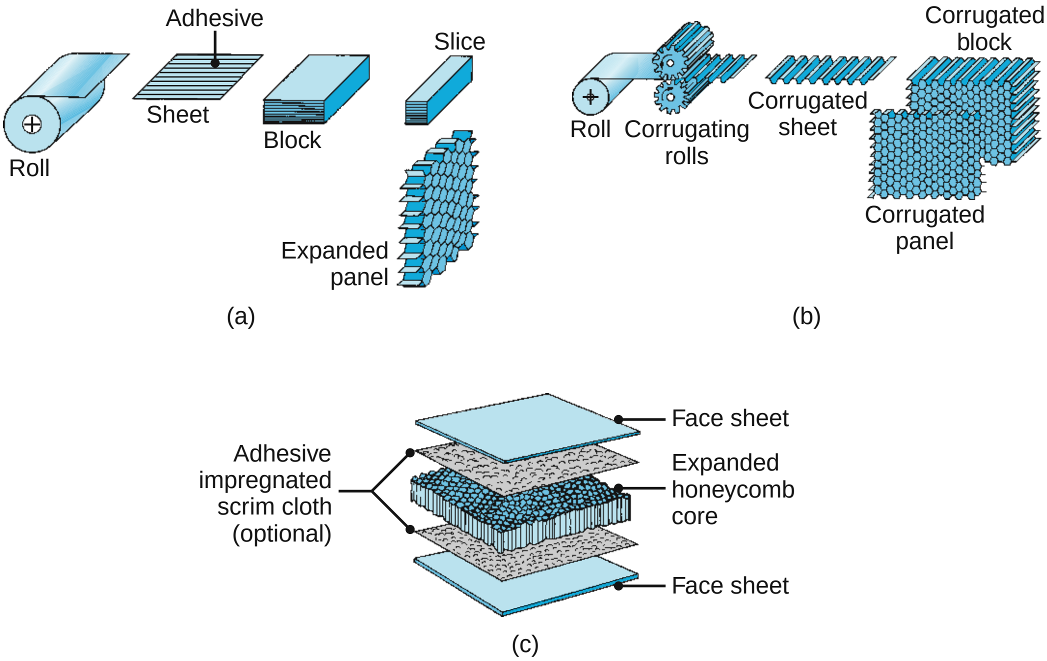


FIGURE 16.54 Methods of manufacturing honeycomb structures: (a) expansion process; (b) corrugation process; (c) assembling a honeycomb structure into a laminate.

Because of their light weight and high resistance to bending forces, metal honeycomb structures are used for aircraft and aerospace components, in buildings, and in transportation equipment. The chassis of the new Koenigsegg (Swedish) sports car, for example, is made partly of aluminum honeycomb with an integrated fuel tank.

Metal honeycomb manufacturing methods are described in this section because they involve operations that are best classified under sheet-metal-forming processes. Note, however, that honeycomb structures also may be made of nonmetallic materials, such as cardboard, polymers, and a variety of composite materials.

Honeycomb structures are made most commonly of 3000-series aluminum. However, they also are made of titanium, stainless steels, and nickel alloys for specialized applications and corrosion resistance. More recent developments include making honeycomb structures by using reinforced plastics, such as aramid-epoxy.

There are two basic methods of manufacturing honeycomb materials. In the **expansion process**, which is the more common method (Fig. 16.54a), sheets first are cut from a coil, and an *adhesive* (see Section 32.4) is applied at intervals (node lines) on their surfaces. The sheets are then stacked and cured in an oven, developing strong bonds at the adhesive joints. The block is finally cut into slices of the desired dimension and stretched to produce a honeycomb structure.

The **corrugation process** (Fig. 16.54b) is similar to the process used in making corrugated cardboard. The sheet metal first passes through a pair of specially designed rolls, becoming a corrugated sheet; it is then cut into desired lengths. Adhesive is applied to the node lines, the corrugated sheets are assembled into a block, and the block is cured. Because the sheets are preformed already, no expansion process is involved. The honeycomb material is finally made into a sandwich structure (Fig. 16.54c) by using face sheets that are joined by adhesives (or *brazed;* see Section 32.2) to the top and bottom surfaces.

