CHAPTER 16

Sheet-metal Forming Processes and Equipment

- 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 description of the shearing operation, 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 such operations as stretch forming, rubber forming, spinning, peen forming, and superplastic forming.
- Deep drawing is then described, along with drawability, as it relates to the production of containers with thin walls.
- The chapter ends with a discussion of sheet-metal parts design, 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 lightweight and versatile shapes.

As described throughout this chapter, there are numerous processes employed for making sheet-metal parts. The terms **pressworking** or **press forming** are commonly used in industry to describe these operations, because they typically are performed on *presses* (described in Sections 14.8 and 16.15), using a 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"). Low-carbon steel is the most commonly used sheet metal, because of its low cost and generally good

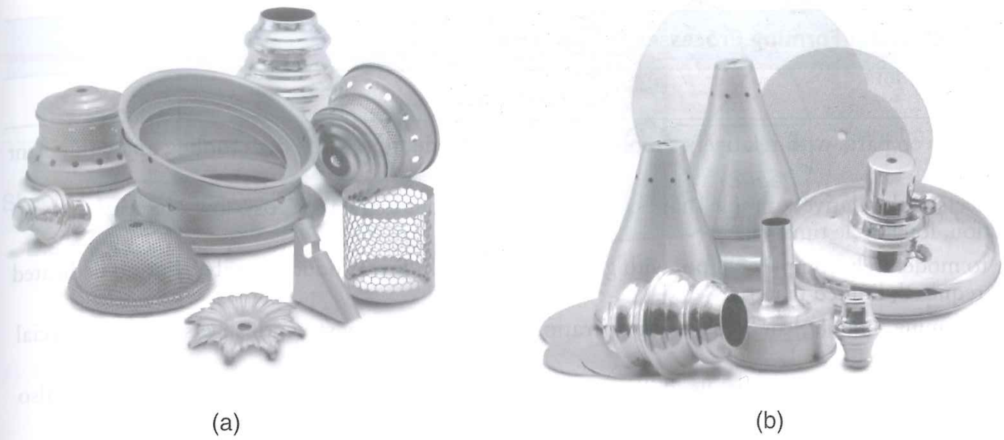


FIGURE 16.1 Examples of sheet-metal parts. (a) Stamped parts. (b) Parts produced by spinning. *Source:* Courtesy of Williamsburg Metal Spinning & Stamping Corp.

strength and formability characteristics. More recently developed alloys, such as TRIP and TWIP steels (see Section 5.5.6), have become more common for automotive applications because of their high strength. They are also well suited for providing good crash protection in a lightweight design. Aluminum is the most common material for such applications as beverage cans, packaging, kitchen utensils, and where corrosion resistance is an important factor. 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 sheet metals 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. 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 (FLDs). All of the major processes of sheet forming and the equipment also are described, as outlined in Table 16.1

16.2 Shearing

All sheet-metal forming operations begin with a **blank** of suitable dimensions and removed from a large sheet (usually from a *coil*) by **shearing**. Shearing subjects the sheet to shear stresses, generally using a punch and a die (Fig. 16.2a). The typical features of the sheared edges of the sheet metal and of the slug are shown in Figs. 16.2b and c, respectively. Note that, in this illustration, 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 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.

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

The major processing parameters in shearing are:

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

The **clearance** is a major factor in determining the shape and the quality of the sheared edge. As clearance increases, the deformation zone (Fig. 16.3a) becomes larger and the sheared-edge surface becomes rougher. With excessive clearances, the sheet tends to be pulled into the die cavity, and the perimeter or edges of the sheared zone become rougher. Unless such edges are acceptable as produced, secondary operations may be necessary to make them smoother, which will increase the production cost. (See also *fine blanking* in Section 16.2.1.)

Edge quality can be improved with increasing punch speed, which may be as high as 10 to 12 m/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, thus adversely affecting the formability of the sheet during subsequent forming operations, such as bending and stretching.

The ratio of the burnished area to the rough areas along the sheared edge increases with increasing ductility of the sheet metal, and decreases with increasing sheet thickness and clearance. The extent of the deformation zone, shown in Fig. 16.3, depends on the punch speed. With increasing speed, the heat generated by plastic

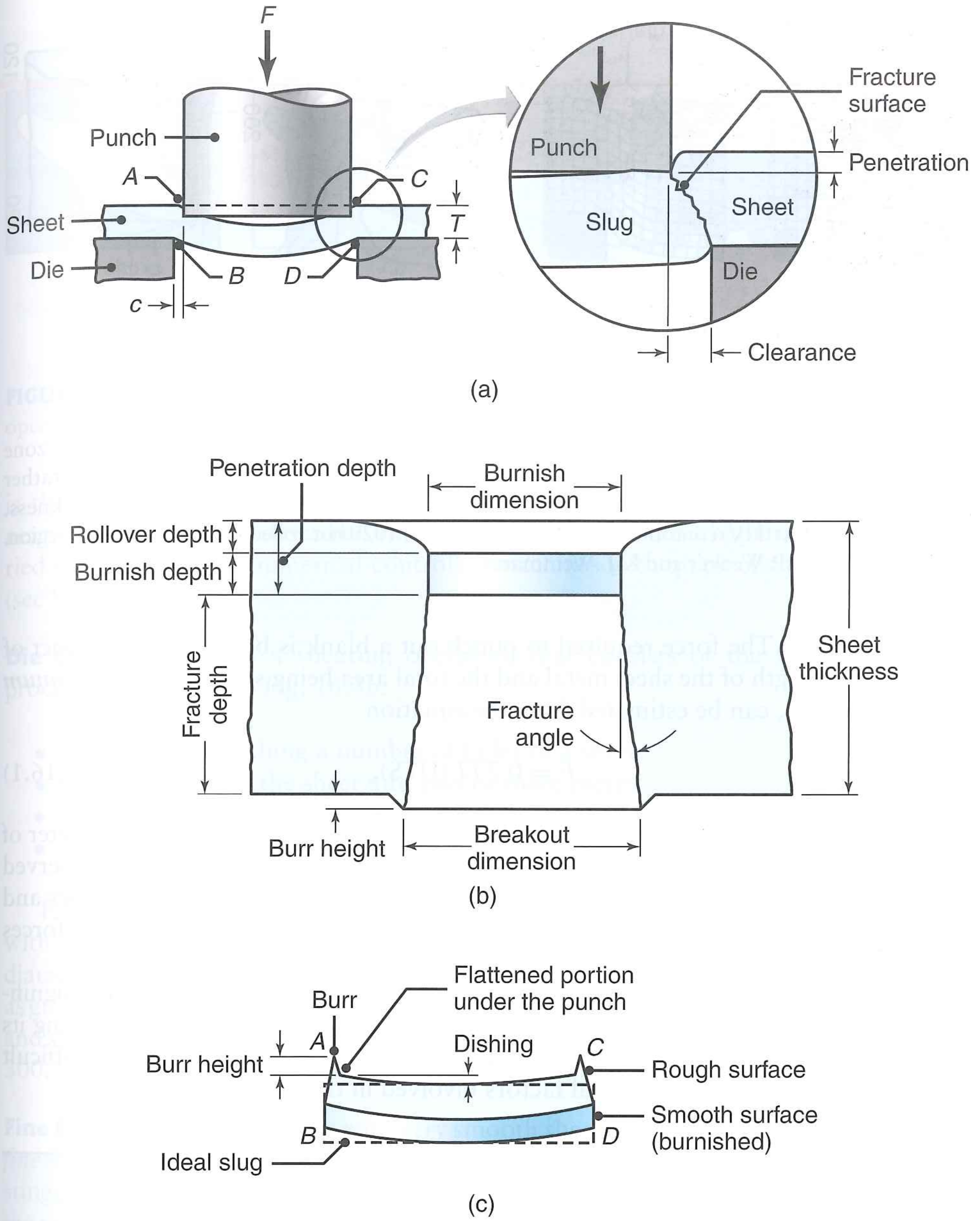


FIGURE 16.2 (a) Schematic illustration of shearing with a punch and die, indicating some of the process variables. Characteristic features of (b) a punched hole and (c) the slug; note that the scales of (b) and (c) are different.

deformation becomes confined to a smaller and smaller zone. Consequently, the sheared zone becomes narrower, and the sheared surface is smoother and exhibits less burr formation.

A **burr** is a thin edge or ridge, as shown in Figs. 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.

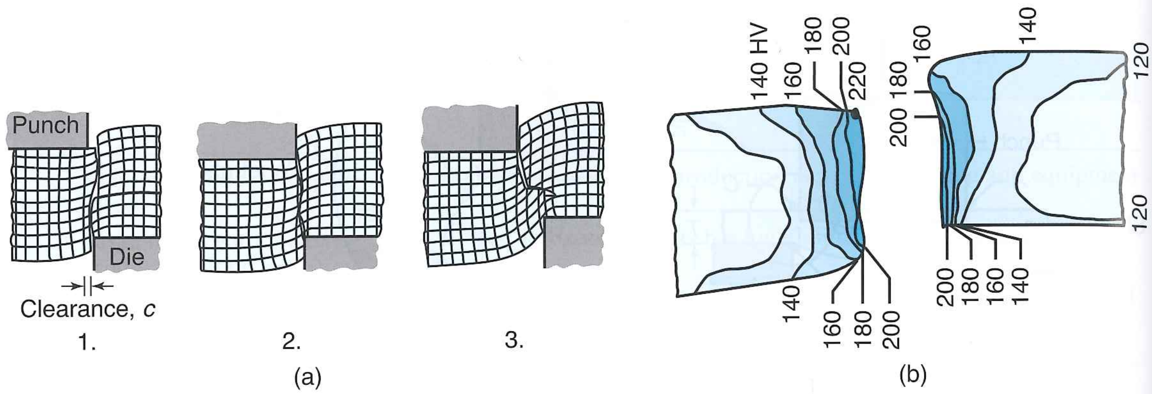


FIGURE 16.3 (a) Effect of the clearance, c, between punch and die on the deformation zone in shearing; as the clearance increases, the material tends to be pulled into the die rather than be sheared. In practice, clearances usually range between 2 and 10% of sheet thickness. (b) Microhardness (HV) contours for a 6.4-mm 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. The *maximum punch force*, F, can be estimated from the equation

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

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. It has been observed that 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 increases the punch force significantly. Furthermore, a force is required to strip the punch from the sheet during its return stroke. This force, which is in opposite direction of the punch force, is difficult to estimate because of the several factors involved in the punching operation.

EXAMPLE 16.1 Calculation of Punch Force

Given: A 25-mm diameter hole is to be punched through a 3.2-mm thick annealed titanium-alloy Ti-6Al-4V sheet at room temperature.

Find: Estimate the force required.

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. Thus,

$$F = 0.7(32)(\pi)(25)(1000) = 0.17\ \text{MN}.$$

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

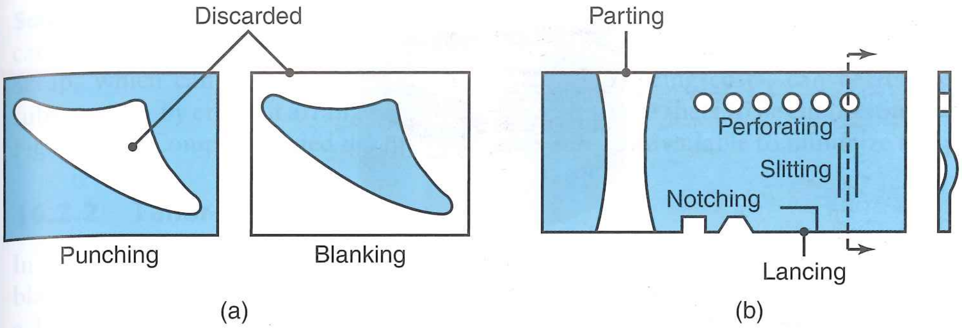


FIGURE 16.4 (a) Punching (piercing) and blanking. (b) Examples of various die-cutting operations on sheet metal; lancing involves slitting the sheet to form a tab.

is the part to be used and the rest is scrap). The shearing operations described next, as well as those described throughout the rest of this chapter, are often carried out on computer-numerical-controlled machines with quick-change toolholders (see Section 16.15).

Die Cutting. This is a shearing operation that consists of the following basic processes, as shown in Fig. 16.4b:

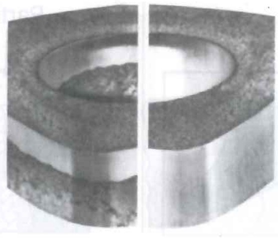
- *Perforating:* punching a number of holes in a sheet
- *Parting:* shearing the sheet into two or more pieces
- *Notching:* removing pieces from edges
- *Lancing:* producing a tab without removing any material

Parts produced by these processes have various uses, particularly in assembly with other sheet-metal components. Perforated sheet metals, for example, with hole diameters ranging from 1 mm to 75 mm 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. 14.19a), at rates as high as 300,000 holes per minute, using special dies and equipment.

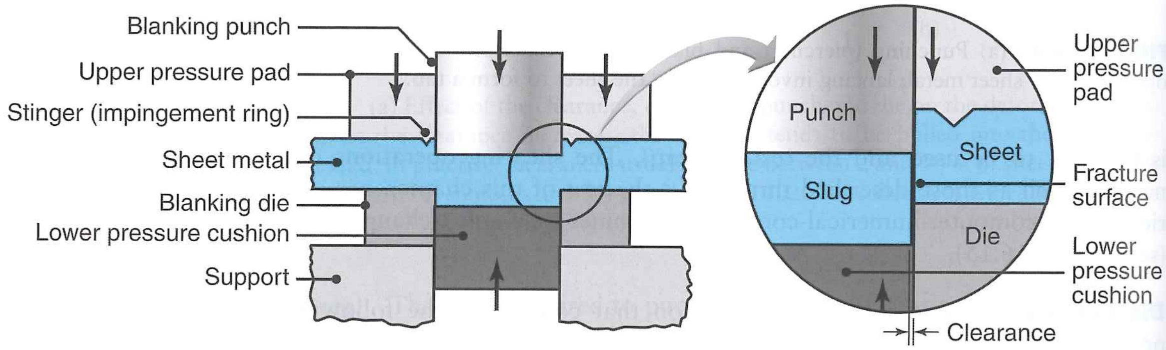
Fine Blanking. Square edges with very smooth sheared surfaces can be produced by *fine blanking* (Fig. 16.5a). One basic die design is shown in Fig. 16.5b. A V-shaped stinger or impingement mechanically locks the sheet tightly in place, and thus prevents the type of distortion of the material shown in Figs. 16.2b and 16.3. The fine-blanking process involves clearances on the order of 1% of the sheet thickness, which may range from 0.5 to 13 mm in most applications. Dimensional tolerances typically are on the order of ± 0.05 mm.

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 cylindrical rolls. If not performed properly, slitting operations can cause various distortions of the sheared edges.

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



(a)



(b)

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:* Reprinted by permission of Feintool U.S. Operations.

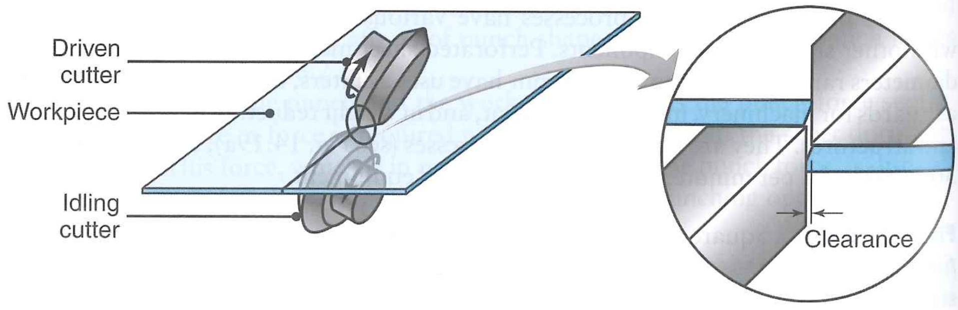


FIGURE 16.6 Slitting with rotary knives, a process similar to opening cans.

shape to be produced, 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 defined by 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 several 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 using standard punches. Because no special dies are required, the process is economical for small production runs.

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, which can be a significant factor in manufacturing costs, can be reduced substantially by efficient arrangement of the shapes on the sheet to be cut (**nesting**, see Fig. 16.59). Computer-aided design techniques are now available to minimize scrap.

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 constant thickness, and cut (blanked) from a large sheet. An important variation from this practice 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. (See Case Study 16.1.)

Because of the small thicknesses involved, the proper alignment of the sheets prior to welding is important. The welded assembly is subsequently formed into a final shape. This technique has become increasingly important, particularly to the automotive industry. Because each piece now can have a different thickness, composition, coating, or other characteristics, the use of tailor-welded blanks has the following advantages:

- Reduction in scrap
- Elimination of the need for subsequent spot welding operations (as in making a car body; see Fig. I.9)
- Better control of dimensions
- Increased productivity

CASE STUDY 16.1 Tailor-welded Sheet Metal for Automotive Applications

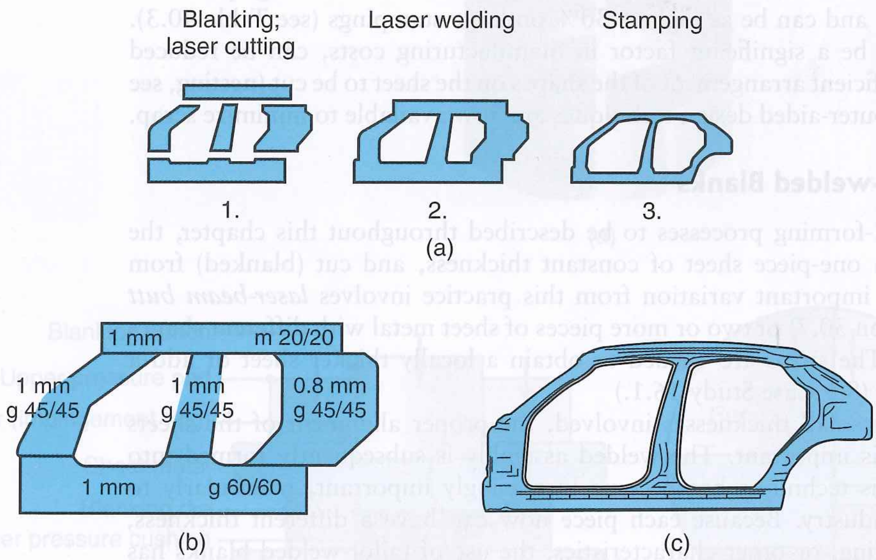
An example of the use of tailor-welded sheet metals in automobile bodies is shown in Fig. 16.7. Note that five different pieces are first blanked, which includes cutting by laser beams. Four of these pieces are 1 mm thick, and one is 0.8 mm thick. The pieces are laser butt welded (Section 30.7) and then 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 and the joints are very strong and reliable. The combination of welding and forming sheet-metal pieces makes possible significant flexibility in product design, formability, structural stiffness, and crash behavior of an automobile. It also makes possible the use of different materials in one product, weight savings, and cost reductions in materials, scrap, assembly, equipment, and labor.

The various components shown in Fig. 16.8 utilize the advantages outlined above. For example, note in Fig. 16.8b 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 varies (depending on its location and on its contribution to such characteristics as stiffness and strength), resulting in significant weight savings without loss of structural strength and stiffness.

More recent advances include the use of *friction stir welding* (Section 31.4) to produce the tailor-welded blank, and in the production of *tailor-welded coils*, where the material and/or thickness can be varied at a given location in the sheet. Tailor-welded blanks have also been used in hot stamping of automotive space frame pillars (Section 16.11). In this application, a steel grade is used to minimize deflections and protect occupants, but a more ductile steel that absorbs energy (see *toughness*, Sections 2.2.4 and 2.10) is used where the pillar is attached to the car frame.

(*continued*)



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.

