Sheet-Metal Forming Processes and Equipment

Ch 16
Sheet-Metal Forming

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.

However, the term pressworking or press forming is used commonly in industry to describe general sheet-forming operations, because they typically are performed on presses using a set of dies.

Examples of sheet-metal parts. (a) Stamped parts. (b) Parts produced by spinning.
Low-carbon steel is the most commonly used sheet metal because of its low cost and generally good strength and formability characteristics.

More recently developed alloys, such as TRIP and TWIP steels, have become popular for automotive applications because of their high strength; they are well suited for providing good crash protection in a lightweight design.

Aluminum is the most common material for such sheet-metal applications as beverage cans, packaging, kitchen utensils, and applications where corrosion resistance is a concern.

Most manufacturing processes involving sheet metal are performed at room temperature. Hot stamping is occasionally performed in order to increase formability and decrease forming loads on machinery. Typical materials in hot-stamping operations are titanium alloys and various high-strength steels.
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<th>Forming process</th>
<th>Characteristics</th>
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<tr>
<td>Drawing</td>
<td>Shallow or deep parts with relatively simple shapes, high production rates, high tooling and equipment costs</td>
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<td>Explosive</td>
<td>Large sheets with relatively simple shapes, low tooling costs but high labor cost, low-quantity production, long cycle times</td>
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<tr>
<td>Incremental</td>
<td>Simple to moderately complex shapes with good surface finish; low production rates, but no dedicated tooling required; limited materials</td>
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<tr>
<td>Magnetic-pulse</td>
<td>Shallow forming, bulging, and embossing operations on relatively low strength sheets, requires special tooling</td>
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<tr>
<td>Peen</td>
<td>Shallow contours on large sheets, flexibility of operation, generally high equipment costs, process also used for straightening formed parts</td>
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<tr>
<td>Roll</td>
<td>Long parts with constant simple or complex cross sections, good surface finish, high production rates, high tooling costs</td>
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<tr>
<td>Rubber</td>
<td>Drawing and embossing of simple or relatively complex shapes, sheet surface protected by rubber membranes, flexibility of operation, low tooling costs</td>
</tr>
<tr>
<td>Spinning</td>
<td>Small or large axisymmetric parts; good surface finish; low tooling costs, but labor costs can be high unless operations are automated</td>
</tr>
<tr>
<td>Stamping</td>
<td>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</td>
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<tr>
<td>Stretch</td>
<td>Large parts with shallow contours, low-quantity production, high labor costs, tooling and equipment costs increase with part size</td>
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<tr>
<td>Superplastic</td>
<td>Complex shapes, fine detail and close dimensional tolerances, long forming times (hence production rates are low), parts not suitable for high-temperature use</td>
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</table>
Shearing

Before a sheet-metal part is made, a blank of suitable dimensions first is removed from a large sheet (usually from a coil) by shearing. This sheet is cut by subjecting it to shear stresses, generally using a punch and a die.

Note that the edges are not smooth nor are they perpendicular to the plane of the sheet.

(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.)
Shearing

Shearing generally starts with the formation of cracks on both the top and bottom edges of the work piece. Cracks eventually meet each other and complete separation occurs.

The rough fracture surfaces are due to the cracks; the smooth and shiny burnished surfaces on the hole and the slug are from the contact and rubbing of the sheared edge against the walls of the punch and die, respectively.

The major processing parameters in shearing are:

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

The clearance is a major factor in determining the shape and the quality of the sheared edge. As the clearance increases, the zone of deformation becomes larger and the sheared edge becomes rougher.

Edge quality can be improved with increasing punch speed; speeds may be as high as 10 to 12 m/s.

(a) Effect of the clearance, c, between punch and die on the deformation zone in shearing. As the clearance increases, the material tends to be pulled into the die rather than be sheared. In practice, clearances usually range between 2 and 10% of the thickness of the sheet. (b) Microhardness (HV) contours for a 6.4-mm (0.25-in.) thick AISI 1020 hot-rolled steel in the sheared region.
The ratio of the burnished area to the rough areas along the sheared edge (a) increases with increasing ductility of the sheet metal and (b) decreases with increasing sheet thickness and clearance.

With increasing speed, the heat generated by plastic deformation is confined to a smaller and smaller zone. Consequently, the sheared zone is narrower, and the sheared surface is smoother and exhibits less burr formation.

Burr height increases with increasing clearance and ductility of the sheet metal.