16.13 Design Considerations in Sheet-metal Forming

As with most other processes described throughout this book, certain design guidelines and practices have evolved with time. Careful design using the best established design practices, computational tools, and manufacturing techniques is the best approach to achieving high-quality designs and realizing cost savings. The following guidelines apply to sheet-metal-forming operations, with the most significant design issues identified.

Blank Design. Material scrap is the primary concern in blanking operations. (See also Table 40.6.) Poorly designed parts will not *nest* properly, and there can be considerable scrap between successive blanking operations (Fig. 16.55). Some restrictions on blank shapes are made by the design application, but whenever possible, blanks should be designed to reduce scrap to a minimum.

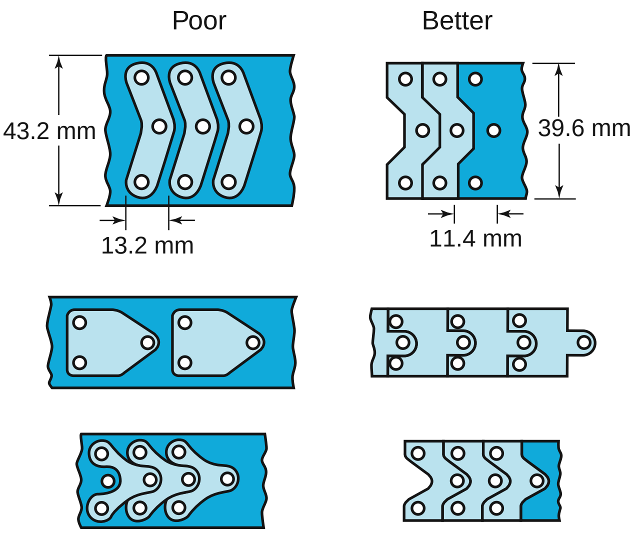


FIGURE 16.55 Efficient nesting of parts for optimum material utilization in blanking. *Source*: Courtesy of Society of Manufacturing Engineers.

Bending. In bending operations, the main concerns are material fracture, wrinkling, and the inability to form the bend. As shown in Fig. 16.56, a sheet-metal part with a flange that is to be bent will force the flange to undergo compression, which can cause buckling (see also *flanging*, Section 16.6). This problem can be controlled with a relief notch cut to limit the stresses from bending, or else a design modification as shown in the figure can be made to eliminate the problem. Right-angle bends have similar difficulties, and relief notches also can be used to avoid tearing (Fig. 16.57).

Because the bend radius is a highly stressed area, all stress concentrations should be removed from the bend-radius location. An example is parts with holes near bends. It is advantageous to move the hole away from the bend area, but when this is not possible, a crescent slot or ear can be used (Fig. 16.58a). Similarly, in bending flanges, tabs and notches should be avoided, since these stress concentrations will greatly reduce formability. When tabs are necessary, large radii should be used to reduce stress concentration (Fig. 16.58b).

When the bending and production of notches is to be used, it is important to orient the notches properly with respect to the grain direction. As shown in Fig. 16.17, bends ideally should be perpendicular to the rolling direction (or oblique if this is not possible) in order to avoid cracking. Bending sharp radii can be accomplished through scoring or embossing (Fig. 16.59), but it should be recognized that this can result in fracturing. Burrs should not be present in a bend allowance, since they are brittle

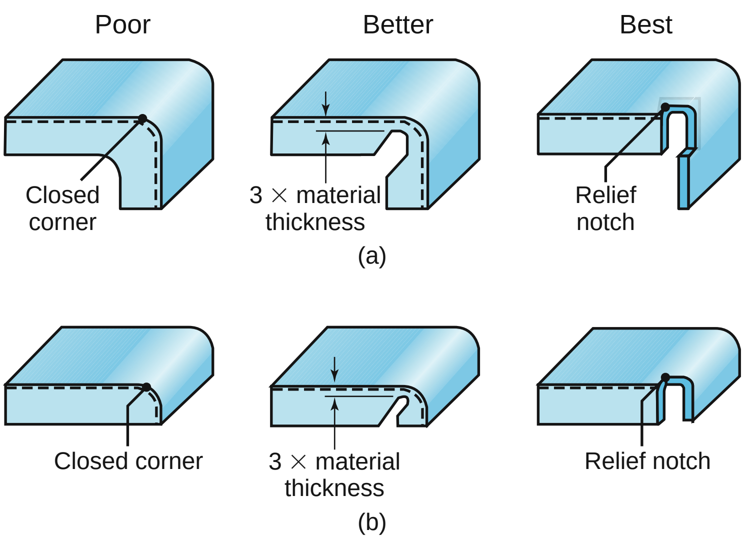


FIGURE 16.56 Control of tearing and buckling of a flange in a right-angle bend. *Source*: Courtesy of Society of Manufacturing Engineers.