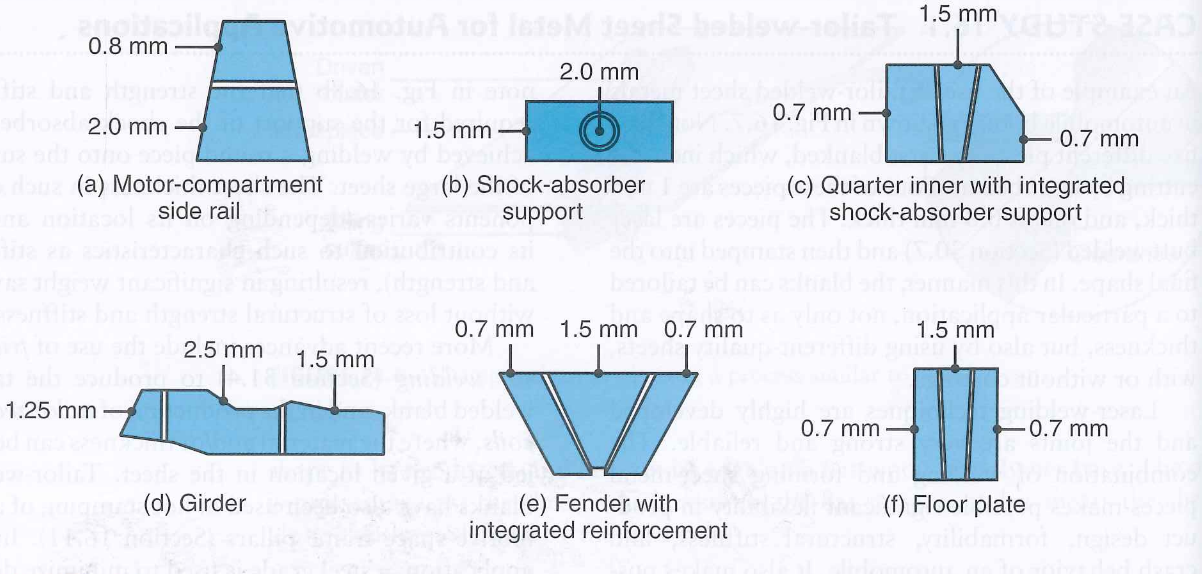


FIGURE 16.8 Examples of laser butt-welded and stamped automotive-body components. *Source:* After M. Geiger and T. Nakagawa.

16.2.3 Characteristics and Types 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

- Type of material and its temper
- Thickness and size of the blank
- 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, although they may be as small as 1% (as in *fine blanking*, Section 16.2.1) 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 must be larger. In using larger clearances, attention must be paid to the rigidity and the alignment of the presses, the dies, and their setups.

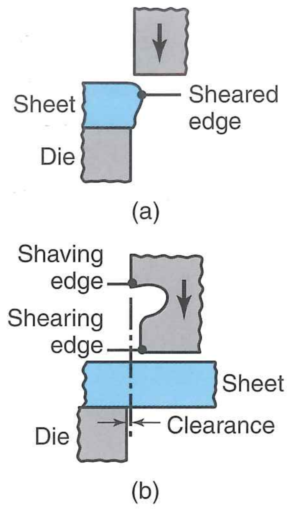


FIGURE 16.9 Schematic illustrations of the shaving process. (a) Shaving a sheared edge. (b) Shearing and shaving combined in one stroke.

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 can be observed by inspecting the tip of the punch. Beveling is suitable particularly for shearing thick sheets, because it reduces the force at the beginning of the stroke and the operation's noise level.

Note in Fig. 16.10c that the punch tip is symmetrical, and in Fig. 16.10d the die is symmetrical, thus 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 it is subjected to a lateral force. Consequently, the punch and press setups 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 and cause damage (as it might at point *B* or *D* in Fig. 16.2a).

Compound Dies. Several operations may be performed on the same sheet in one stroke, and 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, especially for complex dies, to produce than those for individual shearing operations.

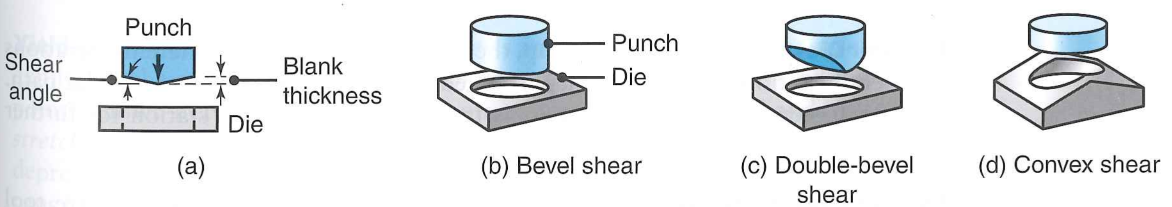


FIGURE 16.10 Examples of shear angles on punches and dies.

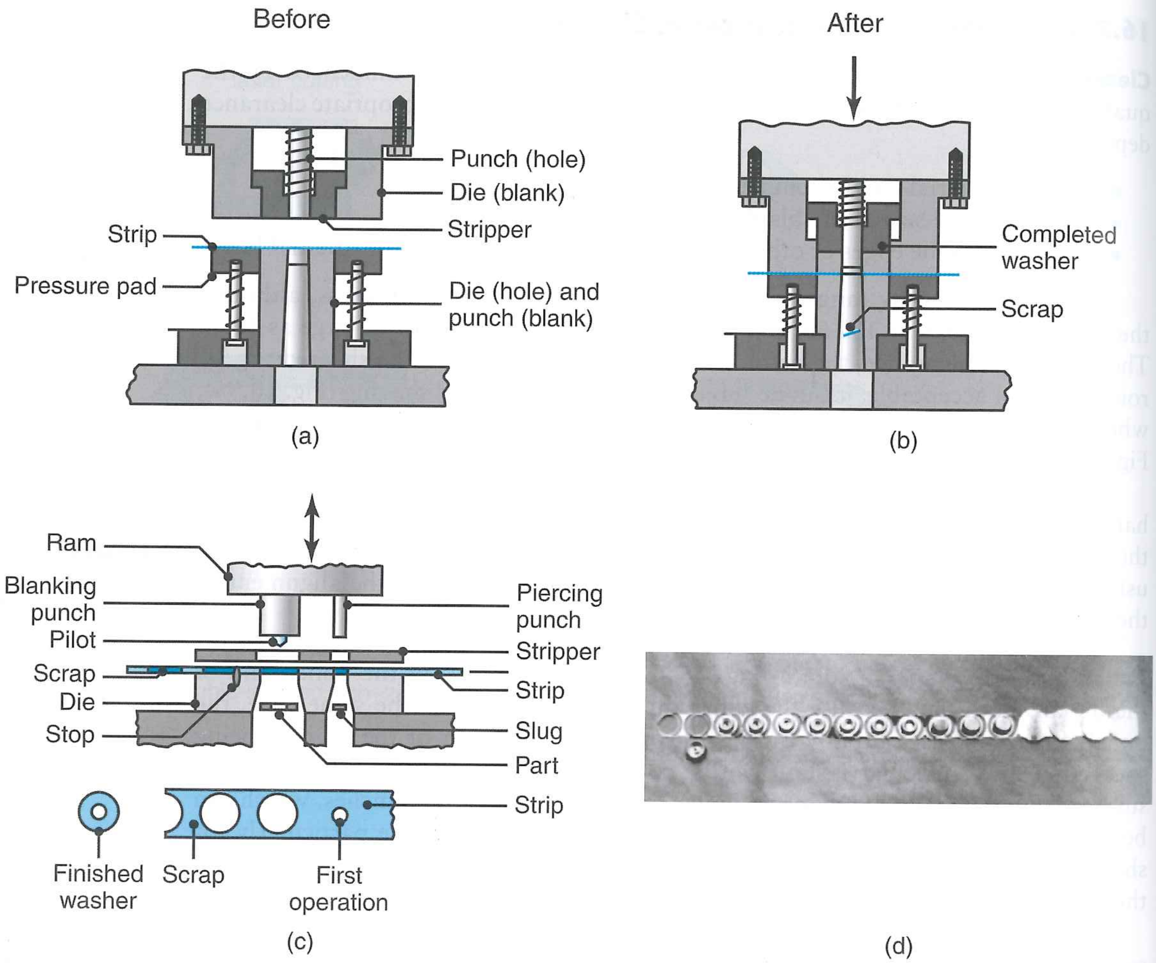


FIGURE 16.11 Schematic illustrations (a) before and (b) after blanking a common washer in a compound die; note the separate movements of the die (for blanking) and the punch (for punching the hole in the washer). (c) Schematic illustration of making a washer in a progressive die. (d) Forming of the top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

Progressive Dies. Parts requiring multiple forming operations can be made, at high production rates, using *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 using 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 metal 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, 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 carbides (for high production rates). (See Tables 5.7–5.9.) Lubrication is important for reducing tool and die wear, thus maintaining edge quality.

16.2.4 Miscellaneous Methods of Cutting Sheet Metal

There are several other methods of cutting metal sheets and plates:

- **Laser-beam cutting** is an important process (Section 27.6), and typically used with computer-controlled equipment to cut a variety of shapes consistently, in various thicknesses, and without the use of dies. The process can also be combined with punching and shearing operations. Some parts with certain features may be produced best by one process, while others, with various features, may best be produced by the other process. Combination machines, incorporating both capabilities, have been designed and built for this reason. (See also Example 27.1.)
- **Water-jet cutting** is effective on metallic as well as nonmetallic materials (Section 27.8).
- Cutting with a **band saw**; this is a chip-removal process.
- **Friction sawing** involves a disk or blade that rubs against the sheet or plate at high surface speeds, thus raising the temperature and separating it into two pieces (Section 24.5).
- **Flame cutting** is another common method, particularly for thick plates; it is used widely in shipbuilding and on heavy structural components (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. This section presents a brief review of those characteristics of sheet metals that have significant effects on forming operations, as outlined in Table 16.2.

Elongation. Sheet-metal forming processes rarely involve simple uniaxial stretching, as 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, the specimen begins to neck and elongation is no longer uniform.

Because in sheet forming the material usually is being stretched, high uniform elongation is essential 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 *diffused*, depending on the *strain-rate sensitivity*, m, of the material, as 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) also is 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, shown in Fig. 16.12a. This phenomenon results in **Lüder's bands** (also called *stretcher-strain marks* or *worms*) on the sheet (Fig. 16.12b), which are elongated depressions on the surface of the sheet, such as can be found on the bottom of steel cans for common household products (Fig. 16.12c). The marks may be objectionable in the formed product, because coarseness on the surface degrades appearance and may cause difficulties in subsequent coating and painting operations.

TABLE 16.2

Important Metal Characteristics for Sheet-metal 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

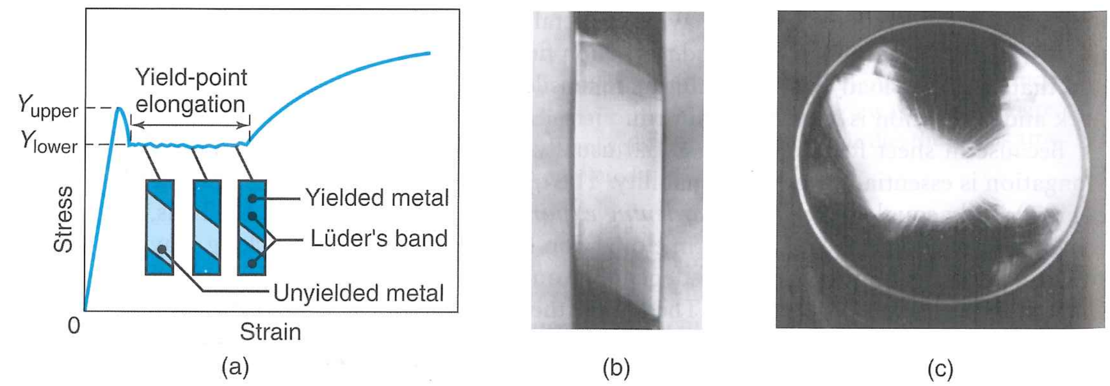


FIGURE 16.12 (a) Yield-point elongation in a sheet-metal specimen. (b) Lüder's bands in a low-carbon steel sheet. (c) Stretcher strains at the bottom of a steel can for household products. *Source:* (b) Courtesy of Caterpillar, Inc.

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, known as **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; thus, the material should be formed within a certain time limit (which depends on the material).

Anisotropy. An important factor that influences sheet-metal forming is *anisotropy* (*directionality*) of the sheet (see Fig. 16.17). 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* (alignment of impurities, inclusions, and voids throughout the thickness of the sheet). The relevance of anisotropy is discussed further in Section 16.4.

Grain Size. As described in Section 1.5, 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, and 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 are commonly found on cars, appliances, and office furniture. They usually are caused by dynamic forces from moving objects hitting the sheet metal. In typical automotive panels, for example, velocities at impact range up to 45 m/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.

The factors significant in dent resistance can be shown to be the yield stress, Y, the sheet metal thickness, T, and the shape of the panel. *Dent resistance* is then expressed by a combination of material and geometrical parameters, as

$$\text{Dent resistance} = \frac{Y^2 T^4}{S}, \tag{16.1a}$$

where S is the panel stiffness, which, in turn, is defined as

$$S = ET^a(\text{shape}), \tag{16.1b}$$

where the value of a ranges from 1 to 2 for most panels. As for shape, the flatter the panel, the greater is its dent resistance, because of the sheet's flexibility. Thus, dent resistance (1) increases with increasing strength and thickness of the sheet, (2) decreases with increasing elastic modulus and stiffness, and (3) decreases with decreasing curvature of the sheet. Consequently, panels rigidly held at their edges have lower dent resistance (because of their higher stiffness) than those held with a set of springs.

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, by pushing a ball-peen hammer against it versus by striking it with the hammer; note how localized the dent will be in the latter case.

16.4 Formability Tests for Sheet Metals

Sheet-metal formability is generally defined as the ability of the sheet metal to undergo the required shape change without failure, such as by cracking, wrinkling, necking, or tearing. As will be noted throughout the rest of this chapter, depending on part shape, sheet metals may undergo two basic modes of deformation: (1) *stretching* and

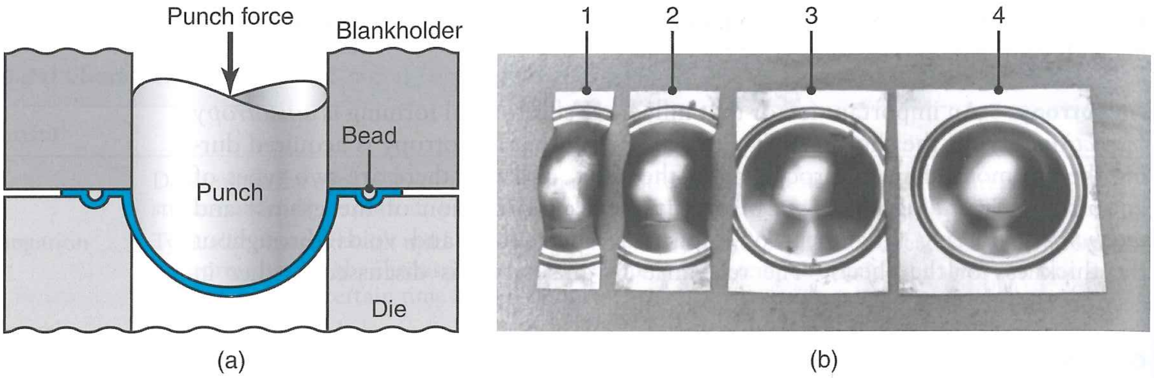


FIGURE 16.13 (a) A cupping test (the Erichsen test) to determine the formability of sheet metals. (b) Bulge-test results on steel sheets of various widths; the specimen farthest left is subjected to, basically, simple tension. The specimen that is farthest right is subjected to equal biaxial stretching.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

(2) *drawing*. There are important distinctions between these two modes, and different parameters are involved in determining formability under 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 a round punch) is forced into the sheet until a crack begins to appear on the stretched specimen. The *punch depth*, d, at which a crack appears is a measure of the formability of the sheet. Although this and other 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 approach for determining the formability of sheet metals is the development of *forming-limit diagrams* (FLD), as shown in Fig. 16.14. For a particular sheet metal, this diagram is constructed by first marking the flat sheet with a grid pattern of circles (Fig. 16.15), using chemical or photoprinting techniques. The blank is then stretched over a punch (Fig. 16.13a), and the deformation of the circles is observed and measured in the region where failure (*necking* or *tearing*) has occurred. Although the circles typically are 2.5 to 5 mm in diameter, for improved accuracy of measurement, they should be made as small as is practical.

In order to simulate the typically unequal stretching encountered in 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) basically undergoes a 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, an FLD is constructed, showing the boundaries between failure and safe zones (Fig. 16.14b).

In order to develop an FLD, the major and minor engineering strains, as measured from the deformation of the original circles, are obtained. Note in Fig. 16.14a that an original circle has deformed into an ellipse, the *major axis* of which represents the major direction and magnitude of stretching. The major strain is the

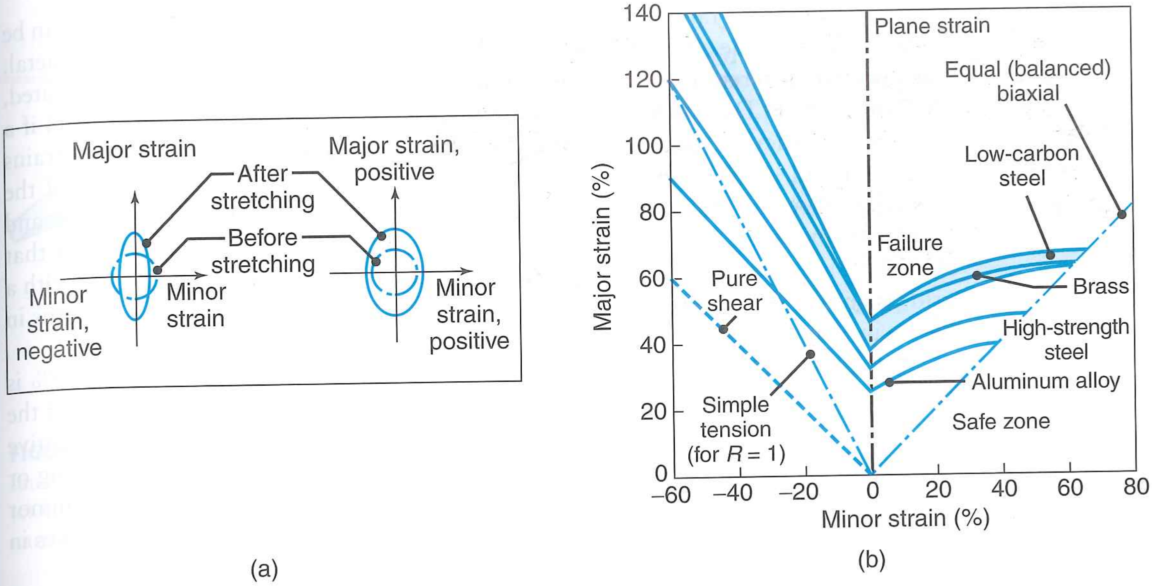


FIGURE 16.14 (a) Strains in deformed circular grid patterns. (b) Forming-limit diagrams (FLD) for various sheet metals. Although the major strain is always positive (stretching), the minor strain may be either positive or negative. R is the normal anisotropy of the sheet, as described in Section 16.7. *Source:* After S.S. Hecker and A.K. Ghosh.

engineering strain in this direction, and is always *positive* (because the sheet is being stretched). The *minor axis* of the ellipse represents the minor direction and magnitude of strain in the *transverse* direction, which may have undergone stretching or shrinking.

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, Section 2.2.1); 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.

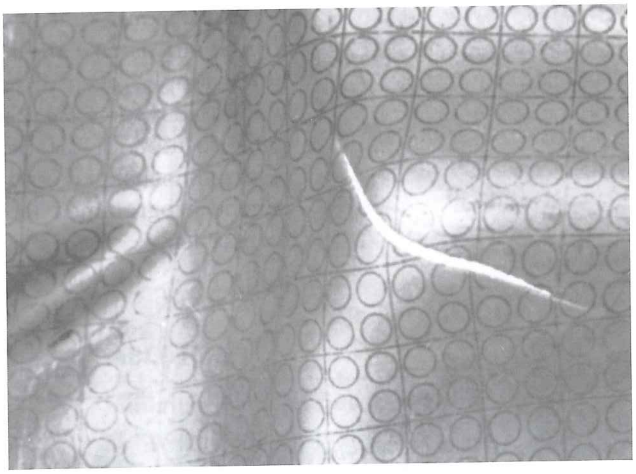


FIGURE 16.15 The deformation of the grid pattern and the tearing of sheet metal during forming; the major and minor axes of the circles are used to determine the coordinates on the forming-limit diagram in Fig. 16.14b. *Source:* After S.P. Keeler.

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 in plastic deformation the volume remains constant, 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 becoming 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 sheet metal. As expected, different materials and conditions, such as cold worked or heat treated, have different FLDs. 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 +20% and −10%, respectively, there would be no tear in that location of the specimen. On the other hand, if at another location on the sheet the major and minor strains were +80% and −40%, respectively, 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 FLDs 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 (i.e., shrinking in the minor direction). In forming complex parts, special tooling or clamps can be designed to take advantage of the beneficial effect of negative minor strains on formability. The effect of sheet thickness on FLDs is to raise the curves in Fig. 16.14b.

