Introduction

- What is Sheet-Metal Forming Processes
  - Forming products from sheet metal
- Sheet metal forming products include
  - File cabinets, car bodies, metal desks
- Advantages
  - Low weight
  - Versatile shape
- Materials
  - Most common is low carbon steel
    - Good strength and formability
<table>
<thead>
<tr>
<th>Forming process</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drawing</td>
<td>Shallow or deep parts with relatively simple shapes, high production rates, high tooling and equipment costs</td>
</tr>
<tr>
<td>Explosive</td>
<td>Large sheets with relatively simple shapes, low tooling costs but high labor cost, low-quantity production, long cycle times</td>
</tr>
<tr>
<td>Magnetic-pulse</td>
<td>Shallow forming, bulging, and embossing operations on relatively low-strength sheets, requires special tooling</td>
</tr>
<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>
</tr>
<tr>
<td>Roll</td>
<td>Long parts with constant simple or complex cross-sections, good surface finish, high production rates, high tooling costs</td>
</tr>
<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>
</tr>
<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>
</tr>
<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>
</tr>
</tbody>
</table>
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 with a Punch and Die

- Cut the sheet by subjecting it to shear stresses
  - Scissors
- A blank is created by shearing it from a larger sheet (coil)
- Shearing geometry
  - Sheared edges are not smooth, nor perpendicular to the plane of the sheet
  - Shearing starts by formation of cracks at A, B, C, and D
  - The cracks meet each other, resulting in separation
    - Results in a rough fracture surface
  - Burnish depth has a smooth surface resulting from rubbing against the walls of the punch and die
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.
Punch Force

- Force required
  - Product of the shear strength and the area sheared

\[ F = 0.7 \cdot T \cdot L \cdot S_{ut} \]

- \( T \) = thickness
- \( L \) = length sheared (perimeter of a hole)
- \( S_{ut} \) = ultimate shearing strength
**Punching** where the sheared slug is scrap

**Blanking** where the slug is the part to be used and the rest is scrap.
Die Cutting.

**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.

**Fine Blanking.** Very smooth and square edges

**Slitting.** Shearing operations can be carried out by means of a pair of circular blades

**Steel Rules**

**Nibbling.** moves a small straight punch up and down rapidly into a die
Slitting with Rotary Knives

- Driven cutter
- Workpiece
- Idling cutter

Clearance
### 16.2.4 Miscellaneous Methods of Cutting Sheet Metal

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

- **Laser-beam cutting** is an important process (Section 26.7) typically used with computer-controlled equipment to cut a variety of shapes consistently, in various thicknesses, and without the use of any dies. Laser-beam cutting also can be combined with punching and shearing. These processes cover different and complementary ranges. Parts with certain features can be produced best by one process; some with other features can be produced best by the other process. Combination machines incorporating both capabilities have been designed and built. (See also Example 27.1.)

- **Water-jet cutting** is effective on many metallic as well as nonmetallic materials (Section 27.8).

- Cutting with a **band saw**; this method is a chip-removal process.

- **Friction sawing** involves a disk or blade that rubs against the sheet or plate at high surface speeds (Section 24.5).

- **Flame cutting** is another common method, particularly for thick plates; it is used widely in shipbuilding and on heavy structural component (Section 30.8).
Scrap in Shearing The amount of scrap (trim loss) produced in shearing operations can be significant and can be as high as 30%.
Clearance
- Dependent on material type and temper, thickness, size of blank, distance from the edge
- Soft materials have lower clearance than hard materials
- The thicker the sheets, the more clearance
- Small holes need more clearance than large holes
- Rough sheared edges are removed by shaving (figure)

Punch and die shapes
- Punch is often beveled
  - To reduce the force needed at the beginning of each stroke
  - Reduces noise levels
**Compound**

- **Compound dies**
  - Several operations on the same strip are performed in one stroke at one station
  - Slow process
  - Expensive dies
  - Simple shapes

- **Progressive dies**
  - The sheet metal is fed through as a coil strip
  - A different operation is performed at the same station with each stroke of a series of punches

- **Transfer dies**
  - Different operations at different stations
  - Sheet metal moves forward

- **Tool and die material**
  - Tool steels
  - Carbides
  - Lubrication reduces tool and die wear and improves edge quality
## Characteristics of Metals Used in Sheet-Forming