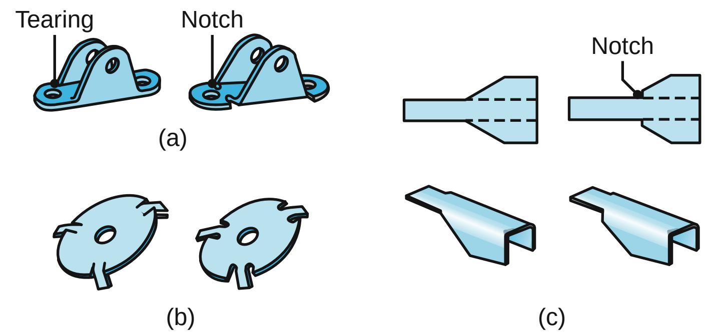


FIGURE 16.57 Application of notches to avoid tearing and wrinkling in right-angle bending operations. *Source*: Courtesy of Society of Manufacturing Engineers.

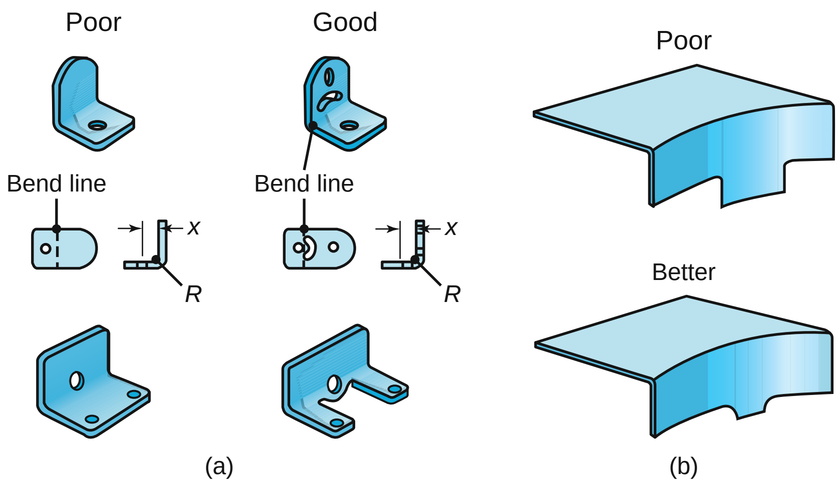


FIGURE 16.58 Stress concentrations near bends. (a) Use of a crescent or ear for a hole near a bend. (b) Reduction of severity of tab in flange. *Source*: Courtesy of Society of Manufacturing Engineers.

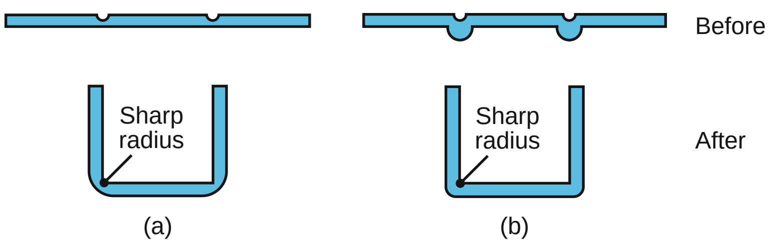


FIGURE 16.59 Application of (a) scoring or (b) embossing to obtain a sharp inner radius in bending. Unless properly designed, these features can lead to fracture. *Source*: Courtesy of Society of Manufacturing Engineers.

(because of strain hardening) and can fracture, leading to a stress concentration that propagates the crack into the rest of the sheet.

Roll Forming. In general, the process should be designed so as to control spring-back. Also, it is not difficult to include perforating rolls in the forming line, so that periodic holes, notches, or embossings can be located on the roll-formed shape.