Friction and lubrication at the interface between the punch and the sheet metal also are 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 surface defects such as notch sensitivity, surface scratches (see *notch sensitivity*, Section 2.9), deep gouges, and blemishes can significantly reduce formability and thereby lead to premature tearing and failure of the part.

A procedure that has been followed with some success to improve sheet-metal formability is to carefully control and vary process parameters during forming. For example, deep drawability (Section 16.7.1) can be improved by varying the blankholder force (see Fig. 16.32) during deep drawing. This force can be changed with position in the die if multiple actuators are used for the blankholder, or it can be changed with respect to time. Carefully optimized velocity profiles can be programmed into servo presses (described in Section 14.8) also improve formability.

16.5 Bending Sheets, Plates, and Tubes

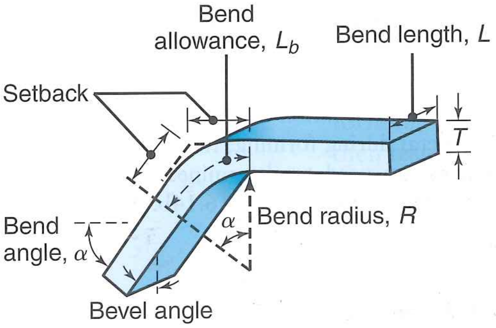


FIGURE 16.16 Bending terminology; note that the bend radius is measured to the inner surface of the bent part.

Bending is one of the most common forming operations, as evidenced by observing automobile bodies, exhaust pipes, appliances, paper clips, or file cabinets. 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 weight. As a specific example, observe the diametral stiffness of a can with and without circumferential beads (see also Section 16.7).

The terminology used in bending sheet or plate is given 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 easily

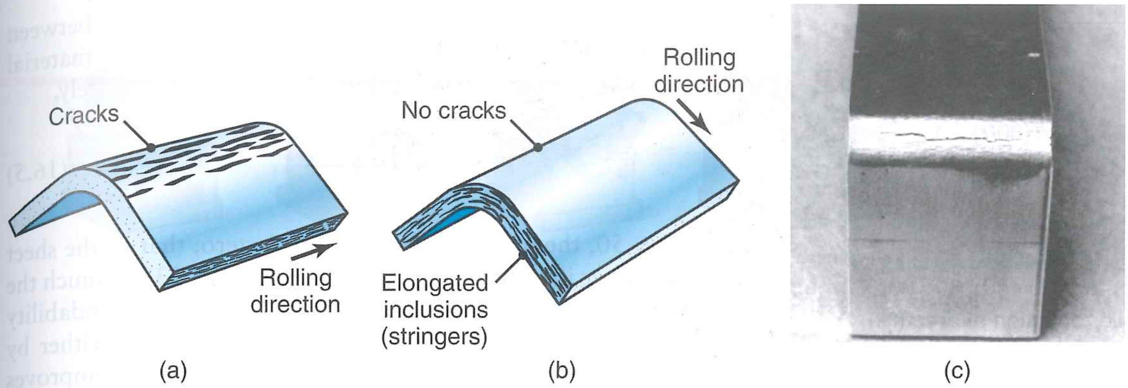


FIGURE 16.17 (a) and (b) The effect of elongated inclusions (stringers) on cracking as a function of the direction of bending with respect to the original rolling direction of the sheet. (c) Cracks on the outer surface of an aluminum strip bent to an angle of 90°. Note also the narrowing of the top surface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

be observed by bending a rectangular rubber eraser, and observing the changes in its cross-section.

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

$$L_b = \alpha\left(R + kT\right), \tag{16.3a}$$

where α is the bend angle (in radians), T is the sheet thickness, R is the bend radius, and k is a constant, which in practice typically ranges 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,

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

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 (i.e., 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.

TABLE 16.3

Minimum Bend Radius for Various Metals at Room Temperature

Material	Condition Soft	Condition 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

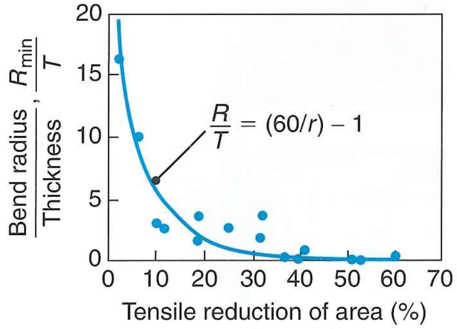


FIGURE 16.18 Relationship between R_{min}/T and tensile reduction of area for sheet metals. Note that sheet metal with a 50% tensile reduction of area can be bent over itself in a process like the folding of a piece of paper without cracking. *Source:* After J. Datsko and C.T. Yang.

It has been shown that there is an inverse relationship between *bendability* and the tensile reduction of the area, r, of the material (Fig. 16.18). The *minimum bend radius*, R_{min}, is, approximately,

$$R_{min} = T\left(\frac{50}{r} - 1\right). \tag{16.5}$$

Thus, for $r = 50$, the minimum bend radius is zero; that is, the sheet can be folded over itself, called *hemming* (see Fig. 16.23), in much the same way as a piece of paper is folded. To increase the bendability of metals, their tensile reduction of area can be increased 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. 2.24). The resistance to edge cracking during bending can be significantly improved by removing the cold-worked regions, by shaving or machining the edges of the part (see Fig. 16.9) or by annealing the sheet to improve its ductility.

Anisotropy of the sheet is another important factor in bendability. Cold rolling results in anisotropy of the sheet by *preferred orientation* or by *mechanical fibering*, due to the alignment of any impurities, inclusions, and voids that may be present, (see also Fig. 1.12). Prior to laying out or *nesting* the blanks (see Fig. 16.59) for subsequent bending or forming, caution should be exercised to cut them, as much as possible, in the proper direction from a rolled sheet.

Springback. Because all materials have a finite modulus of elasticity, plastic deformation is always followed by some elastic recovery when the load is removed (see Fig. 2.3). In bending, this recovery is called *springback*, which can easily be observed by bending and then releasing a piece of sheet metal or wire. As noted in Fig. 16.19, the final bend angle of a sheet metal after springback is smaller than the angle to which the sheet was bent, and the final bend radius is larger than before springback.

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

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

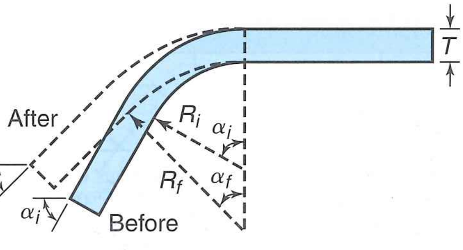


FIGURE 16.19 Springback in bending; the part tends to recover elastically after bending, and its bend radius becomes larger. Under certain conditions, it is possible for the final bend angle to be smaller than the original angle (negative springback).

Note from this formula that springback increases as the R/T ratio and the yield stress, Y, of the material increase, and 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 is a condition caused by the nature of the deformation occurring within the sheet metal just when 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.

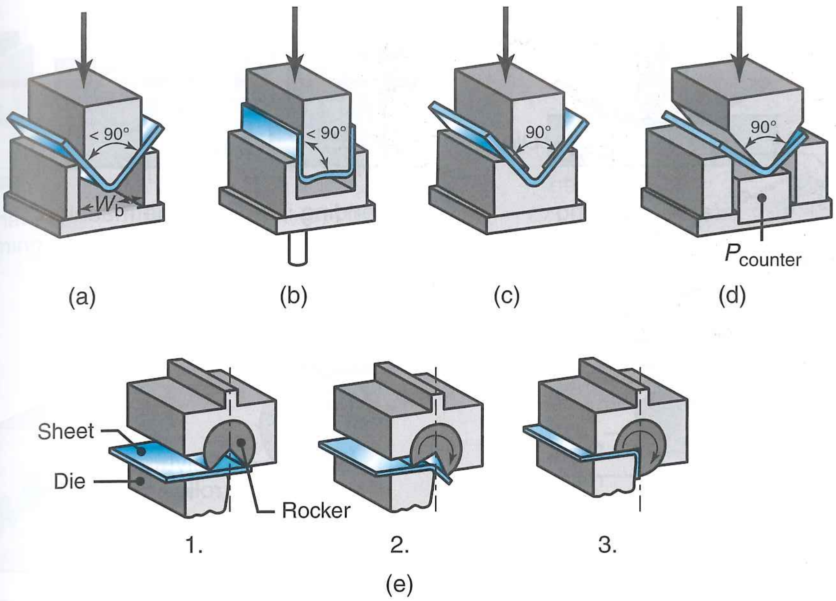


FIGURE 16.20 Methods of reducing or eliminating springback in bending operations.

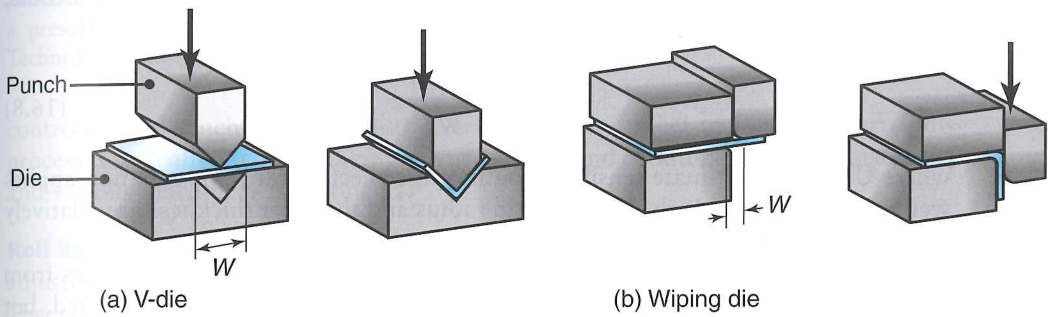


FIGURE 16.21 Common die-bending operations showing the die-opening dimension, W, used in calculating bending forces.

Compensation for Springback. Springback in forming operations usually is compensated by overbending the part (Figs. 16.20a and b), although 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 (Figs. 16.20c and d), a technique called *bottoming the punch*. In another method, the part is subjected to *stretch bending*, in which it is under external tension while being bent (see also *stretch forming*, Section 16.6). In Fig. 16.20e, the upper die rotates clockwise as the dies close.

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 (see Fig. 16.21). Excluding friction, the *maximum bending force*, P, is

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

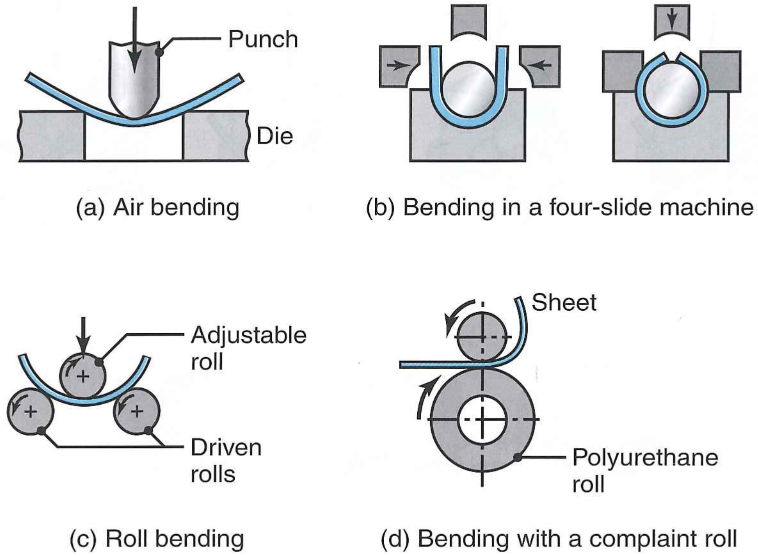


FIGURE 16.22 Examples of various bending operations.

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 (Fig. 16.21), and Y is the yield stress of the material.

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

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

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 being completed, but then it increases sharply as the punch reaches the bottom of its stroke. In air bending (Fig. 16.22a), however, the force does not increase again after it begins to decrease, because the sheet has no resistance to its free movement downward.

16.6 Miscellaneous Bending and Related Forming Operations

Press-brake Forming. Sheet metal or plate can easily be bent with simple fixtures using a press. Sheets or narrow strips that are 7 m 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, the motions are only up and down, and is easily adaptable to a wide variety of part shapes. The operation 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. For most applications, carbon-steel or gray-iron dies are generally 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. The lateral movements of the dies are

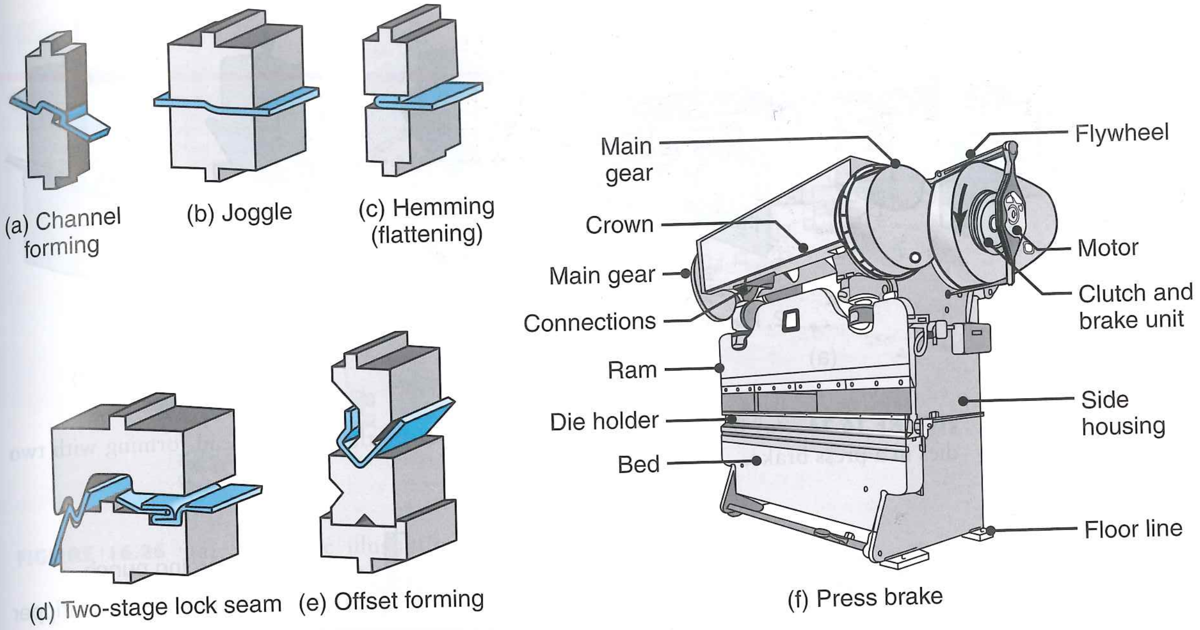


FIGURE 16.23 (a) through (e) Schematic illustrations of various bending operations in a press brake. (f) Schematic illustration of a press brake. *Source:* Enprotech Industrial Technologies Inc.

controlled and synchronized with the vertical die movement to form the part. This process is typically used for 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. The 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 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 in 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 may be hazardous.

Flanging. This is a process of bending the edges of sheet metals, usually to 90° (see also Section 16.7). In **shrink flanging** (Fig. 16.25a), the flange is subjected to compressive hoop stresses which, if excessive, can cause the flange periphery to wrinkle. The wrinkling tendency increases with decreasing radius of curvature of the flange. In *stretch flanging*, the flange periphery is subjected to tensile stresses which, if excessive, can lead to cracking along the periphery (see Fig. 16.25c).

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

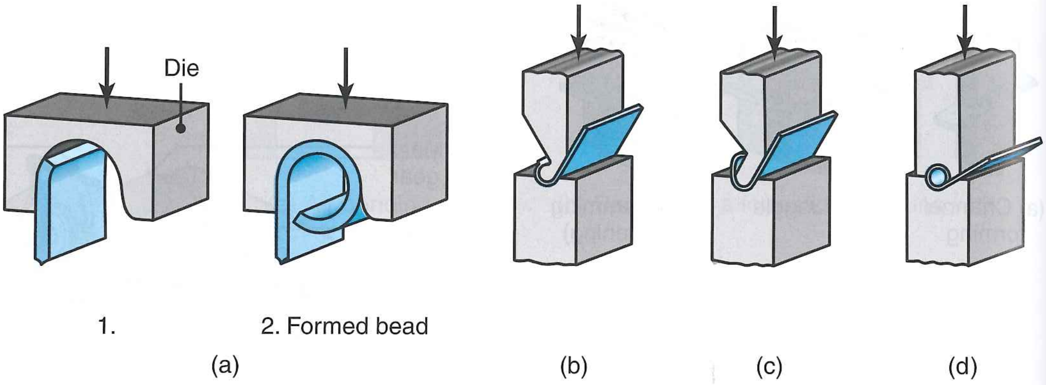


FIGURE 16.24 (a) Bead forming with a single die. (b) through (d) Bead forming with two dies in a press brake.

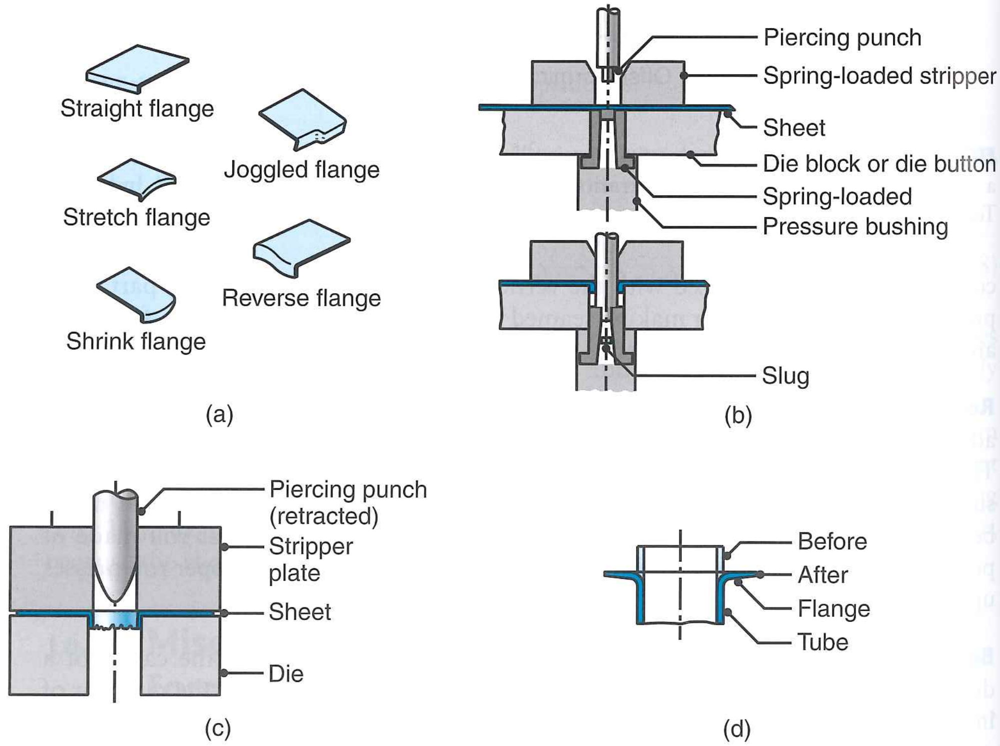


FIGURE 16.25 Various flanging operations. (a) Flanges on flat sheet. (b) Dimpling. (c) The piercing of sheet metal to form a flange. In this operation, a hole does not have to be prepunched before the punch descends; note the rough edges along the circumference of the flange. (d) The flanging of a tube;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

Typical roll-formed products are door and picture frames, panels, 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 sheet metal supplied to the rolls from a coiled stock. Sheet thickness usually ranges from about 0.125 to 20 mm. Forming speeds are generally below 1.5 m/s, although they can be much higher for special applications.

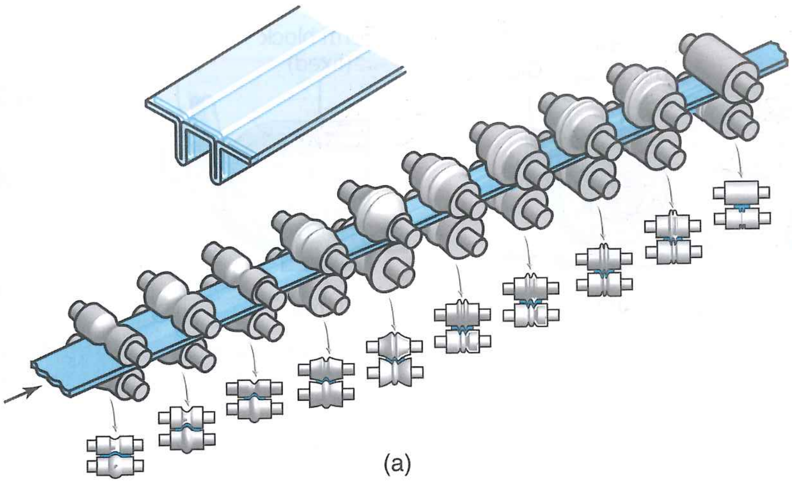


FIGURE 16.26 (a) Schematic illustration of the roll-forming process.