**Punch force**

The maximum punch force, \( F \), can be estimated from the equation

\[
F = 0.7TL(UTS)
\]

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.
**EXAMPLE 16.1 Calculation of Punch Force**

Estimate the force required for punching a 25-mm diameter hole through a 3.2-mm thick annealed titanium-alloy Ti-6Al-4V sheet at room temperature.

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

\[ F = 0.7(32)(\pi)(25)(1000) = 0.18 \text{ MN}. \]
Shearing Operations

The most common shearing operations are punching—where the sheared slug is scrap or may be used for some other purpose—and blanking—where the slug is the part to be used and the rest is scrap—generally are carried out on computer-numerical-controlled machines with quick-change tool holders. Such machines are useful, particularly in making prototypes of sheet-metal parts requiring several operations to produce.

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

This is a shearing operation that consists of the following basic processes:

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

Parts produced by these processes have various uses, particularly in assembly with other components. Perforated sheet metals with hole diameters ranging from around **1 mm 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.
**Fine Blanking.** Very smooth and square edges can be produced by fine blanking. A **V-shaped stinger** or impingement mechanically locks the sheet tightly in place and prevents the type of distortion of the material.

![Diagram of fine blanking setup](image)

(a) Comparison of sheared edges produced by conventional (left) and by fine blanking (right) techniques. (b) Schematic illustration of one setup for fine blanking.
Slitting. Shearing operations can be carried out by means of a pair of circular blades similar to those in a can opener. In slitting, the blades follow either a straight line, a circular path, or a curved path.
Steel Rules.
Soft metals (as well as paper, leather, and rubber) can be blanked with a steel-rule die. Such a die consists of a thin strip of hardened steel bent into the shape to be produced (a concept similar to that of a cookie cutter) and held on its edge on a flat wood or polymer base. The die is pressed against the sheet, which rests on the flat surface, and it shears the sheet along the shape of the steel rule.

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. Scrap can be a significant factor in manufacturing cost, and it can be reduced substantially by efficient arrangement of the shapes on the sheet to be cut. Computer-aided design techniques have been developed to minimize the scrap from shearing operations.
Tailor-welded Blanks

In the sheet-metal-forming processes to be described throughout this chapter, the blank is usually a one-piece sheet of one thickness cut from a large sheet. An important variation from these conditions involves laser-beam butt welding.

Production of an outer side panel of a car body by laser butt welding and stamping.
Tailor-welded Blanks

This technique is becoming increasingly important, particularly to the automotive industry. Because each subpiece now can have a different thickness, grade, coating, or other property, tailor-welded blanks possess the needed properties in the desired locations in the blank. The result is Reduction in scrap, Elimination of the need for subsequent spot welding ,Better control of dimensions and Improved productivity.

Examples of laser butt-welded and stamped automotive-body components.
Characteristics and Type of Shearing Dies

Clearance

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

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

Clearances generally range between 2 and 8% of the sheet thickness, but they may be as small as 1% (as in fine blanking) or as large as 30%. The smaller the clearance, the better is the quality of the edge. If the sheared edge is rough and not acceptable, it can be subjected to a process called shaving.

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

Punch and Die Shape

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.

Examples of the use of shear angles on punches and dies.
Bending Sheets, Plates, and Tubes

Bending is one of the most common industrial forming operations. We merely have to look at an automobile body, appliance, paper clip, or file cabinet to appreciate how many parts are shaped by bending.

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.

Bending terminology. Note that the bend radius is measured to the inner surface of the bent part.
depends on the radius and the bend angle (as described in texts on mechanics of materials). An approximate formula for the bend allowance is

\[ L_b = \alpha (R + kT) \]

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

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

\[ e = \frac{1}{(2R/T) + 1}. \]

Thus, as R/T decreases (that is, as the ratio of the bend radius to the thickness becomes smaller), the tensile strain at the outer fiber increases and the material eventually develops cracks.