Stamping and Progressive-die Operations. In progressive dies (see Section 16.2.3), the cost of the tooling and the number of stations are determined by the number and spacing of features on a part. Therefore, it is advantageous to hold the number of features to a minimum in order to minimize tooling costs. Closely spaced features may provide insufficient clearance for punches and may require two punches. Narrow cuts and protrusions also are problematic for forming with a single punch and die.

Deep Drawing. After a deep-drawing operation, a cup invariably will spring back towards its original shape. For this reason, designs that use a vertical wall in a deep-drawn cup may be difficult to form. Relief angles of at least 3° on each wall are easier to produce. Cups with sharp internal radii are difficult to produce, and deep cups often require one or more ironing operations.

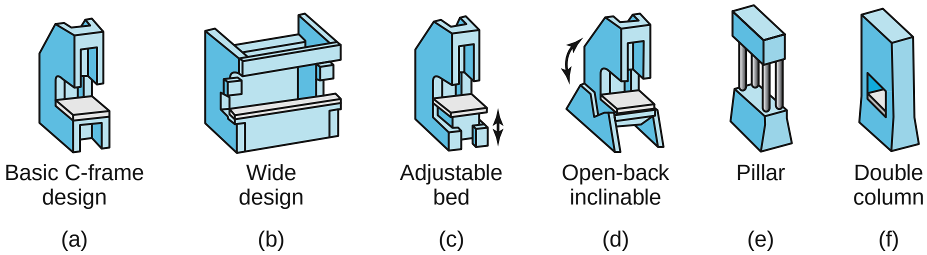
16.14 Equipment for Sheet-metal Forming

For most general pressworking operations, the basic equipment consists of mechanical, hydraulic, pneumatic, or pneumatic–hydraulic presses with a wide variety of designs, features, capacities, and computer controls. Typical designs for press frames are shown in Fig. 16.60 (see also Figs. 14.17 and 16.23f). The proper design, stiffness, and construction of such equipment is essential to the efficient operation of the system and to achieving a high production rate, good dimensional control, and high product quality.

The traditional **C-frame** structure (Fig. 16.60a) has been used widely for ease of tool and workpiece accessibility, but it is not as stiff as the **box-type pillar** (Fig. 16.60e) or the **double-column frame** structure (Fig. 16.60f). Furthermore, accessibility has become less important due to advances in automation and in the use of industrial robots and computer controls.

Press selection for sheet-metal forming operations depends on several factors:

1. Type of forming operation, the size and shape of the dies, and the tooling required.
2. Size and shape of workpieces.
3. Length of stroke of the slide, the number of strokes per minute, the operating speed, and the *shut height* (the distance from the top of the bed to the bottom of the slide with the stroke down).
4. Number of slides. Single-action presses have one reciprocating slide. Double-action presses have two slides, reciprocating in the same direction. They typically are used for deep drawing—one slide for the punch and the other for the blankholder. Triple-action presses have three slides; they are typically used for reverse redrawing and for other complicated forming operations.
5. Maximum force required (press capacity and tonnage rating).
6. Type of mechanical, hydraulic, and computer controls.
7. Features for changing dies. Because the time required for changing dies in presses can be significant (as much as a few hours) and thus affect productivity, rapid die-changing systems have been developed. Following a system called *single-minute exchange of die* (SMED), die setups can be changed in less than 10 minutes by using computer-controlled hydraulic or pneumatic systems.
8. Safety features.