In designing the rolls and their sequence, 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 gray iron, and they may be chromium plated for a better surface finish of the formed product and to reduce wear of the rolls. Lubricants may be used to reduce wear, improve surface finish, and cool the rolls and the sheet being formed.

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 can note while 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 fill it with loose particles (commonly sand), and then bend it in 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 sand. Note that, because of its lower tendency for buckling, a relatively thick tube can be bent safely without using fillers or plugs. (See also *tube hydroforming*, Section 16.8.)

The beneficial effect of forming metals under highly compressive stresses is demonstrated in Fig. 16.28 for bending a tube with relatively sharp corners. Note that, in this operation, the tube is subjected to longitudinal compressive stresses, which reduce the stresses in the outer fibers in the bend area, thus improving the bendability of the material.

Dimpling, Piercing, and Flaring. In *dimpling* (Fig. 16.25b), a hole is first punched and then expanded into a flange. Flanges also may be produced by *piercing* with a shaped punch (Fig. 16.25c), and 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 sheared edges (see Fig. 16.3) is important in these operations, because 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 therefore be a tendency for cracking along the outer periphery of the flange. To reduce this

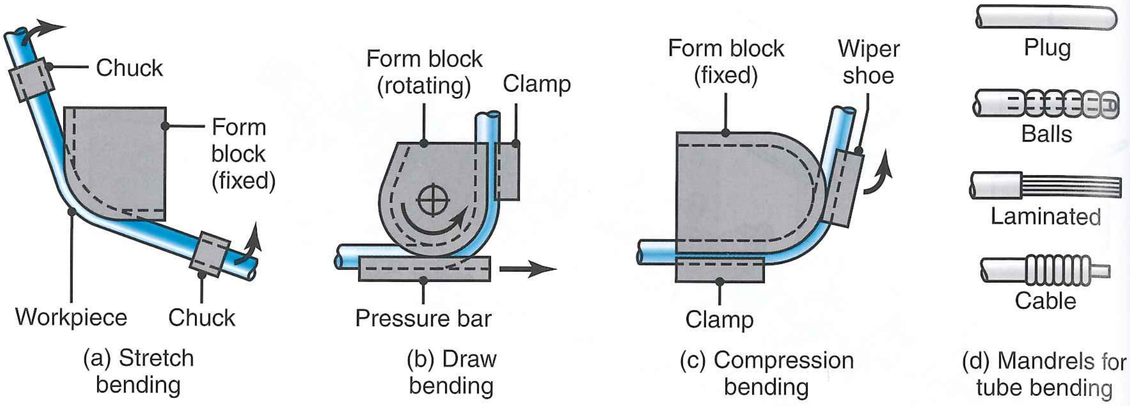


FIGURE 16.27 Methods of bending tubes. Internal mandrels or filling of tubes with particulate materials such as sand are often necessary to prevent collapse of the tubes during bending. Tubes also can be bent by a technique in which a stiff, helical tension spring is slipped over the tube. The clearance 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.

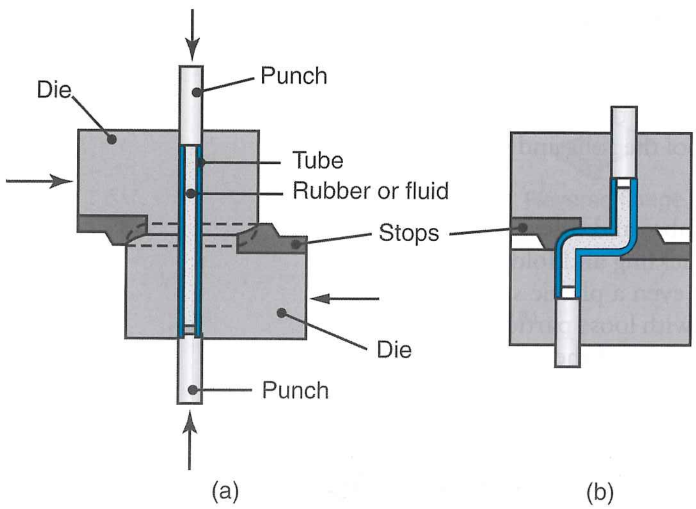


FIGURE 16.28 A method of forming a tube with sharp angles, applying an axial compressive force; compressive stresses are beneficial in forming operations because they delay fracture. Note that the tube is supported internally with rubber or fluid to avoid collapsing during forming. *Source:* After J.L. Remmerswaal and A. Verkaik.

possibility, sheared or punched edges could 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 rolls for watertight and airtight joints, such as those 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. 16.29a). 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 be able to apply higher pressures at critical regions of the part. The major advantages of using polyurethane plugs are that they are highly resistant to abrasion and wear, and do not damage the surface finish of the part being formed.

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. The segments are then retracted to remove the formed part. These dies are relatively inexpensive, and they can be used for large production runs.

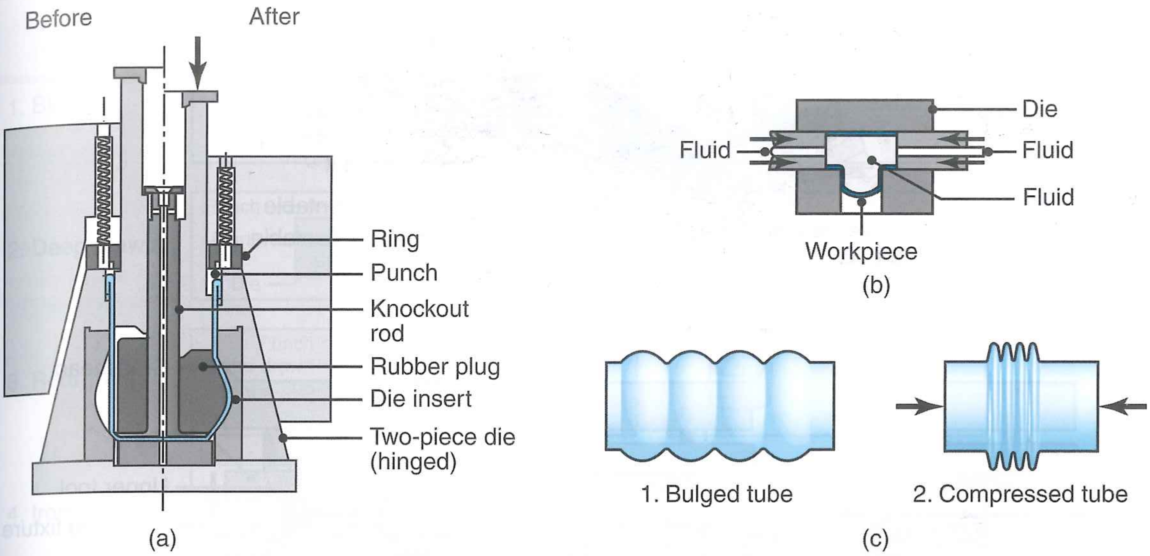


FIGURE 16.29 (a) The bulging of a tubular part with a flexible plug; water pitchers can be made by this method. (b) Production of fittings for plumbing by expanding tubular blanks under internal pressure; the bottom of the piece is then punched out to produce a "T." (c) Steps in manufacturing bellows. *Source:* (b) After J.A. Schey, Introduction to Manufacturing Processes, 3rd ed., 2000, McGraw-Hill, p. 425. ISBN No. 0-07-031136-6.

Stretch Forming. In *stretch forming*, the sheet metal is clamped along its edges and then stretched over a male die, called *form block* or *form punch*. The die can move upward, downward, or sideways, depending on the particular design of the machine (Fig. 16.30). 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. The rectangular sheets are 12 m $\times$ 2.5 m $\times$ 6.4 mm. Although this process is generally used for lowvolume production, it is versatile and economical, particularly for applications in 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 its 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. 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.

16.7 Deep Drawing

It can be noted that numerous sheet metal parts are *cylindrical* or *box shaped*, such as pots and pans, all types of containers for food and beverages (Fig. 16.31), 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, as shown in Fig. 16.32a. Deep drawing is one of the most important metalworking processes because of its widespread use.

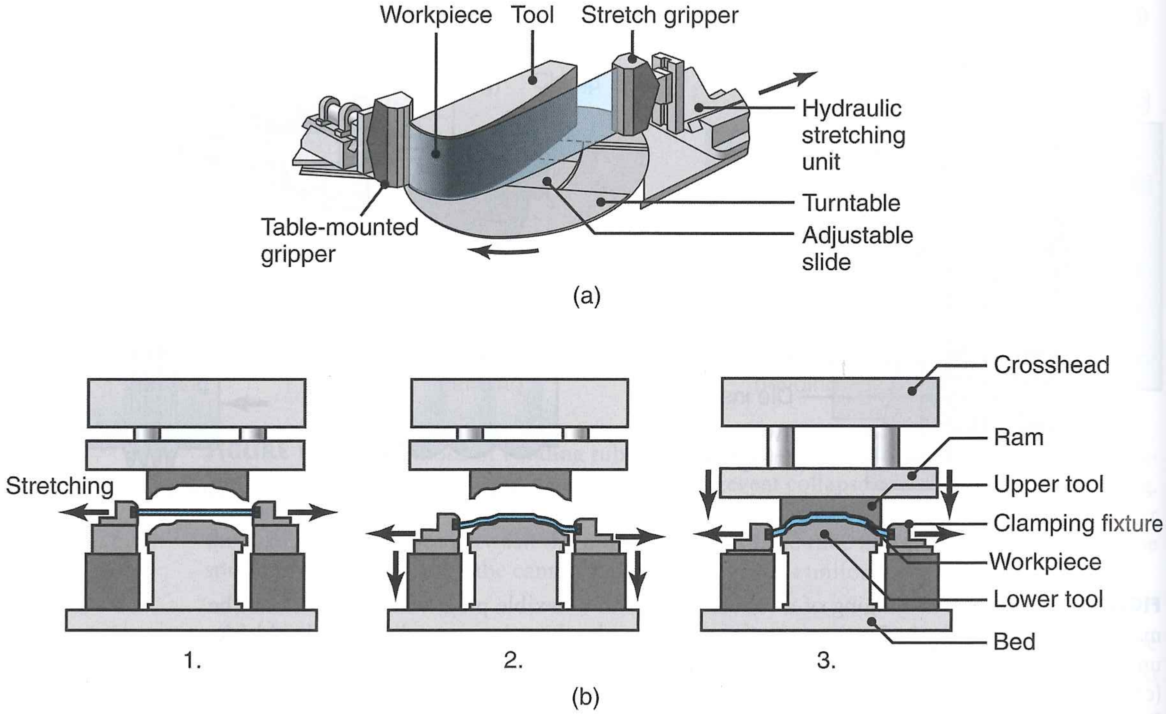


FIGURE 16.30 Schematic illustration of a stretch-forming process; aluminum skins for aircraft can be made by this method. *Source:* (a) Courtesy of Cyril Bath Co.

Consider the case of a round sheet-metal blank placed over a circular die opening, and held in place with a **blankholder**, or *hold-down ring* (Fig. 16.32b). The punch travels downward, forcing the blank into the die cavity, thus forming a cup. The major variables in this process are (a) properties of the sheet metal, (b) ratio of blank diameter, D_o, (c) punch diameter, D_p, (d) clearance, c, between punch and die; (e) punch radius, R_p, (f) die-corner radius, R_d, (g) blankholder force; and (h) friction and lubrication between all contacting interfaces.

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. Wrinkling can be reduced or eliminated if a blankholder is pressed downward with a certain force. In order to improve performance, the magnitude of this force can be computer controlled as a function of punch travel or location in the blankholder.

Because of the several 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

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

where the nomenclature is the same as that in Fig. 16.32b. It can be seen that the force increases with increasing blank diameter, sheet thickness, strength, and the ratio (D_o/D_p). The wall of the cup being drawn 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.

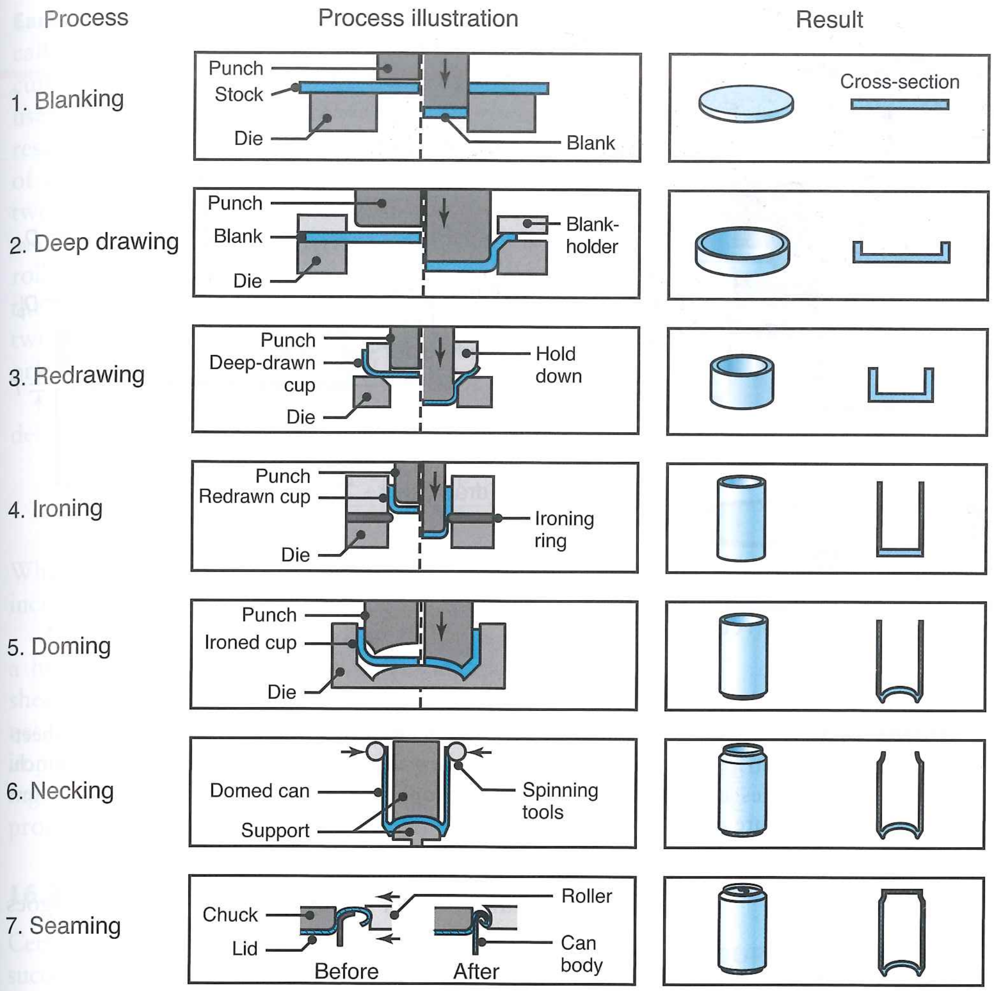


FIGURE 16.31 The metal-forming processes employed in manufacturing two-piece aluminum beverage cans.

16.7.1 Deep Drawability

In a deep-drawing operation, failure generally is a result of *thinning* of the cup wall under the high longitudinal tensile stresses due to the action of the punch. Following 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 is generally expressed by the **limiting drawing ratio** (LDR) as

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

Whether a particular sheet metal can be deep drawn successfully into a round cup 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

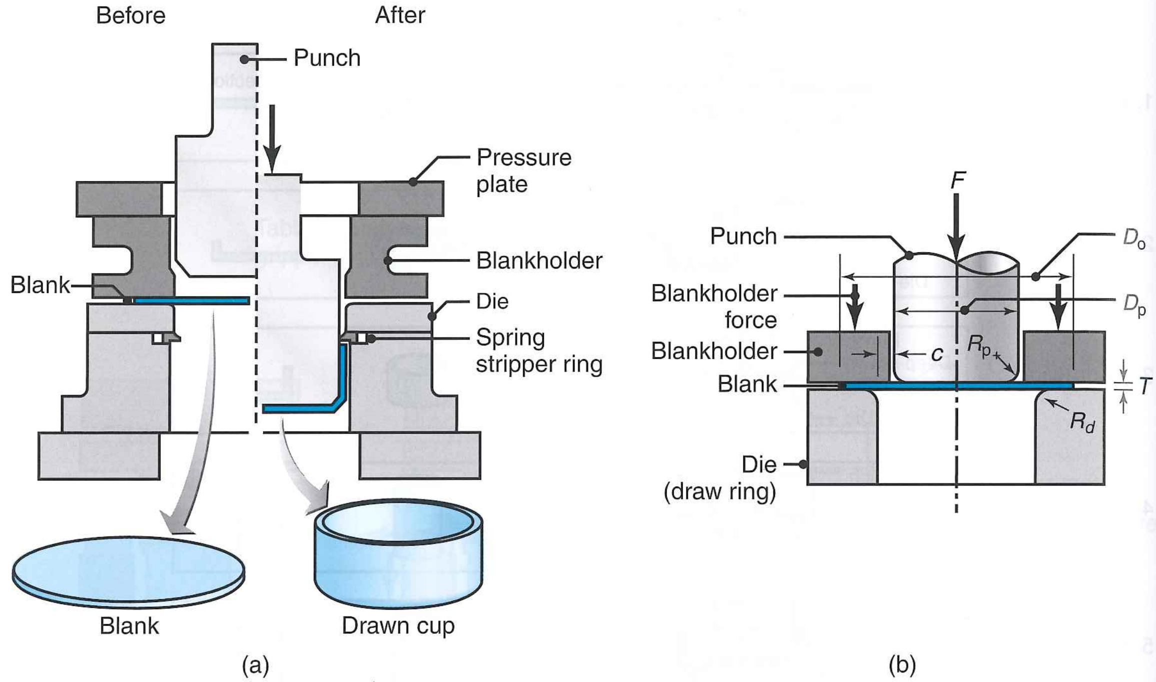


FIGURE 16.32 (a) Schematic illustration of the deep-drawing process on a circular sheet-metal blank; the stripper ring facilitates the removal of the formed cup from the punch. (b) Process variables in deep drawing. Except for the punch force, F, all the parameters indicated in the figure are independent variables.

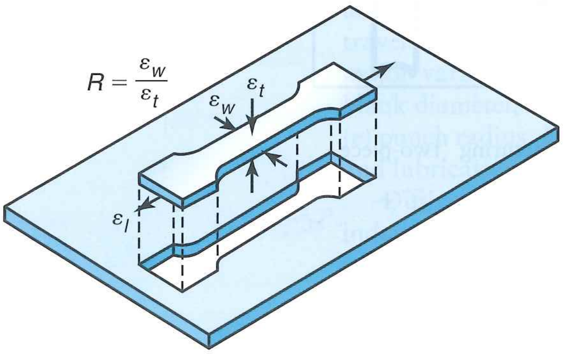


FIGURE 16.33 Strains on a tensile-test specimen removed from a piece of sheet metal; these strains are used in determining the normal and planar anisotropy of the sheet metal.

of the true strains that a tensile-test specimen undergoes (Fig. 16.33):

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

In order to determine the magnitude of R, a specimen is first prepared and subjected to an elongation of 15–20%. The true strains that the sheet undergoes are then calculated, in the manner described in Section 2.2. Because cold-rolled sheets are generally anisotropic 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. 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 LDR is shown in Fig. 16.34. It has been established that no other mechanical property of sheet metal shows a more consistent 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 LDR of a material can be determined.

Earing. In deep drawing, the edges of cups may become wavy, called *earing* (Fig. 16.35). 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** of the sheet metal, and the number of ears produced may be two, four, or eight, depending on the processing history and microstructure of the material. 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, indicated by ΔR, is defined in terms of directional R values, from the equation

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

When $\Delta R = 0$ no ears form, and 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 continue to be developed to improve drawability, by controlling the type of alloying elements in the material and by adjusting various processing parameters during cold rolling of the sheet.