(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).
Minimum Bend Radius

The bend radius usually is expressed (reciprocally) in terms of the thickness, such as 2T, 3T, 4T, and so on. 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>
<thead>
<tr>
<th>Material</th>
<th>Condition</th>
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<tbody>
<tr>
<td></td>
<td>Soft</td>
</tr>
<tr>
<td>Aluminum alloys</td>
<td>0</td>
</tr>
<tr>
<td>Beryllium copper</td>
<td>0</td>
</tr>
<tr>
<td>Brass (low-leaded)</td>
<td>0</td>
</tr>
<tr>
<td>Magnesium</td>
<td>5T</td>
</tr>
<tr>
<td>Steels</td>
<td></td>
</tr>
<tr>
<td>Austenitic stainless</td>
<td>0.5T</td>
</tr>
<tr>
<td>Low-carbon, low-alloy, and HSLA</td>
<td>0.5T</td>
</tr>
<tr>
<td>Titanium</td>
<td>0.7T</td>
</tr>
<tr>
<td>Titanium alloys</td>
<td>2.6T</td>
</tr>
</tbody>
</table>

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

\[ R = \frac{T}{r} \left( \frac{50}{r} - 1 \right) \]

where \( r \) is the tensile reduction of area of the sheet metal. Thus, for \( r = 50 \), the minimum bend radius is zero; that is, the sheet can be folded over itself.
Relationship between $R/T$ and tensile reduction of area for sheet metals. Note that sheet metal with a 50% tensile reduction of area can be bent over itself in a process like the folding of a piece of paper without cracking.

To increase the bendability of metals, we may increase their tensile reduction of area either by heating or by bending in a high-pressure environment (which improves the ductility of the material;
Springback

Because all materials have a finite modulus of elasticity, plastic deformation always is followed by some elastic recovery when the load is removed.

In bending, this recovery is called springback, which can be observed easily by bending and then releasing a piece of sheet metal or wire.

Springback occurs not only in flat sheets and plates, but also in solid or hollow bars and tubes of any cross section.

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).
Compensation for Springback

Springback in forming operations usually is compensated for by overbending the part.

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.

Methods of reducing or eliminating springback in bending operations.
**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, \( W \)

\[
P = \frac{kYLT^2}{W}
\]

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

Common die-bending operations showing the die-opening dimension, \( W \), used in calculating bending forces.
Bending force

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

\[ P = \frac{(UTS)LT^2}{W} \]

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

Examples of various bending operations.
(a) Bead forming with a single die. (b) through (d) Bead forming with two dies in a press brake.
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.
Stretch Forming

In stretch forming, the sheet metal is clamped along its edges and then stretched over a male die (form block or form punch). The die moves upward, downward, or sideways, depending on the particular design of the machine. 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 X 2.5 m X 6.4 mm. Although this process generally is used for low volume production, it is versatile and economical, particularly for the aerospace industry.

Schematic illustration of a stretch-forming process. Aluminum skins for aircraft can be made by this method.
Deep Drawing

Numerous parts made of sheet metal are cylindrical or box shaped, such as pots and pans, all types of containers for food and beverages 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. Although the process generally is called deep drawing (because of its capability for producing deep parts), it also is used to make parts that are shallow or have moderate depth. It is one of the most important metalworking processes because of its widespread use.

In the basic deep-drawing process, a round sheet-metal blank is placed over a circular die opening and is held in place with a blank holder, or hold-down ring.
The metal-forming processes involved in manufacturing a two-piece aluminum beverage can.

Deep Drawing

1. Blanking

2. Deep drawing

3. Redrawing

4. Ironing

5. Domining

6. Necking

7. Seaming
Deep Drawing

(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.

The punch travels downward and forces the blank into the die cavity, forming a cup. The important variables in deep drawing are the properties of the sheet metal, the ratio of blank diameter, $D_o$; the punch diameter, $D_p$; the clearance, $c$; the punch radius, $R_p$; the die-corner radius, $R_d$; the blank holder force; and friction and lubrication between all contacting surfaces.
Punch force  Deep Drawing

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

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

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

It can be seen that the force increases with increasing blank diameter, thickness, strength, and the ratio $(D_o/D_p)$. The wall of the cup is subjected principally to a longitudinal (vertical) tensile stress due to the punch force. Elongation under this stress causes the cup wall to become thinner and, if excessive, can cause tearing of the cup.
What is the force required to punch a square hole 60 mm on each side in a 1-mm thick 5052-O aluminum sheet by using flat dies?

UTS is 190 MPa for 5052-O aluminum

\[ F = 0.7TL(UTS) \]
What is the force required to punch a square hole 60 mm on each side in a 1-mm thick 5052-O aluminum sheet by using flat dies?

$$F = 0.7TL(UTS)$$

$$F = 0.7(0.001)(0.24)(190 \times 10^6) = 31.9 \text{ kN}$$