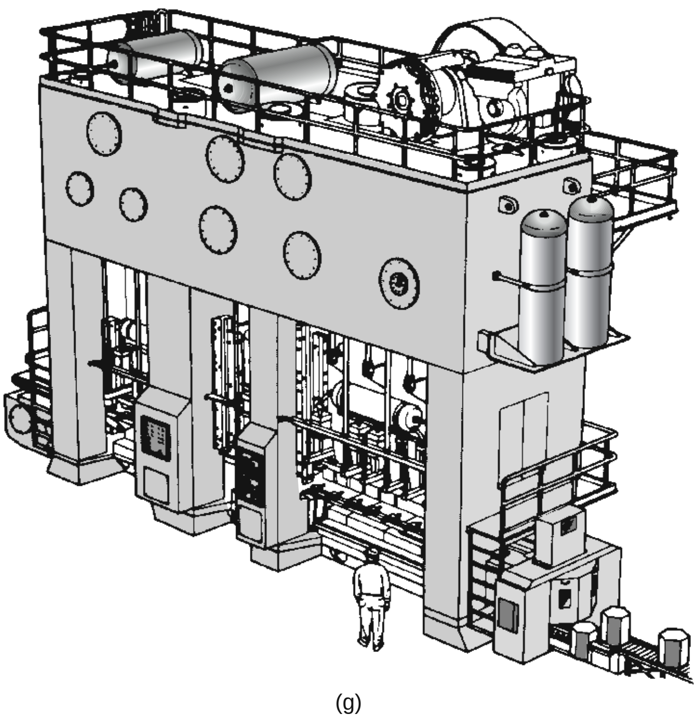


FIGURE 16.60 (a) through (f) Schematic illustrations of types of press frames for sheet-forming operations. Each type has its own characteristics of stiffness, capacity, and accessibility. (g) A large stamping press. *Source*: (a) through (f) *Engineer's Handbook*, VEB Fachbuchverlag, 1965; (g) Verson Allsteel Company.

Because a press is a major capital investment, its present and future use for a broad variety of parts and applications should be investigated. Versatility and multiple use are important factors in press selection, particularly for product modifications and for making new products to respond to continually changing global markets.

16.15 Economics of Sheet-forming Operations

Sheet-metal forming involves economic considerations similar to those for the other processes that have been described. Sheet-forming operations are very versatile, and a number of different processes can be used to produce the same part. The costs involved (see also Chapter 40) depend on the particular operations (such as die and equipment costs and labor). For small and simple sheet-metal parts, die costs and

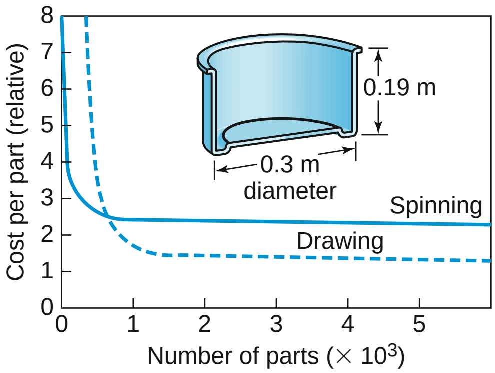


FIGURE 16.61 Cost comparison for manufacturing a round sheet-metal container either by conventional spinning or by deep drawing. Note that for small quantities, spinning is more economical.

lead times to make the dies are rather low. On the other hand, these costs for large-scale operations (such as stretch forming of aircraft panels and boat hulls) are very high. Furthermore, because the number of such parts needed is rather low, the cost per piece can be very high (see Fig. 14.18).

Similar considerations are involved in other sheet-forming operations. Deep drawing requires expensive dies and tooling, but a very high number of parts, such as containers, cans, and similar products, are produced with the same setup. These costs for other processes, such as punching, blanking, bending, and spinning, vary considerably, depending on part size and thickness.

Equipment costs vary widely and depend largely on the complexity of the forming operation, part loading and unloading features, part size and shape, and level of automation and computer control required. Automation, in turn, directly affects the amount of labor required and the skill level. The higher the extent of automation, the lower the skill level required. Furthermore, many sheet-metal parts generally require some finishing operations—one of the most common being deburring of the edges of the part, which generally is labor intensive, although some advances have been made in automated deburring (which itself requires computer-controlled equipment; hence, it can be costly).

As an example of the versatility of sheet-forming operations and the costs involved, note that a cup-shaped part can be formed by deep drawing, spinning, rubber forming, or explosive forming. Moreover, it also can be formed by impact extrusion, casting, or fabrication from different pieces. The part shown in Fig. 16.61 can be made either by deep drawing or by conventional spinning, but the die costs for the two processes are significantly different.