TABLE 16.4

Typical Ranges of Average Normal Anisotropy, for Various Sheet Metals

Material	Range of R_{avg}
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 (alpha)	3.0–5.0
Stainless steels	0.9–1.2
High-strength, low-alloy steels	0.9–1.2

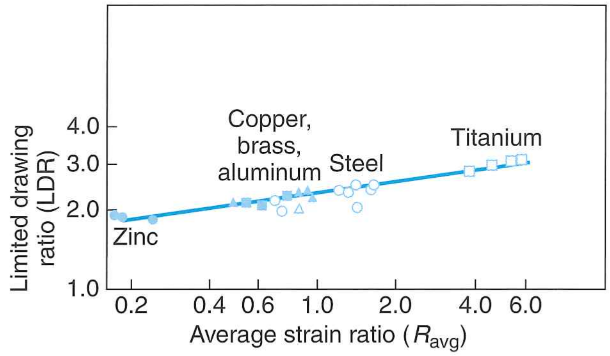


FIGURE 16.34 The relationship between average normal anisotropy and the limiting drawing ratio for various sheet metals. *Source:* After M. Atkinson.

16.7.2 Deep-drawing Practice

Certain guidelines have been established over the years for successful deep-drawing practice. The blankholder pressure is chosen generally as 0.7–1.0% 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 of the cup flange will occur.

Clearances are usually 7–14% greater than sheet thickness. If they are 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, called *puckering*.

Draw beads (Fig. 16.36) are often necessary to control the flow of the blank into the die cavity. They 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. Draw beads also help to reduce the necessary blankholder forces, because the beaded sheet has a higher stiffness (due to its higher moment of inertia) and, thus, less tendency to wrinkle. Draw-bead diameters may range from 13 to 20 mm, the latter applicable to large stampings, such as automotive panels.

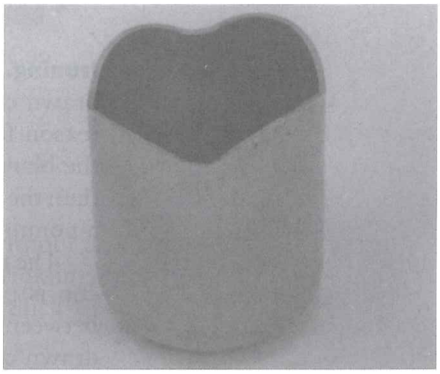


FIGURE 16.35 Earing in a drawn steel cup, caused by the planar anisotropy of the sheet metal.

Draw beads also are useful in drawing *box-shaped* and *nonsymmetric* parts (Figs. 16.36b and c). Note in Fig. 16.36c, for example, that various regions of the part

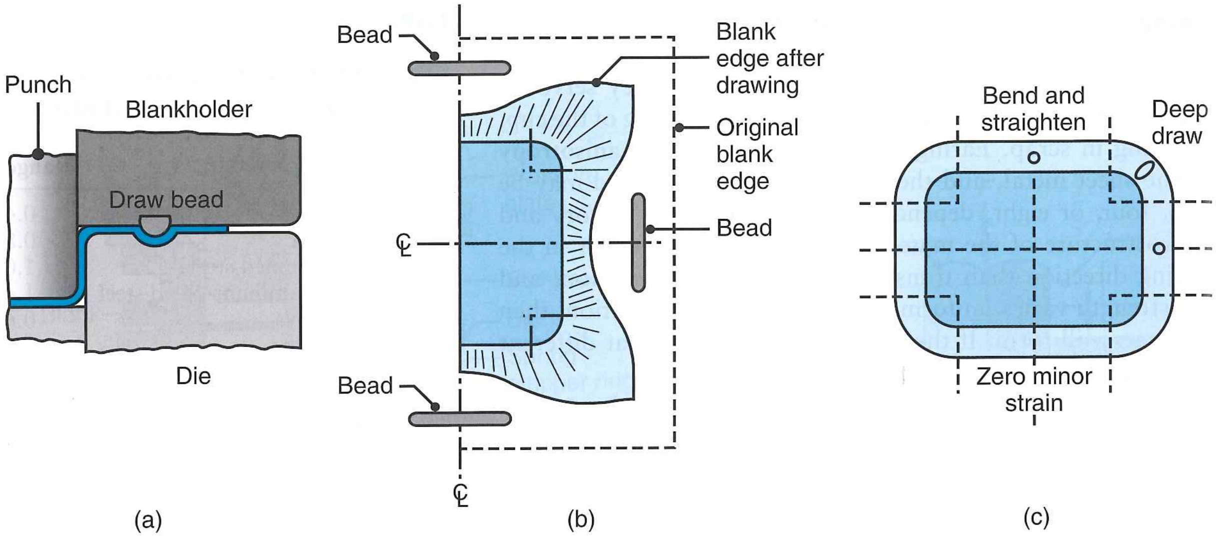


FIGURE 16.36 (a) Schematic illustration of a draw bead. (b) Metal flow during the drawing of a box-shaped part while using beads to control the movement of the material. (c) Deformation of circular grids in the flange in deep drawing.

being drawn 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:

- Proper design and location of draw beads
- Large die radii
- Effective lubrication
- Proper blank size and shape
- Cutting off of corners of square or rectangular blanks at 45° to reduce tensile stresses that develop during drawing
- Using blanks that are free of internal and external defects, including burrs

Ironing. 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 (see Fig. 16.32). 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 wall can be controlled by *ironing*, a process in which a drawn cup is pushed through one or more ironing rings (see Fig. 16.31). The clearance between the punch and ironing rings is less than the cup wall thickness, thus the drawn cup essentially has a constant wall thickness. Aluminum beverage cans, for example, are pushed through a set of two or three ironing rings, in one stroke.

Redrawing. Containers that are too difficult to draw in one operation generally undergo *redrawing* (see Fig. 16.37). 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 undergoes bending in the direction opposite to its original configuration.

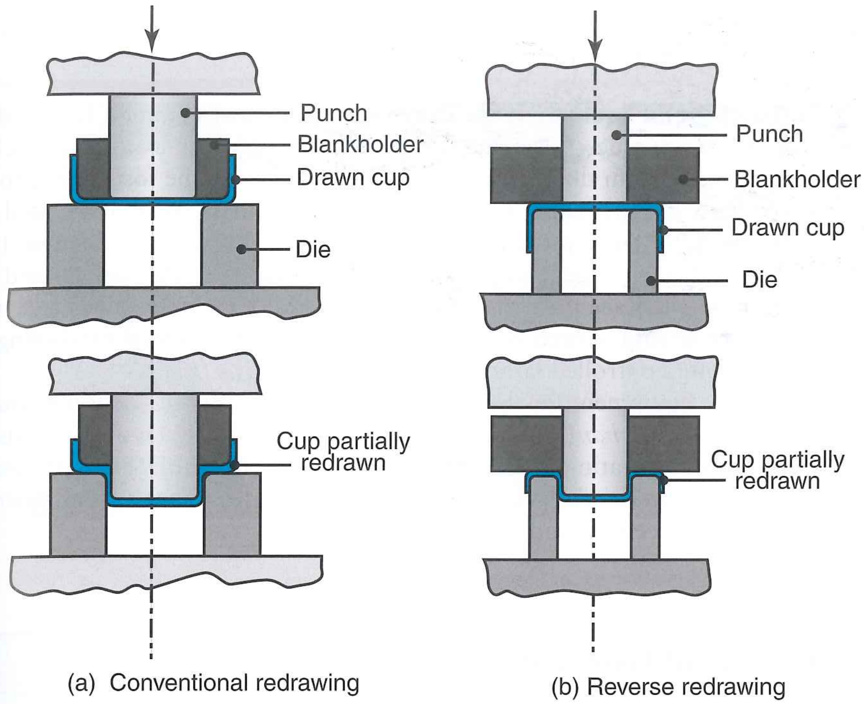


FIGURE 16.37 Reducing the diameter of drawn cups by redrawing operations: (a) conventional redrawing and (b) reverse redrawing. Small-diameter deep containers may undergo several redrawing operations.

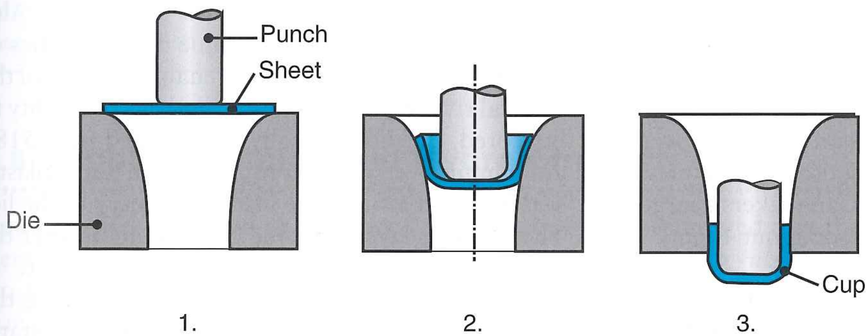


FIGURE 16.38 Stages in deep drawing without a blankholder, using a *tractrix* die profile.

Drawing without Blankholder. Deep drawing also may be carried out without a blankholder. The dies are specially contoured for this operation to prevent wrinkling; one example is shown in Fig. 16.38. The sheet metal must be sufficiently thick to prevent wrinkling. The following formula is a general guide:

$$D_o - D_p < 5T, \qquad (16.14)$$

where T is the sheet thickness. Thus, the thicker the sheet, the larger the blank diameter, and the deeper the cup that can be made, without wrinkling.

Embossing. This is an operation consisting of shallow or moderate drawing, made with male and female matching shallow dies (Fig. 16.39). Embossing is used

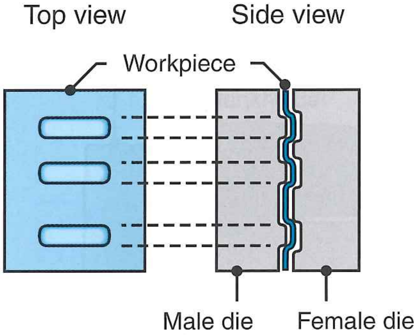


FIGURE 16.39 An embossing operation with two dies; letters, numbers, and designs on sheet-metal parts can be produced by this process.

principally for the stiffening of flat sheet-metal panels and for decorating, numbering, and lettering.

Tooling and Equipment for Drawing. The most common tool and die materials for deep drawing are tool steels and cast irons, and include dies made from ductile-iron castings produced by the lost-foam process (Section 11.3.1). Other materials, such as carbides, also may be used (see Table 5.7). Die-manufacturing methods are described 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 such equipment as high-speed machining on computer-controlled lathes (Section 25.5).

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.

CASE STUDY 16.2 Manufacturing of Food and Beverage Cans

Can manufacturing is a major and competitive industry, 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 15 g, and they are under an internal pressure of 620 kPa, 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.

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. 16.40a). 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, typically made by forming a seam on a sheet metal blank.

Drawn and ironed can bodies are produced from a number of alloys, but the most common are 3004-H19 aluminum (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 has a demanding set of design requirements, as can be appreciated by reviewing Fig. 16.40b. Not only must the can lid be *scored* easily (curved grooves around the tab), but an integral rivet is formed and headed (Section 14.4) 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 inside periphery of the lid. The 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. 16.31. The process starts with 140 mm-diameter blanks produced from rolled sheet stock. The blanks are (a) *deep drawn* to a diameter of about 90 mm, (b) *redrawn* to the final diameter of around 65 mm, (c) *ironed* through two or three ironing rings in one pass, and (d) *domed* for shaping the can bottom. The deep-drawing and ironing operations are performed in a special type of press, typically producing 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. 15.21a, where a thin-walled tubular part is

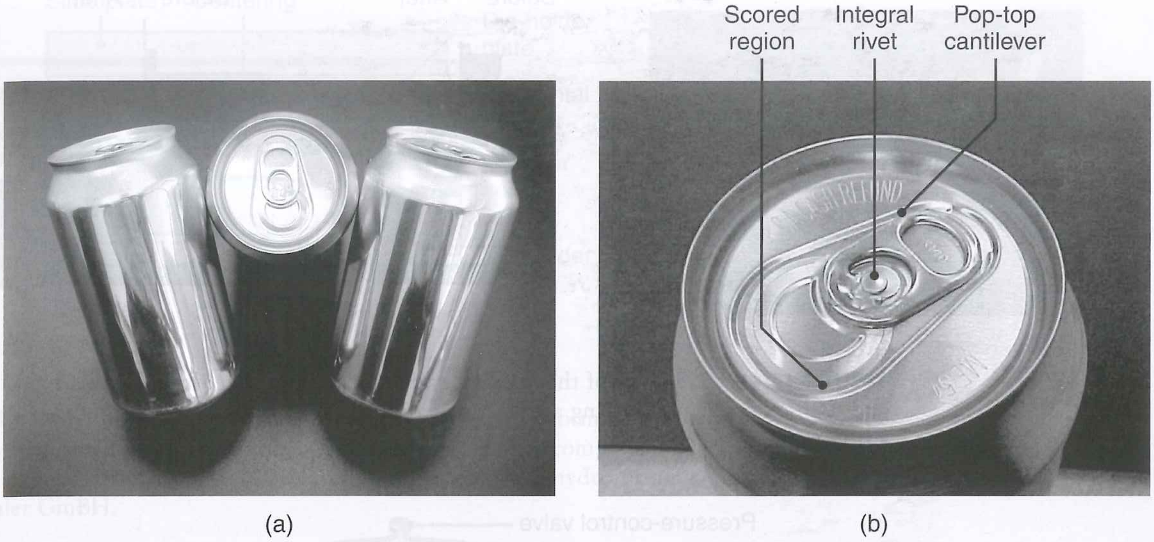


FIGURE 16.40 (a) Aluminum beverage cans; note the smooth surface. (b) Detail of the can lid, showing the integral rivet and scored edges for the pop-top.

pushed into the die), and 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 material cost. It should also be noted that the cost of a can often is calculated to millionths of a dollar, hence any design feature that reduces cost will be exploited by this competitive industry.

Source: Printed with permission 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. 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 (Section 7.9).

In bending and embossing of sheet metal by this process, the female die is replaced with a rubber pad (Fig. 16.41). Note that the outer surface of the sheet is protected from damage or scratches, because it is not in direct contact with a hard metal surface during forming. Pressures in rubber forming are typically on the order of 10 MPa.

In the **hydroform** or *fluid-forming process* (Fig. 16.42), the pressure over the rubber membrane is controlled throughout the forming cycle, with a maximum pressure of up to 100 MPa. 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.

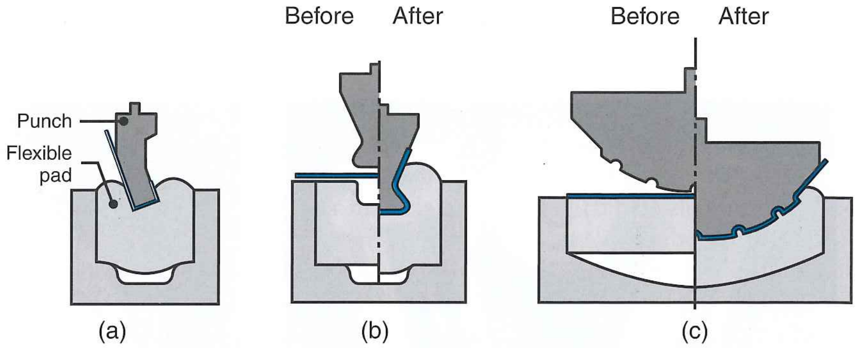


FIGURE 16.41 Examples of the bending and embossing of sheet metal with a metal punch and with a flexible pad serving as the female die. *Source:* Courtesy of Polyurethane Products Corporation.

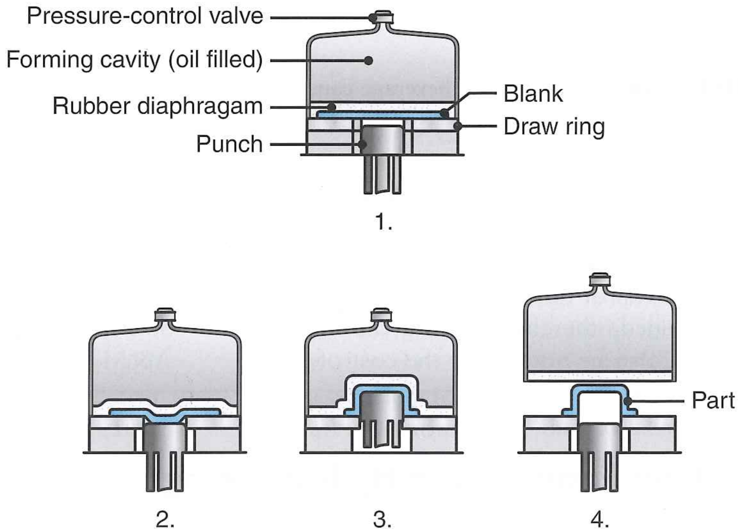
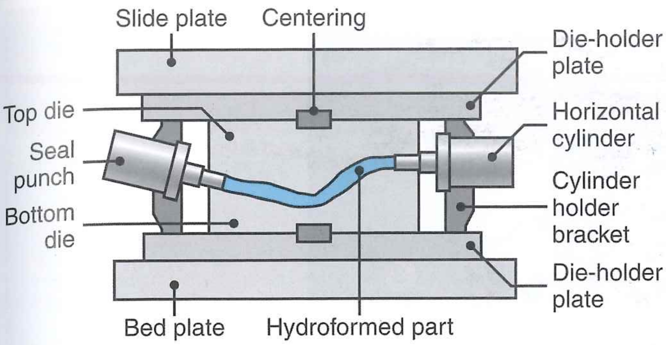


FIGURE 16.42 The hydroform (or fluid-forming) process; note that, in contrast to the ordinary deep-drawing process, the pressure in the dome forces the cup walls against the punch. The cup travels with the punch; in this way, deep drawability is improved.

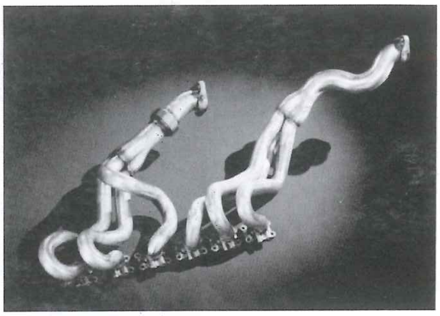
The control of frictional conditions in rubber forming, as well as other sheet-forming operations, can be a critical factor in making parts successfully. The use of proper lubricants and their method of application is also important.

In **tube hydroforming** (Fig. 16.43a), 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 either simple tubes or various intricate hollow shapes (Fig. 16.43b). Parts made 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 made of various materials and coatings, (c) flexibility and ease of operation, (d) avoiding damage to the surfaces of the sheet, (e) low die wear, and (f) low tooling cost.



(a)



(b)

FIGURE 16.43 (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 16.3 Tube Hydroforming of an Automotive Radiator Closure

The conventional assembly used to support an automotive radiator, or radiator closure, is constructed through stamping of the components, which are subsequently welded together. To simplify the design and to achieve weight savings, a hydroformed assembly was designed, as shown in Fig. 16.44. Note that this design uses varying cross-sections, an important feature to reduce weight and provide surfaces to facilitate assembly and mounting of the radiator.

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 operations performed on one of the tube components of the closure is shown in Fig. 16.45. 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 the end caps are attached.

FIGURE 16.44 Hydroformed automotive radiator closure, which serves as a mounting frame for the radiator.

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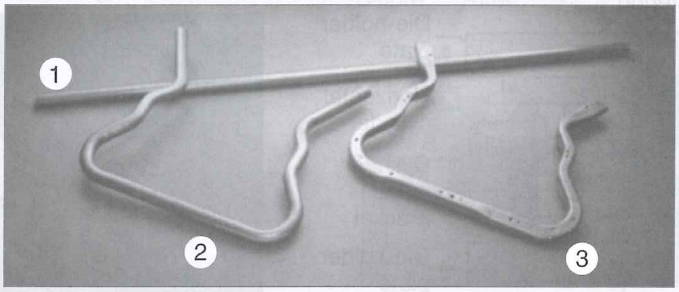

FIGURE 16.45 Sequence of operations in producing a tube-hydroformed component: (1) tube as cut to length; (2) after bending; and (3) after hydroforming.

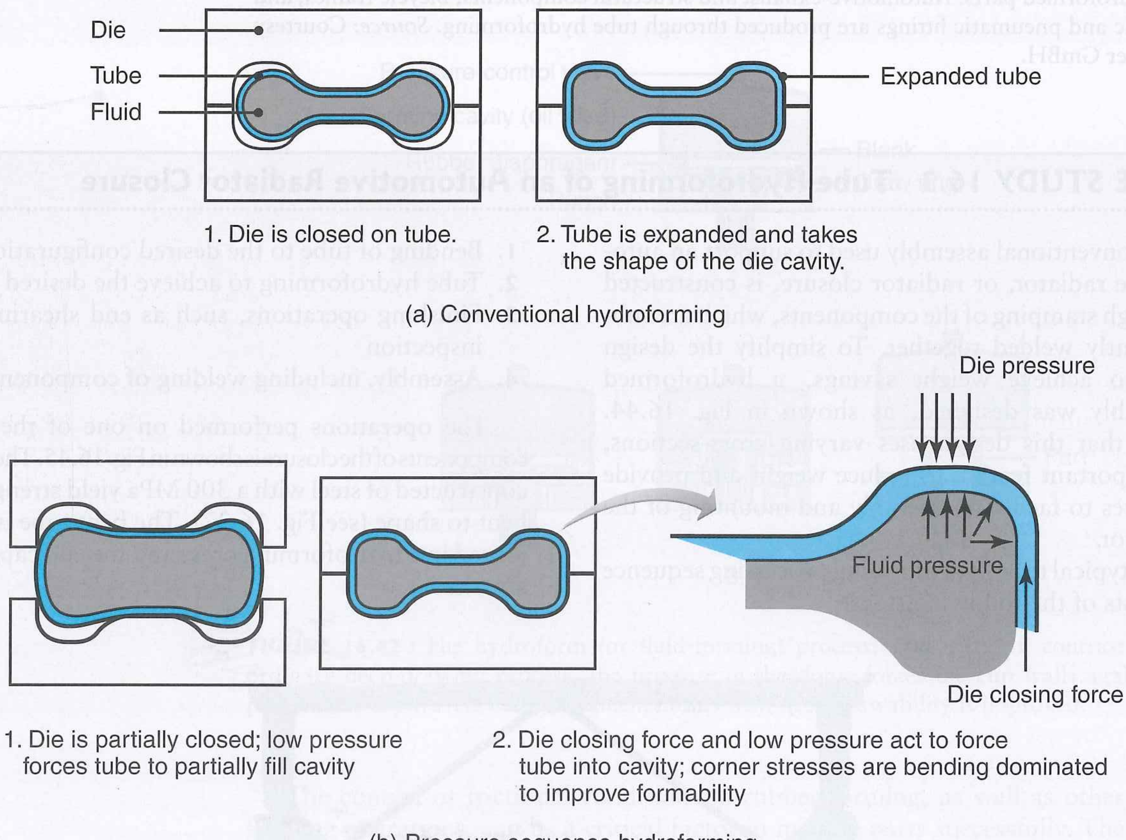

FIGURE 16.46 Schematic illustration of expansion of a tube to a desired cross-section through (a) conventional hydroforming and (b) pressure sequence hydroforming.

Conventional hydroforming involves closing the die onto the tube, followed by internal pressurization to force the tube to the desired shape. Figure 16.46a shows a typical cross-section. Note that as the tube is expanded, there is significant wall thinning, especially at the corners, because of friction at the tube–die interface. A sequence of pressures that optimize corner formation is therefore used, as shown in Fig. 16.46b.

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

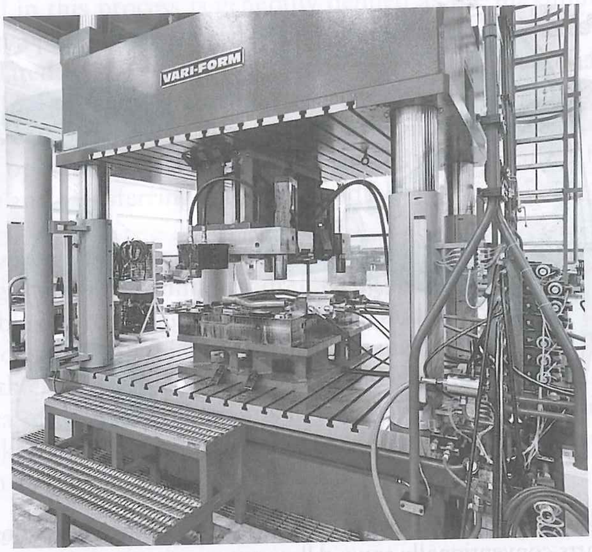

FIGURE 16.47 View of the tube-hydroforming press, with bent tube in place in the forming die.

the cross-sectional corners. After the die is completely closed, the internal pressure is increased to lock-in the form and provide support needed for hole piercing. This sequence has the benefit of forming the sharp corners in the cross-section by bending, as opposed to pure stretching as in conventional hydroforming. The resulting wall thickness is much more uniform, producing a more structurally sound component. Figure 16.47 shows a part being hydroformed in a press.

The assembly shown in Fig. 16.44 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), using 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 versus 14.1 kg. Furthermore, the stiffness of the enclosure and the water cooling areas are both significantly increased.

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

16.9 Spinning

Spinning is a process that involves forming of axisymmetric parts over a mandrel, using various tools and rollers; a process similar to that of shaping 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 shapes the material over the mandrel (Fig. 16.48a). 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 requires considerable skill. Conventional spinning is particularly suitable for making conical and curvilinear shapes (Fig. 16.48b), with part diameters ranging up to 6 m, which otherwise would be difficult or uneconomical to produce. Although most spinning is performed at

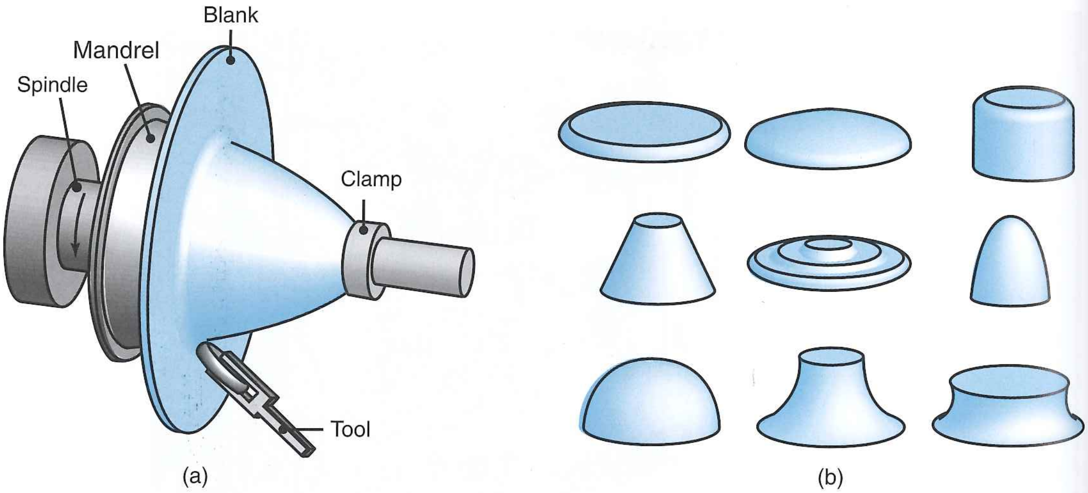

FIGURE 16.48 (a) Schematic illustration of the conventional spinning process. (b) Types of parts conventionally spun. All parts are axisymmetric.

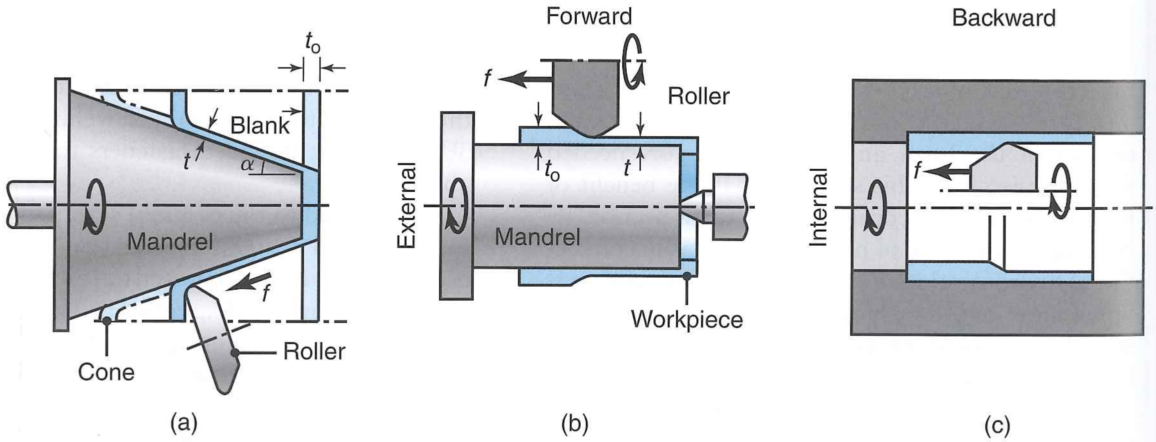

FIGURE 16.49 (a) Schematic illustration of the shear-spinning process for making conical parts; the mandrel can be shaped so that curvilinear parts can be spun. (b) and (c) Schematic illustrations of the tube-spinning process.

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 blank diameter (Fig. 16.49a). A single forming roll can be used, but two rolls are preferable in order to balance the radial forces acting on the mandrel. Typical parts made are rocket motor casings and missile nose cones. Parts up to 3 m in diameter can be formed by shear spinning. This operation produces little waste of 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 is generally 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, in one pass, by as much as 80%. For metals with low ductility, the operation is carried out at elevated temperatures, by heating the blank in a furnace and transferring it to the mandrel.

Tube Spinning. In *tube spinning*, the thickness of hollow, cylindrical blanks is reduced or shaped by spinning them on a round mandrel, using rollers (Figs. 16.49b and c). This operation is capable of producing various external and internal profiles, from cylindrical blanks with constant wall thickness. The parts may be spun *forward* or *backward*. 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. 16.50a), 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, made in one or more passes. Proper lubrication is essential.

CNC incremental forming uses a computer numerical control machine tool (see Section 37.3) programmed to follow contours at different depths across the sheet-metal surface. The blank is clamped and is stationary, and the forming tool rotates. 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 16.50b depicts an example of a part that is produced by CNC incremental forming. Note that the part does not have to be axisymmetric. The main advantages of CNC incremental forming are low tooling costs and high flexibility in the shapes that can be produced. This process has been used for rapid prototyping of sheet-metal parts (see Chapter 20). The main drawbacks to incremental forming include low production rates and limitations on materials that can be formed.

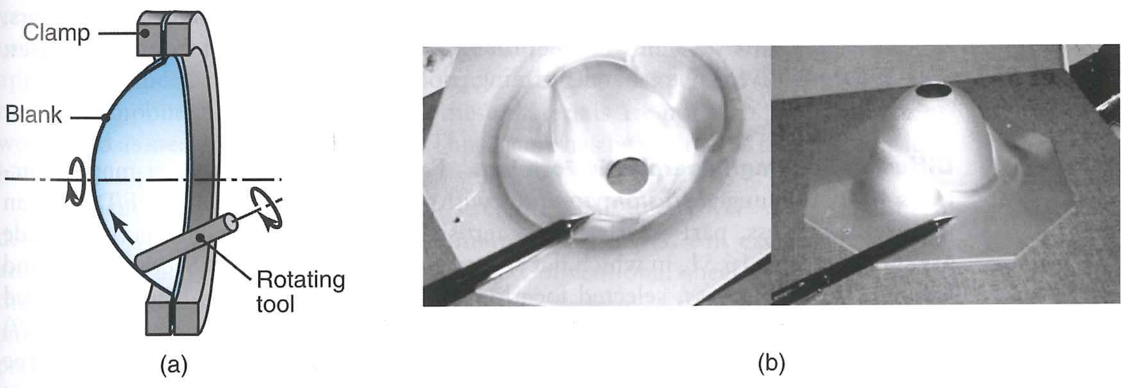

FIGURE 16.50 (a) Illustration of an incremental-forming operation; note that no mandrel is used and that the final part shape depends on the path of the rotating tool. (b) An automotive headlight reflector produced through CNC incremental forming. Note that the part does not have to be axisymmetric. *Source:* Courtesy of J. Jeswiet, Queen's University, Ontario.

16.10 Superplastic Forming

The superplastic behavior of certain metals and alloys, described in Section 2.2.7, involves tensile elongations of up to 2000%, exhibited within certain temperature ranges. Examples of such materials are zinc–aluminum and titanium alloys, with very fine grains, typically less than 10–15 μm (see Table 1.1). Superplastic alloys can be formed into complex shapes by *superplastic forming* (SPF), a process that employs common metalworking techniques, as well as by polymer-processing techniques (such as thermoforming, vacuum forming, and blow molding, described in Chapter 19). The behavior of the material in SPF 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, can also be formed by bulk-deformation processes, including closed-die forging, coining, hubbing, and extrusion. Commonly used die materials in SPF are low-alloy steels, cast tool steels, ceramics, graphite, and plaster of paris. Their 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 from one piece, with fine detail, close tolerances, and elimination of secondary operations.
- Weight and material savings can be significant, because of the good formability of the materials.
- Little or no residual stresses are present 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, thus tooling costs are lower.

On the other hand, SPF has the following limitations:

- The material must not be superplastic at service temperatures, as otherwise the part will undergo shape changes during use.
- Because of the high strain-rate sensitivity of the superplastic material (see Section 2.2.7), 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; cycle times are thus much longer than those of conventional forming processes; consequently, SPF 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. 16.51, in which flat sheets are *diffusion bonded* (Section 31.7) and formed. In this process, selected locations of the sheets are first diffusion bonded while the rest of the interfaces remains unbonded, using a layer of material (*stop-off*) to prevent bonding. The structure is then expanded in a mold (thus taking the shape of the mold), typically by using pressurized neutral (argon) gas. These structures have high stiffness-to-weight ratios, because they are thin and, by design, have high section moduli. This important feature makes this process particularly attractive in aircraft and aerospace applications.

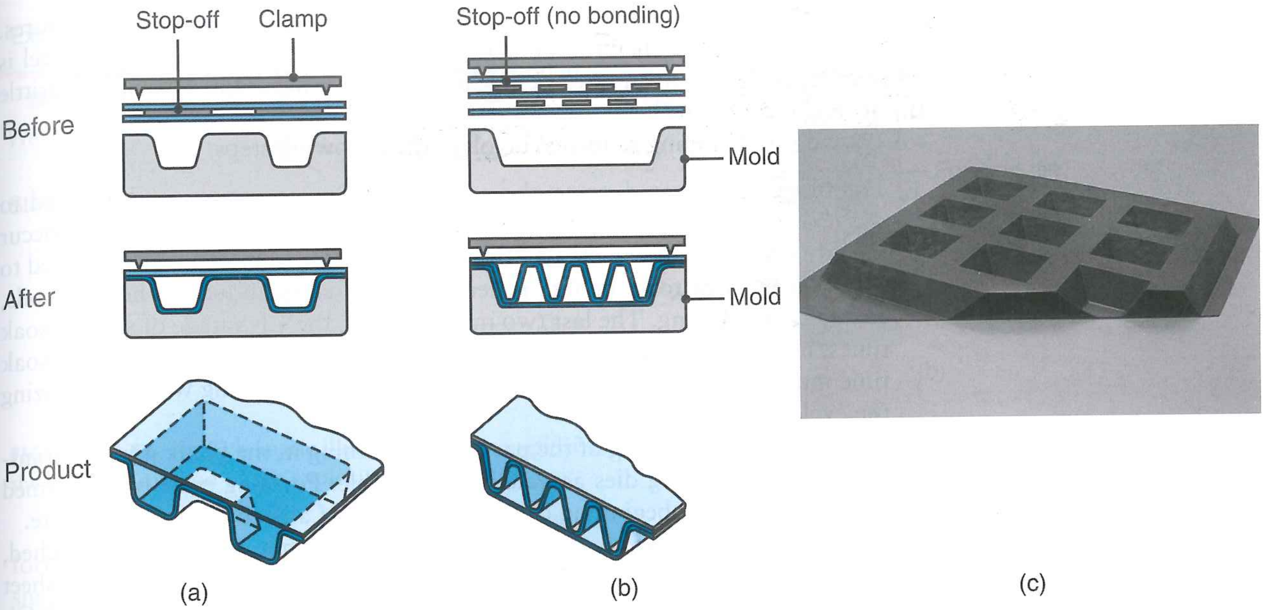

FIGURE 16.51 Types of structures made by superplastic forming and diffusion bonding of sheet metals; such structures have a high stiffness-to-weight ratio. *Source:* (a) and (b) Courtesy of the Boeing Company. Printed with permission. (c) courtesy of Triumph Group, Inc.

The SPF/DB process improves productivity by eliminating mechanical fasteners, and 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 SPF include various nickel alloys.

16.11 Hot Stamping

Increasing fuel economy in automobiles has received considerable attention in recent years for both environmental and economic reasons. To achieve increased fuel economy, without compromising performance or safety, manufacturers have increasingly applied advanced materials in automobiles. Die-cast magnesium or extruded aluminum components are examples, but these materials are not sufficiently stiff or as well suited as steel for occupant safety. Thus, there has been a recent trend to consider hot stamping of advanced high-strength steels.

As discussed in Section 5.5.5, high-strength TRIP and TWIP steels have been developed, with yield strengths and ultimate strengths that can exceed 1300 MPa and 2000 MPa, respectively (see Table 5.4). Conventional sheet metal forming of these materials would be difficult or impossible, because of the high forces required and the excessive springback after forming. For these reasons, the sheet metal is preheated to above 900°C (usually 1000°–1200°C) and hot stamped. To extend die life and to quench the material within the die (as discussed below), the tooling is maintained at a much lower temperature, typically 400°–500°C.

Hot stamping allows exploitation of steel phases to facilitate forming and maximize part strength. Basically, the steel is maintained at elevated temperatures to form austenite (see Section 4.4), which has a ductile fcc structure at elevated temperatures. When formed and brought into contact with the much cooler tooling, the steel is rapidly quenched to form martensite, which is a very hard and strong but brittle form of steel (Section 4.7).

A typical hot-stamping sequence involves the following steps:

1. The material is heated up to the austenization temperature, and allowed to *dwell* or *soak* for a sufficiently long time to ensure that quenching will occur quickly when it contacts the die, but not before. Three basic means are used to heat blanks prior to stamping: roller hearth furnaces, induction heating coils, and resistive heating. The last two methods have the advantage of shorter soak times, but may not lead to uniform temperatures throughout the part. The soak time must be optimized in order to ensure proper quenching while minimizing the cycle time.
2. In order to avoid cooling of the part before forming it, the blank must be transferred to the forming dies as quickly as possible. Forming must be performed quickly, before the beginning of transformation of austenite into martensite.
3. Once the part is formed, the dies remain closed while the part is quenched, which takes from 2 to 10 s, depending on sheet thickness, temperature of sheet and die, and workpiece material. The cooling rate must be higher than 27°C/s to obtain martensite. Thus, forming is performed in steel tools that have cooling channels incorporated in them, in order to maintain proper tooling temperature. A complete transformation into martensite results in the high strengths given in Table 5.4. It should be noted that quenching from austenite to martensite results in an increase in volume, which influences the residual stress distribution and workpiece distortion in forming.

A more recent development is to use *pressurized hot gas* (air or nitrogen) as a working media to form the material, similar to hydroforming. This method improves formability, and with proper process control, allows for more uniform blank and tooling temperatures, and thus lower residual stresses and warping.

Because the workpiece is hot and quenching must be done very rapidly, hot stamping is usually performed without a lubricant, and often shot blasting (Section 26.8) is required after forming to remove scale from part surfaces. The steel may also be coated with an aluminum-silicon layer, to prevent oxidation and eliminate the grit blasting step. In such a case, the coating requires a slightly longer soak time, in order to properly bond to the steel substrate.

Hot stamping is not restricted to steels. Magnesium alloys ZEK100, AZ31, and ZE10 are also of great interest, because of their lightweight; however, these materials have limited formability at room temperature, and are therefore stamped at up to 300°C. Also, some advanced aluminum-alloy sheets are formed at elevated temperatures in order to attain improved ductility, and even develop superplastic behavior.

16.12 Specialized Forming Processes

Although not as commonly used as the other processes described 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 destructive purposes. However, controlling their quantity and shape makes it possible to use explosives as a source of energy for sheet-metal

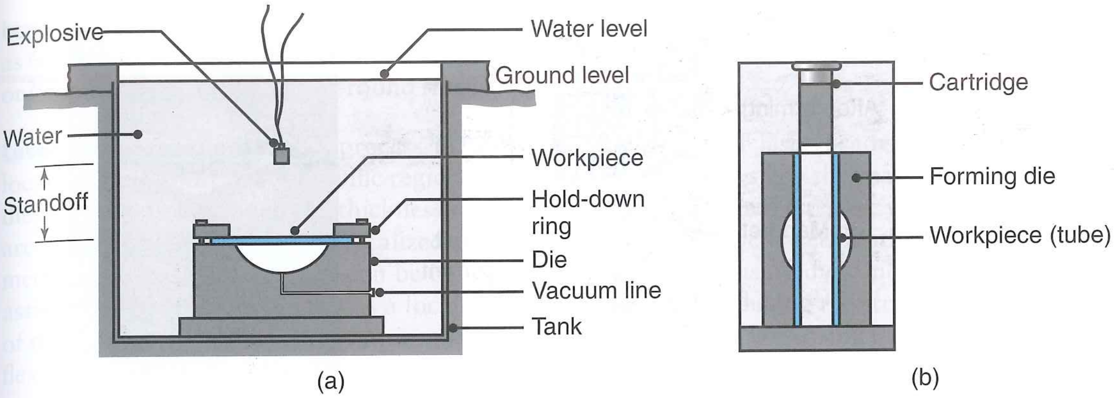

FIGURE 16.52 (a) Schematic illustration of the explosive-forming process. (b) Illustration of the confined method of the explosive bulging of tubes.