Deep-drawing dies have many components, and they cost much more than the relatively simple mandrels and tools employed in spinning. Consequently, the die cost per part in drawing will be high if only a few parts are needed. However, this part can be formed by deep drawing in a much shorter time than by spinning, even if the latter operation is automated and computer controlled. Furthermore, spinning generally requires more skilled labor. Considering these factors, the break-even point can be seen as around 700 parts, and deep drawing is more economical for quantities greater than that. Chapter 40 describes further details of the economics of manufacturing.

SUMMARY

- Sheet-metal-forming processes are among the most versatile of all operations. They generally are used on workpieces having high ratios of surface area to thickness. Unlike bulk deformation processes such as forging and extrusion, sheet forming often prevents the thickness of the material from being reduced (to avoid necking and tearing).
- Important material parameters are the quality of the sheared edge of the sheet metal prior to forming, the capability of the sheet to stretch uniformly, the material's resistance to thinning, its normal and planar anisotropy, its grain size, and its yield-point elongation (for low-carbon steels).
- The forces and energy required in sheet-metal-forming processes are transmitted to the workpiece through solid tools and dies, by flexible rubber or polyurethane members, or by electrical, chemical, magnetic, and gaseous means.

- Because of the relatively thin materials used, springback, buckling, and wrinkling are significant problems in sheet forming. Springback is a function of the yield stress, the elastic modulus, and the ratio of bend radius to thickness. These problems can be reduced or eliminated by proper tool and die design, by minimizing the unsupported length of the sheet during processing, and by controlling the thickness of the incoming sheet and its mechanical properties.
- Among important developments is the superplastic forming of diffusion-bonded sheets. The process is capable of producing complex sheet-metal structures, particularly for aerospace applications (which require particularly high stiffness-to-weight ratios).
- Several test methods have been developed for predicting the formability of sheet metals. In bending operations, the tensile reduction of the area of the sheet gives an indication of its bendability (minimum bend radius); this also applies to, the spinnability parameter of metals (maximum reduction in thickness per pass).
- For general stamping operations, forming-limit diagrams are very useful, because they establish quantitative relationships among the major and minor principal strains that limit safe forming. For deep-drawing operations, the important parameter is the normal or plastic anisotropy of the sheet (the ratio of width strain to thickness strain in tensile testing).

KEY TERMS

Beading
Bendability
Bend allowance
Bending
Blankholder
Blanking
Bulging
Burnished surface
Burr
Clearance
Compound dies
Deburring
Deep drawing
Dent resistance
Dimpling
Drawbead
Drawing
Earing
Electrohydraulic forming
Embossing
Explosive forming
Fine blanking
Flanging
Formability
Forming-limit diagram
Hemming
Honeycomb structures
Hydroform process
Incremental forming
Ironing
Laser forming
Limiting drawing ratio
Lüder's bands
Magnetic-pulse forming
Microforming
Minimum bend radius
Nesting
Nibbling
Normal anisotropy
Peen forming
Planar anisotropy
Plastic anisotropy
Press brake
Progressive dies
Punching
Redrawing
Roll forming
Rubber forming
Shaving
Shearing
Slitting
Spinning
Springback
Steel rule
Stretch forming
Superplastic forming
Tailor-welded blanks
Transfer dies
Wrinkling

BIBLIOGRAPHY

ASM Handbook, Vol. 14B: **Metalworking: Sheet Forming,** ASM International, 2006.

Benson, S., **Press Brake Technology,** Society of Manufacturing Engineers, 1997.

Boljanovic, V., **Sheet Metal Forming Process and Die Design,** Industrial Press, 2004.

Davies, G., **Materials for Automobile Bodies**, Butterworth-Heinemann, 2003.

Fundamentals of Tool Design, 5th ed., Society of Manufacturing Engineers, 2005.

Gillanders, J., **Pipe and Tube Bending Manual**, FMA International, 1994.

Hosford, W.F., and Caddell, R.M., **Metal Forming: Mechanics and Metallurgy**, 3rd ed., Cambridge, 2007.

Hu, J., Marciniak, Z., and Duncan, J., **Mechanics of Sheet Metal Forming**. Butterworth-Heinemann, 2002.

Pearce, R., **Sheet Metal Forming**, Springer, 2006.

Progressive Dies, Society of Manufacturing Engineers, 1994.

Rapien, B.L., **Fundamentals of Press Brake Tooling,** Hanser Gardner, 2005.