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. 16.52a). The air in the die cavity is then evacuated, an explosive charge is placed at a certain height, and the charge is detonated.

The explosive generates a shock wave, developing 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 MPa, K is a constant, which 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 as 1.15.

A variety of shapes can be formed by explosive forming, provided that the material is sufficiently ductile at the high rates of deformation encountered in 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 thick and 3.6 m in diameter have been formed by this method, as have tubes with wall thicknesses as much as 25 mm.

The explosive-forming method also can be used at a much smaller scale, as shown in Fig. 16.52b. In this case, a *cartridge* (canned explosive) is used as the source of energy. The process can be useful in 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. 16.53).

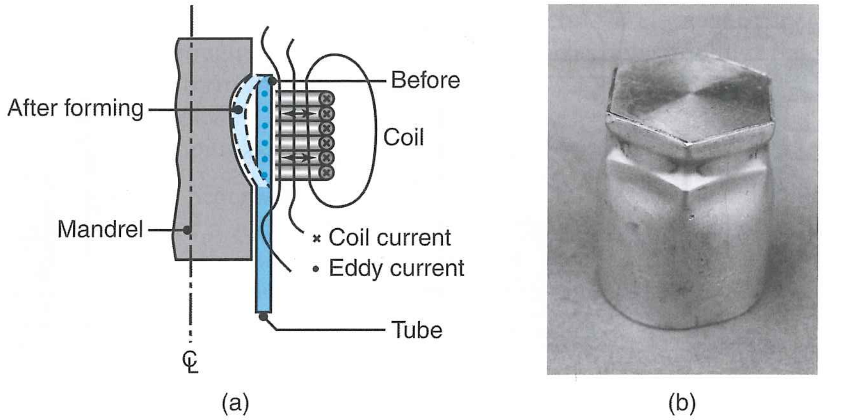

FIGURE 16.53 (a) Schematic illustration of the magnetic-pulse-forming process used to form a tube over a plug. (b) Aluminum tube collapsed over a hexagonal plug by the magnetic-pulse-forming process.

The mechanics of this process is based on the fact that a magnetic field, produced by the coil (Fig. 16.53a), 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 tube over the inner piece. The higher the electrical conductivity of the workpiece, the higher the magnetic forces. Note that it is not necessary for the workpiece material to have magnetic properties, but it must be electrically conducting.

It has been shown that the basic advantages of this process are that the formability of the material is increased, dimensional accuracy is improved, and springback and wrinkling are reduced. Magnetic coil design is an important factor in the success of the operation. Flat magnetic coils also can be made for use in such operations as embossing and shallow drawing of sheet metals.

First used in the 1960s, this process has been demonstrated to be particularly effective for aluminum alloys. Electromagnetically assisted forming has been 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.

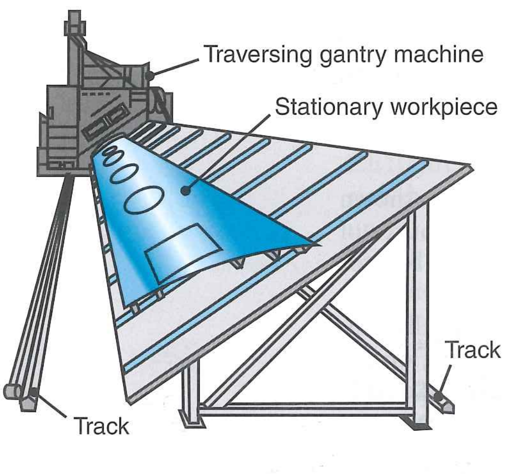

FIGURE 16.54 Schematic illustration of a peen-forming machine to shape a large sheet-metal part, as an aircraft-skin panel; note that the sheet is stationary and the peening head travels along its length. *Source:* Metal Improvement Company.

Peen Forming. As shown in Fig. 16.54, 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 metal.

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 in diameter, traveling at speeds of 60 m/s, have been used to form wing panels 25 m long. For heavy sections, shot diameters as large as 6 mm 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 Beam Forming. This process involves the application of laser beams as a localized heat source over 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 includes a family of processes that are used to produce very small metallic parts and components. Examples of *miniaturized products* include a wristwatch with an integrated digital camera and a one-gigabyte 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 part weights are on the order of milligrams.

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

CASE STUDY 16.4 Cymbal Manufacture

Cymbals (Fig. 16.55a) 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. 16.55b) are 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. The manufacturing sequence for producing a bronze cymbal is shown in Fig. 16.56. The B20 metal is first cast into mushroom-shaped ingots, and then cooled in ambient temperature. The ingot is then 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, in order to minimize anisotropy and develop an even, round shape. The as-rolled blanks are then reheated and stretch formed (pressed) into the cup or bell shape, which determines the cymbal's overtones. The cymbals are then 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 "Turkish dish" form that controls the cymbal's pitch.

Automatic peen-forming is done on machinery (Fig. 16.57) and without templates, since the

(*continued*)

(a) (b)

FIGURE 16.55 (a) Selected common cymbals. (b) Detailed view of different surface textures and finishes of cymbals. *Source:* Courtesy of W. Blanchard, Sabian Ltd.

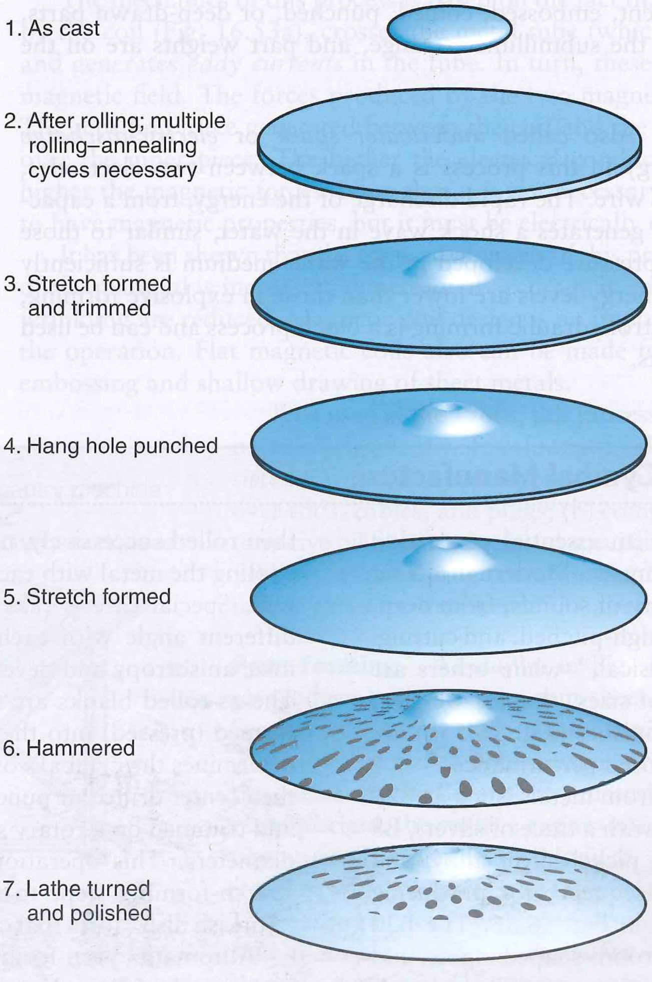

FIGURE 16.56 Manufacturing sequence for the production of cymbals. *Source:* Courtesy of W. Blanchard, Sabian Ltd.

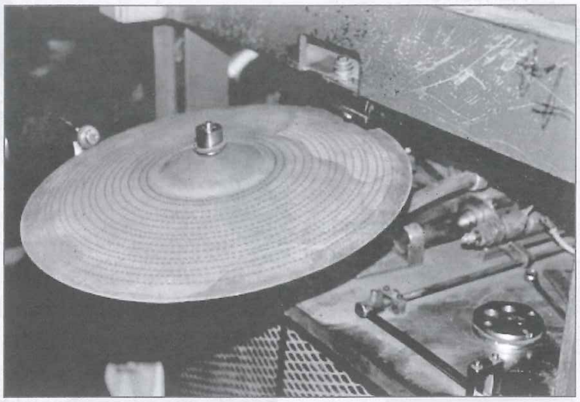

FIGURE 16.57 Automated hammering of a cymbal on a peening machine. *Source:* Courtesy of W. Blanchard, Sabian Ltd.

cymbals have already been pressed into shape, but the peening 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 by hand, which involves placing the bronze blank on a steel anvil, where the cymbals then are struck manually by hand hammers.

Several finishing operations are performed on the cymbals. These can involve merely 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 turned on a lathe (without using 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, the surface finish becomes lustrous and, in some cases, also 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 appreciated by musicians. Various surface finishes associated with modern cymbals are shown in Fig. 16.55b.

Source: Courtesy of W. Blanchard, Sabian Ltd.

16.13 Manufacturing of Metal Honeycomb Structures

A *honeycomb structure* basically consists of a core of honeycomb, or other corrugated shapes, bonded to two thin outer skins (Fig. 16.58). 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. Because of their lightweight and high resistance to bending, metal honeycomb structures are used for aircraft and aerospace components, in buildings, and in transportation equipment. The chassis of the Koenigsegg (Swedish) sports car, for example, is made partly of aluminum honeycomb with an integrated fuel tank. Honeycomb structures also may be made of nonmetallic materials, such as polymers and various composite materials.

Honeycomb structures are made most commonly of 3000-series aluminum, but may also be made of titanium, stainless steels, and nickel alloys, for specialized applications and corrosion resistance. Reinforced plastics, such as aramid-epoxy, also are used to make these structures.

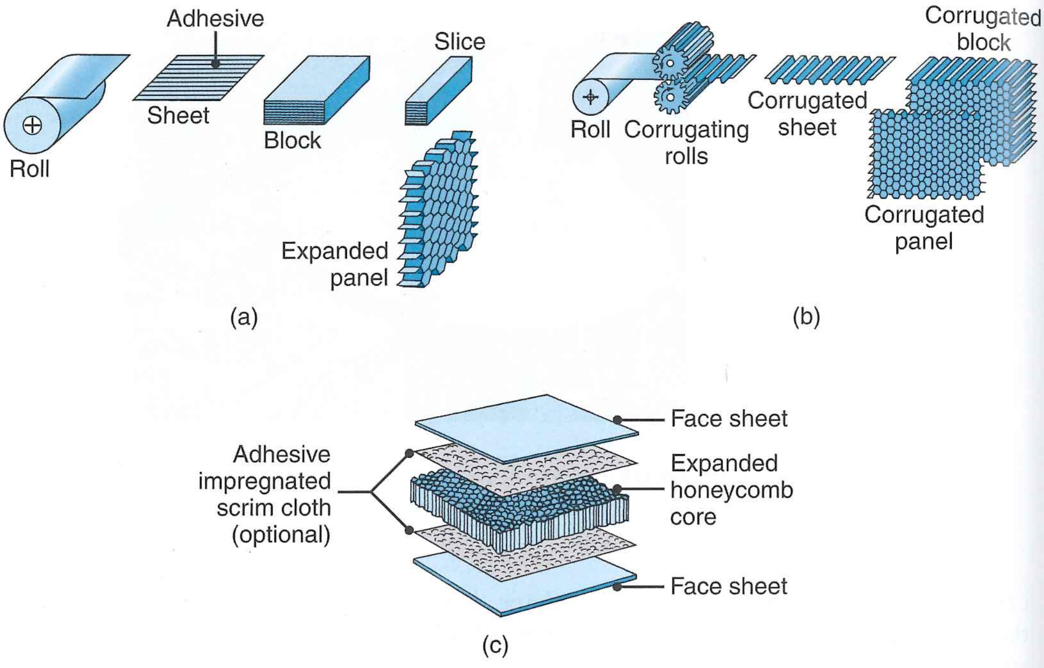

FIGURE 16.58 Methods of manufacturing honeycomb structures: (a) expansion process; (b) corrugation process; and (c) assembling a honeycomb structure into a laminate.

There are two basic methods of manufacturing honeycomb materials. In the **expansion process**, which is the more common method (Fig. 16.58a), sheets are first 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 surfaces. The block is then cut into slices of the desired dimensions, and stretched to produce a honeycomb structure.

In the **corrugation process** (Fig. 16.58b) 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 stacked into a block, and the block is cured. Because the sheets are already preformed, no expansion process is involved. The honeycomb is finally made into a sandwich structure (Fig. 16.58c), using face sheets that are joined by adhesives (or *brazed*; see Section 32.2) to the top and bottom surfaces.

16.14 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 produced (Fig. 16.59).

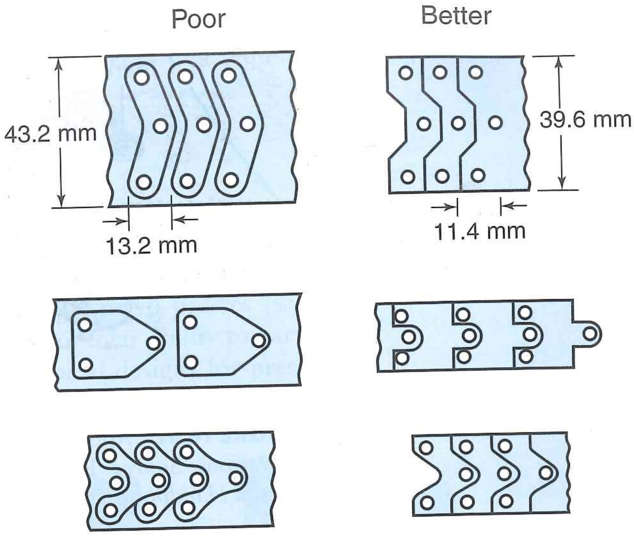

FIGURE 16.59 Efficient nesting of parts for optimum material utilization in blanking. *Source:* Reuse with permission from Society of Manufacturing Engineers in *Die Design Handbook*, 3rd edition, edited by David Smith.

Bending. The main concerns in bending operations are material fracture, wrinkling, and the inability to properly form the bend. As shown in Fig. 16.60, a sheet-metal part with a flange will force the flange to undergo compression, which may cause buckling (see also *flanging*, Section 16.6). Buckling can be controlled with a relief notch, cut to limit the stresses developed during bending, or else a design modification as shown in the figure can be made. Right-angle bends have similar difficulties, and relief notches can be used to avoid tearing (Fig. 16.61).

Because the bend radius is a highly stressed area, all stress concentrations should be removed from the bend-radius location, such as 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. 16.62a). Similarly, in bending flanges, tabs and notches should be avoided, since their stress concentrations will greatly reduce formability. When tabs are necessary, large radii should be used to reduce stress concentration (Fig. 16.62b).

If notches are to be used, it is important to orient them properly with respect to the grain direction of the sheet metal. As shown in Fig. 16.17, bends ideally should be perpendicular to the rolling direction of the sheet (or oblique, if this is not possible) in order to avoid cracking. Bending to sharp radii can be accomplished by scoring or embossing (Fig. 16.63), but this operation can result in fracture. Burrs should not be present in a bend allowance (see Fig. 16.16), because they are less ductile (due to strain hardening) and can lead to crack initiation and propagation into the rest of the sheet.

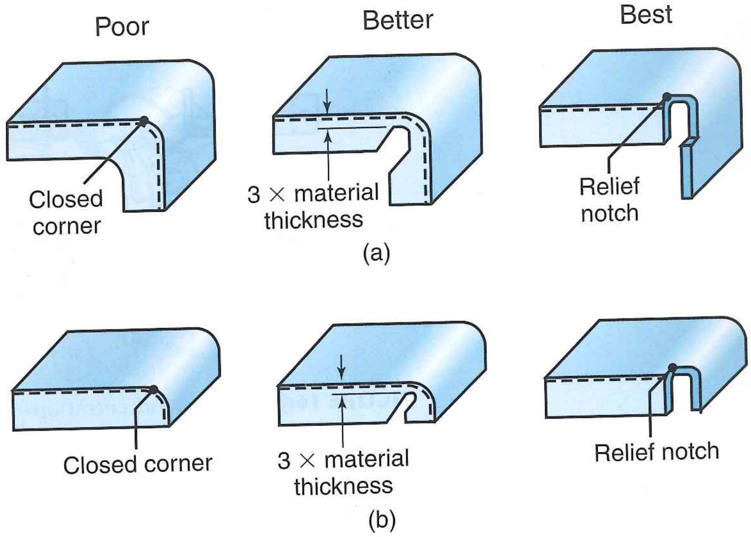

FIGURE 16.60 Control of tearing and buckling of two different flanges in a right-angle bend. *Source:* Reuse with permission from Society of Manufacturing Engineers in *Die Design Handbook*, 3rd edition, edited by David Smith.

Roll Forming. The process should, in general, be designed so as to control springback. 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, the cost of the tooling and the number of stations are determined by the number and spacing of the features on a part. Thus, it is advantageous to keep 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 may present difficulties in forming with a single set of punch and die.

Deep Drawing. After a cup is deep drawn, it invariably will spring back, slightly toward its original shape. For this reason, designs that require a vertical wall may be

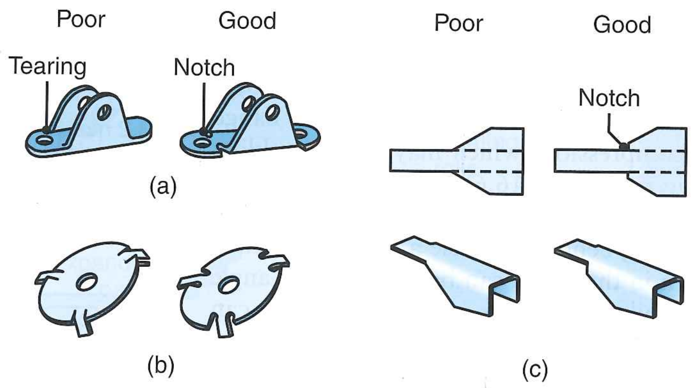

FIGURE 16.61 Application of notches to avoid tearing and wrinkling in right-angle bending operations. *Source:* Reuse with permission from Society of Manufacturing Engineers in *Die Design Handbook*, 3rd edition, edited by David Smith.

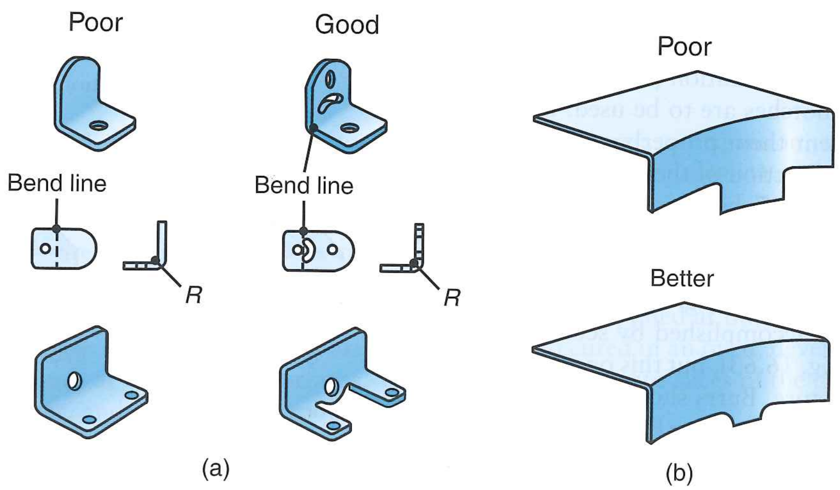

FIGURE 16.62 Stress concentrations near bends. (a) Use of a crescent or ear for a hole near a bend. (b) Reduction of severity of tab in flange. *Source:* Reuse with permission from Society of Manufacturing Engineers in *Die Design Handbook*, 3rd edition, edited by David Smith.

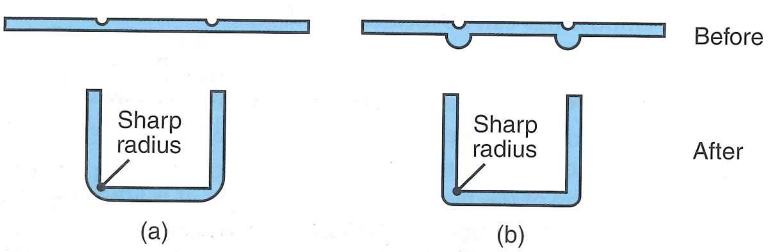

FIGURE 16.63 Application of (a) scoring or (b) embossing to obtain a sharp inner radius in bending. Unless properly designed, these features can lead to fracture. *Source:* Reuse with permission from Society of Manufacturing Engineers in *Die Design Handbook*, 3rd edition, edited by David Smith.

difficult to draw. 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 will often require one or more ironing operations.

16.15 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. Recently, servo presses (see Section 14.8) are being used for sheet-metal forming, because of their ability to vary speed and forces in a controlled manner during forming. Typical designs for press frames are shown in Fig. 16.64 (see also Figs. 14.19 and 16.23f). The proper design,

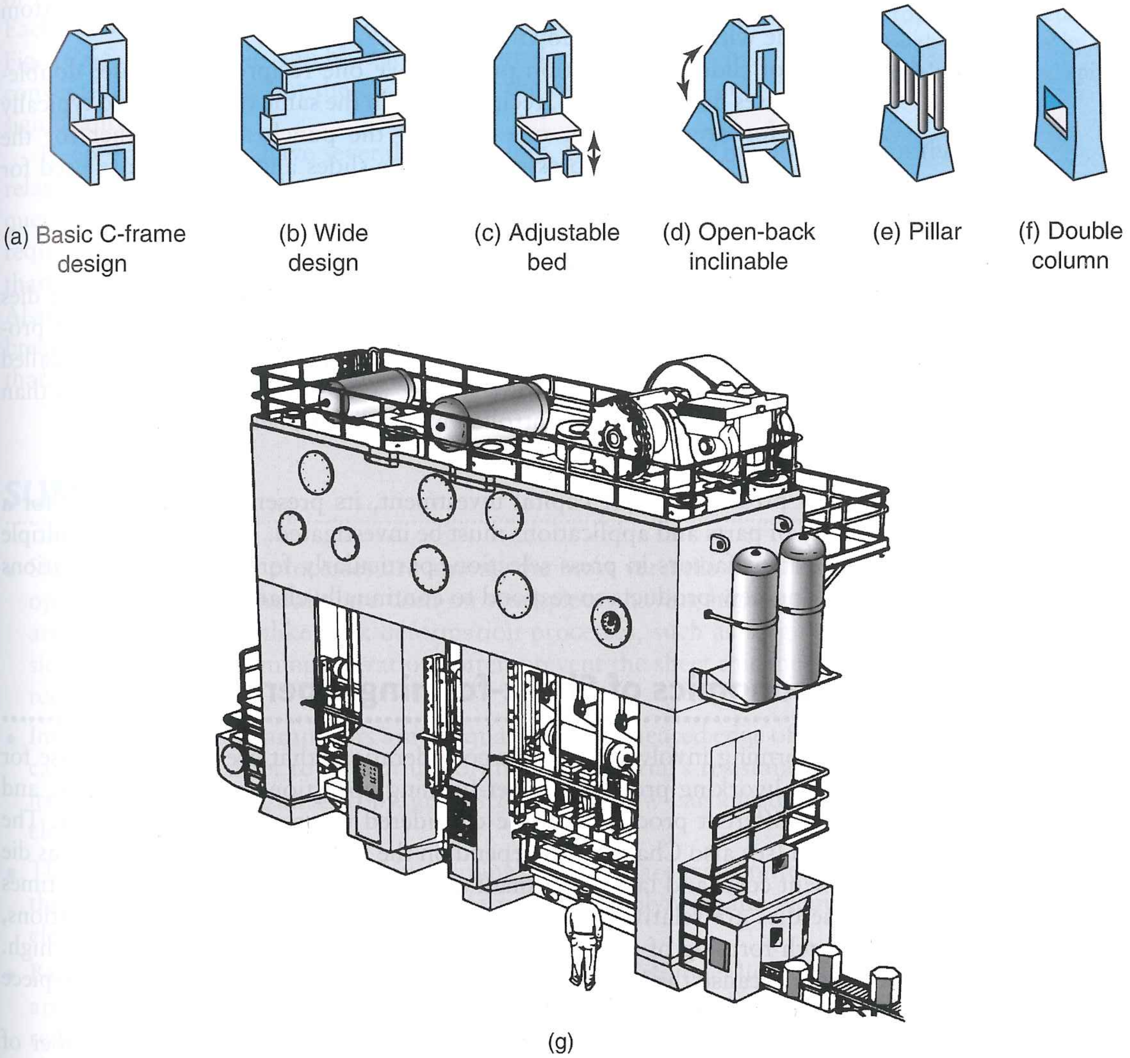

FIGURE 16.64 (a) through (f) Schematic illustrations of types of press frames for sheet-forming operations; each type has its own characteristics of stiffness, capacity, and accessibility. (g) A large stamping press. *Source:* (g) Printed with permission from Enprotech Industrial Technologies, Inc.

stiffness, and construction of such equipment is essential to the efficient operation of the system, and to achieving high production rate, good dimensional control, and high product quality.

The traditional **C-frame** structure (Fig. 16.64a) has been used widely for ease of tool and workpiece accessibility, but it is not as stiff as the **box-type pillar** (Fig. 16.64e) or the **double-column frame** structure (Fig. 16.64f). Accessibility to working areas in presses 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 the parts
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, and typically are used for deep drawing, one slide for the punch and the other for the blankholder; triple-action presses have three slides and generally are used for reverse redrawing and for other complicated forming operations
5. Maximum force required (press capacity and tonnage rating)
6. Type and level of mechanical, hydraulic, and computer controls
7. Features for changing the 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; in a system called *single-minute exchange of die* (SMED), die setups can be changed in less than 10 min, by using computer-controlled hydraulic or pneumatic systems
8. Safety features

Because a press is a major capital investment, its present and future use for a broad variety of parts and applications must 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 markets.

16.16 Economics of Sheet-forming Operations

Sheet-metal forming involves economic considerations that are similar to those for the other metalworking processes. Sheet-forming operations are very versatile, and a number of different processes can be considered 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 parts, die costs and lead times to make the dies are relatively low. On the other hand, for large-scale operations, such as stretch forming of aircraft panels and boat hulls, these costs are very high. Furthermore, because the number of such parts required is low, the cost per piece can be very high (see Fig. 14.21).

Deep drawing requires expensive dies and tooling, but a very high number of parts, such as containers, cans, and similar household products, can be produced with the same setup. These costs for other processes, such as punching, blanking, bending, and spinning, vary considerably.

Equipment costs vary widely, depending largely on the complexity of the forming operation, part loading and unloading features, part size and shape, and level of automation and computer controls required. Automation, in turn, directly affects the labor and the skill level required. Note that 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 part made, which generally is labor intensive. However, significant 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, recall that a cup-shaped part can be formed by deep drawing, spinning, rubber forming, or explosive forming. The part also may be formed by impact extrusion, casting, or fabrication by assembling or welding together different pieces. Each of these methods involves different costs. The part shown in Fig. 16.65, for example, can be made either by deep drawing or by conventional spinning, but the die costs for the two processes are significantly different.

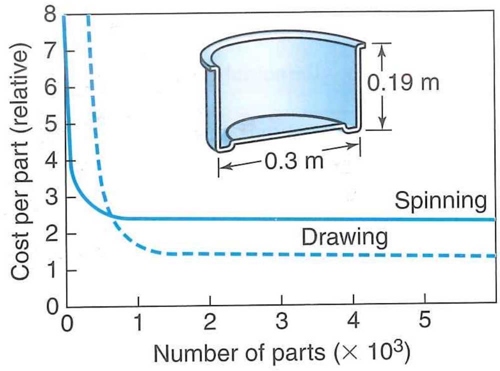

FIGURE 16.65 Cost comparison for manufacturing a round sheet-metal container either by conventional spinning or by deep drawing; note that for small quantities, spinning is more economical.

Deep-drawing dies have several components, and they cost much more than the relatively simple mandrels and tools employed in a process such as spinning. Consequently, the die cost per part in drawing will be high, especially if only a few parts are required. This part also can be formed by deep drawing and in a much shorter time than by spinning, even if the latter operation is automated and computer controlled. Also, spinning generally requires more skilled labor. Considering these factors, the break-even point for this part is around 700 parts, and for quantities greater than that, deep drawing is more economical.

SUMMARY

- Sheet-metal forming processes are among the most versatile of all metalworking 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-metal forming operations often prevent the sheet thickness from being reduced.
- Important material parameters are the quality of the sheared edge of the blank, the capability of the sheet to stretch uniformly, the material's resistance to thinning, its normal and planar anisotropy, grain size, and for low-carbon steels, yield-point elongation.
- The forces and energy required in forming processes are transmitted to the sheet 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 factors in sheet forming. These difficulties can be eliminated or reduced by proper tool and die design, minimizing the unsupported length of the sheet during processing, and controlling the thickness and surface finish of the incoming sheet and its mechanical properties.
- Superplastic forming of diffusion-bonded sheets is an important process for making complex sheet-metal structures, particularly for aerospace applications in which high stiffness-to-weight ratios are important.

- Several test methods have been developed for predicting the formability of sheet metals.
- 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.

KEY TERMS

Beading
Bendability
Bend allowance
Bending
Blankholder
Blanking
Bulging
Burnished surface
Burr
Clearance
Compound dies
Deburring
Deep drawing
Dent resistance
Dimpling
Draw bead
Drawing
Earing
Electrohydraulic forming
Embossing
Explosive forming
Fine blanking
Flanging
Formability
Forming-limit diagram
Hemming
Honeycomb structures
Hot stamping
Hydroform process
Incremental forming
Ironing
Laser-assisted 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

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REVIEW QUESTIONS

16.1 How does sheet-metal forming differ from rolling, forging, and extrusion?

16.2 What causes burrs? How can they be reduced or eliminated?

16.3 Explain the difference between punching and blanking.

16.4 Describe the difference between compound, progressive, and transfer dies.

16.5 Describe the characteristics of sheet metals that are important in sheet-forming operations. Explain why they are important.

16.6 Describe the features of forming-limit diagrams (FLDs).

16.7 List the properties of materials that influence springback. Explain why and how they do so.

16.8 Give one specific application for each of the common bending operations described in this chapter.

16.9 Why do tubes buckle when bent? What is the effect of the tube thickness-to-diameter ratio?

16.10 Define normal anisotropy, and explain why it is important in determining the deep drawability of a material.

16.11 Describe earing and why it occurs.

16.12 What are the advantages of rubber forming? Which processes does it compete with?

16.13 Explain the difference between deep drawing and redrawing.

16.14 How is roll forming fundamentally different from rolling?

16.15 What is nesting? What is its significance?

16.16 Describe the differences between compound, progressive, and transfer dies.

16.17 What is microforming?

16.18 Explain the advantages of superplastic forming.

16.19 What is hot stamping? For what materials is it used?

16.20 What is springback? What is negative springback?

QUALITATIVE PROBLEMS

16.21 Explain the differences that you have observed between products made of sheet metals and those made by casting and forging.

16.22 Take any three topics from Chapter 2, and, with specific examples for each, show their relevance to the topics covered in this chapter.

16.23 Do the same as for Problem 16.22, but for Chapter 3.

16.24 Identify the material and process variables that influence the punch force in shearing, and explain how each of them affects this force.

16.25 Explain why springback in bending depends on yield stress, elastic modulus, sheet thickness, and bend radius.

16.26 Explain why cupping tests may not predict well the formability of sheet metals in actual forming processes.

16.27 Identify the factors that influence the deep-drawing force, F, in Fig. 16.32b, and explain why they do so.

16.28 Why are the beads in Fig. 16.36b placed in those particular locations?

16.29 A general rule for dimensional relationships for successful drawing without a blankholder is given by Eq. (16.14). Explain what would happen if this limit were exceeded.

16.30 Section 16.2 stated that the punch stripping force is difficult to estimate because of the many factors involved. Make a list of these factors, with brief explanations about why they would affect the stripping force.

16.31 Is it possible to have ironing take place in an ordinary deep-drawing operation? What is the most important factor?

16.32 Note the roughness of the periphery of the flanged hole in Fig. 16.25c, and comment on its possible effects when the part is used in a product.

16.33 What recommendations would you make in order to eliminate the cracking of the bent piece shown in Fig. 16.17c? Explain your reasons.

16.34 It has been stated that the quality of the sheared edges can influence the formability of sheet metals. Explain why.

16.35 Give several specific examples from this chapter in which friction is desirable and several in which it is not desirable.

16.36 As you can see, some of the operations described in this chapter produce considerable scrap. Describe your thoughts regarding the reuse, recycling, or disposal of this scrap. Consider its size, shape, and contamination by metalworking fluids during processing.

16.37 Through changes in clamping or die design, it is possible for a sheet metal to undergo a negative minor strain. Explain how this effect can be advantageous.

16.38 How would you produce the part shown in Fig. 16.43b other than by tube hydroforming?

16.39 It has been stated that the thicker the sheet metal, the higher is the curve in the forming-limit diagram. Explain why.

16.40 If a cupping test (see Fig. 16.13) were to be performed using a pressurized lubricant instead of a spherical die, would you expect the forming limit diagram to change? Why or why not?

QUANTITATIVE PROBLEMS

16.41 Calculate R_{avg} for a metal where the R values for the 0°, 45°, and 90° directions are 0.9, 1.7, and 1.8, respectively. What is the limiting drawing ratio (LDR) for this material?

16.42 Calculate the value of ΔR in Problem 16.41. Will any ears form when this material is deep drawn? Explain.

16.43 Estimate the limiting drawing ratio for the materials listed in Table 16.4.

16.44 Using Eq. (16.15) and the K value for TNT, plot the pressure as a function of weight, W, and R, respectively. Describe your observations.

16.45 Section 16.5 states that the k values in bend allowance depend on the relative magnitudes of R and T. Explain why this relationship exists.

16.46 For explosive forming, calculate the peak pressure in water for 1.2 N of TNT at a standoff distance of 1200 mm. Comment on whether or not the magnitude of this pressure is sufficiently high to form sheet metals.

16.47 Measure the respective areas of the solid outlines in Fig. 16.14a, and compare them with the areas of the original circles. Calculate the final thicknesses of the sheets, assuming that the original sheet is 1 mm thick.

16.48 Plot Eq. (16.6) in terms of the elastic modulus, E, and the yield stress, Y, of the material, and describe your observations.

16.49 What is the minimum bend radius for a 1.0-mm-thick sheet metal with a tensile reduction of area of 30%? Does the bend angle affect your answer? Explain.

16.50 Survey the technical literature and explain the mechanism by which negative springback can occur in V-die bending. Show that negative springback does not occur in air bending.

16.51 Using the data in Table 16.3 and referring to Eq. (16.5), calculate the tensile reduction of area for the materials and the conditions listed in the table.

16.52 What is the force required to punch a square hole 50 mm on each side in a 0.1-mm-thick 5052-O aluminum sheet by using flat dies? What would be your answer if beveled dies are used?

16.53 In Case Study 16.2, it was stated that the reason for reducing the tops of cans (necking) is to save material for making the lid. How much material will be saved if the lid diameter is reduced by 10%? By 15%?

16.54 A cup is being drawn from a sheet metal that has a normal anisotropy of 3. Estimate the maximum ratio of cup height to cup diameter that can be drawn successfully in a single draw. Assume that the thickness of the sheet throughout the cup remains the same as the original blank thickness.

16.55 Estimate the percent scrap in producing round blanks if the clearance between blanks is one tenth of the radius of the blank. Consider single and multiple-row blanking, as sketched in Fig. P16.55.

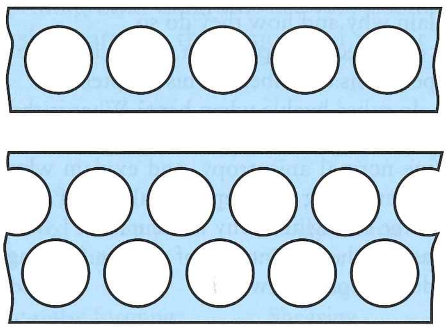

FIGURE P16.55

16.56 Plot the final bend radius as a function of initial bend radius in bending for (a) 5052-O aluminum; (b) 5052-H34 aluminum; (c) C24000 brass; and (d) AISI 304 stainless steel.

16.57 Figure P16.57 shows a parabolic profile that will define the mandrel shape in a spinning operation. Determine the equation of the parabolic surface. If a spun part will be produced from a 10-mm thick blank, determine the minimum required blank diameter.

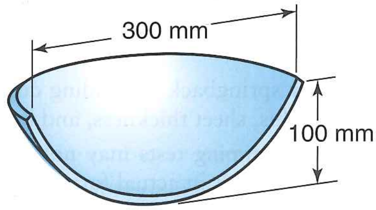

FIGURE P16.57

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

SYNTHESIS, DESIGN, AND PROJECTS

16.59 Examine some of the products in your home or in an automobile that are made of sheet metal, and discuss the process or combination of processes by which you think they were made.

16.60 Consider several shapes to be blanked from a large sheet (such as oval, triangular, L-shaped, and so forth) by laser-beam cutting, and sketch a nesting layout to minimize scrap generation.

16.61 Give several specific product applications for (a) hemming and (b) seaming.

16.62 Many axisymmetric missile bodies are made by spinning. What other methods could you use if spinning processes were not available?

16.63 Give several structural designs and applications in which diffusion bonding and superplastic forming can be used jointly. Comment on whether this combination is capable of producing parts at high volume.

16.64 Metal cans are either two-piece (in which the bottom and sides are integral) or three-piece (in which the sides, the bottom, and the top are each separate pieces). For a three-piece can, should the vertical seam in the can body be (a) in the rolling direction, (b) normal to the rolling direction, or (c) oblique to the rolling direction? Prove your answer.

16.65 The design shown in Fig. P16.65 is proposed for a metal tray, the main body of which is made from cold-rolled sheet steel. Noting its features and that the sheet is bent in two different directions, comment on various manufacturing considerations. Include factors such as anisotropy of the rolled sheet, its surface texture, the bend directions, the nature of the sheared edges, and the way the handle is snapped in for assembly.

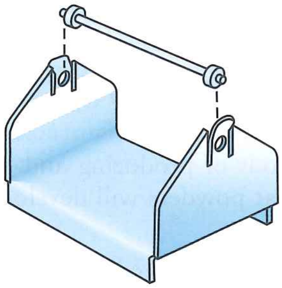

FIGURE P16.65

16.66 Suggest consumer-product designs that could utilize honeycomb structures. For example, an elevator can use a honeycomb laminate as a stiff and lightweight floor material.

16.67 How would you produce the part shown in Fig. 16.44 other than by tube hydroforming? Give two options.

16.68 Using a ball-peen hammer, strike the surface of aluminum sheets of various thicknesses until they develop a curvature. Describe your observations about the shapes produced.

16.69 Inspect a common paper punch and observe the shape of the punch tip. Compare it with those shown in Fig. 16.10 and comment on your observations.

16.70 Obtain an aluminum beverage can and slit it in half lengthwise with a pair of tin snips. Using a micrometer, measure the thickness of the can bottom and the wall. Estimate the thickness reductions in ironing and the diameter of the original blank.

16.71 In order to improve its ductility, a coil of sheet metal is placed in a furnace and annealed. However, it is observed that the sheet has a lower limiting drawing ratio than it had before being annealed. Explain the reasons for this behavior.

16.72 With automotive parts, it is often advantageous to have a part with tailored properties. For example, a pillar that provides structural support for the operator's compartment may be strong but less ductile at the center, but more ductile and less strong where the pillar attaches to the remainder of the car structure. List ways of producing such tailored properties in hot stampings.

16.73 Give three examples of sheet metal parts that (a) can and (b) cannot be produced by incremental forming.

16.74 Conduct a literature search and obtain the equation for a tractrix curve, as used in Fig. 16.38.

16.75 On the basis of experiments, it has been suggested that concrete, either plain or reinforced, can be a suitable material for dies in sheet-metal forming operations. Describe your thoughts regarding this suggestion, considering die geometry and any other factors that may be relevant.

16.76 Investigate methods for determining optimum shapes of blanks for deep-drawing operations. Sketch the optimally shaped blanks for drawing rectangular cups, and optimize their layout on a large sheet of metal.

16.77 Design a box that will contain a 100 mm × 150 mm × 75 mm volume. The box should be produced from two pieces of sheet metal and require no tools or fasteners for assembly.

16.78 Repeat Problem 16.77, but design the box from a single piece of sheet metal.