### TABLE 16.2

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elongation</td>
<td>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.</td>
</tr>
<tr>
<td>Yield-point elongation</td>
<td>Typically observed with mild-steel sheets (also called Lüders bands or stretcher strains), flamelike depressions on the sheet surface, can be eliminated by temper rolling but sheet must be formed within a certain time after rolling.</td>
</tr>
<tr>
<td>Anisotropy (planar)</td>
<td>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.</td>
</tr>
<tr>
<td>Anisotropy (normal)</td>
<td>Determines thinning behavior of sheet metals during stretching, important in deep drawing.</td>
</tr>
<tr>
<td>Grain size</td>
<td>Determines surface roughness on stretched sheet metal, the coarser the grain—the rougher the appearance (orange peel), also affects material strength.</td>
</tr>
<tr>
<td>Residual stresses</td>
<td>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.</td>
</tr>
<tr>
<td>Springback</td>
<td>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.</td>
</tr>
<tr>
<td>Wrinkling</td>
<td>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.</td>
</tr>
<tr>
<td>Quality of sheared edges</td>
<td>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.</td>
</tr>
<tr>
<td>Surface condition of sheet</td>
<td>Depends on sheet rolling practice; important in sheet forming as it can cause tearing and poor surface quality.</td>
</tr>
</tbody>
</table>
Sheet Metal

- Elongation
  - Uniform region
    - Desirable elongation
  - Necking: after the ultimate tensile stress has been reached

- Yield Point Elongation
  - Common with low carbon steels
  - Have an upper and a lower yield point (material starts yielding in one region before another)
  - Results in Lueder’s bands (stretcher strain marks)
    - Reduce effect of these by reducing the thickness of the sheet or by cold rolling

- Anisotropy (different properties in different directions)
  - Two types
    - Crystallographic anisotropy
      - Preferred orientation of the grains
    - Mechanical fibering
      - Alignment of impurities and voids

- Grain Size
  - Grain size affects the mechanical properties and surface appearance
  - The coarser the grain, the coarser the surface finish
Bending Sheet and Plate

- Bending: one of the most common forming operations
  - Where do you see it?
    - File cabinets, paper clips
  - Why do you bend?
    - Form flanges, seams and corrugations
    - Increase stiffness by modifying the moment of inertia
- Terminology
  - Length: width of the part
    - L is smaller at the outer radius than at the inner radius (due to Poisson’s ratio)
      - Observe by bending a rubber eraser
  - Bend radius
  - Setback
  - Bend radius
  - Bevel angle
  - Bend angle

- Bend allowance ($L_b$): length of the neutral axes in the bend
  \[ L_b = \alpha \cdot (R + k \cdot T) \]
  - T: thickness, R: bend radius, $\alpha$: bend angle, k: constant related to location of the neutral axes
    - Ideal case $k = 0.5$
    \[ L_b = \alpha \cdot \left( R + \frac{T}{2} \right) \]
    - $k$: from 0.33 (for R<2T) to 0.5 (for R>2T)
Minimum Bend Radius

- Engineering Strain
  \[ e = \frac{1}{\left(2 \cdot \frac{R}{T}\right) + 1} \]
  - As R/T decreases, the tensile stress increases on the outer surface → leading to cracks

- Minimum bend radius
  - The ratio at which cracks start to appear
  - 2T, 3T, 4T...

- Bendability decreases with
  - edge roughness
  - cold working
    - Annealing or machining can help
  - inclusions

- Anisotropy affects bendability
  - Cut the sheet in an advantageous direction

Narrowing due to Poisson's effect
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 degrees. Note also the narrowing of the top surface in the bend area (due to Poisson effect).
Figure 16.19 Springback in bending. The part tends to recover elastically after bending, and its bend radius becomes larger. Under certain conditions, it is possible for the final bend angle to be smaller than the original angle (negative springback).
Springback

- When the load is applied,
  - Elastic deformation begins
  - Plastic deformation follows

- As load is removed
  - Some elastic recovery occurs
    - Called “springback”

- Springback
  - Angle after springback is smaller
  - Bend radius will be a little larger

\[
\frac{R_i}{R_f} = 4 \left( \frac{R_i \cdot Y}{ET} \right)^3 - 3 \left( \frac{R_i \cdot Y}{E \cdot T} \right) + 1
\]

- $R_i$, $R_f$ as shown
- $Y$: yield stress
- $E$: elastic modulus
- Springback increases with
  - $R/T$
  - $Y$
- Decreases w/ $E$
Methods of Reducing or Eliminating Springback

- Compensation for springback
  - Overbending (fig a, b)
  - Bottoming the punch
    - Apply high compressive stresses between the punch tip and the die (fig c, d)

(a)  
(b)  
(c)  
(d)  

(e)
Common Die-Bending Operations

Bending Force

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

where

\( k = 0.3 \) for wiping die,
\( k = 0.7 \) for a U-die,
\( k = 1.3 \) for a V-die

- **P**: maximum bending force
- **k**: factor dependent on the type of die
  - Typical values from 0.3 – 1.3
- **Y**: yield strength
- **T**: thickness
- **W**: die opening dimension

Figure 16.21 Common die-bending operations showing the die-opening dimension, \( W \), used in calculating bending forces.
Roll-bending
- Plates are bent using a set of rolls
- Various curvatures can be obtained by adjusting the position of the rolls

Bending in a 4-slide machine
- Bending of short pieces
- **Hemming**
  - Also called flattening
  - Edge of sheet is folded over itself
  - Increase stiffness, improve appearance
- **Seaming**
  - Joining two edges of sheet metal by hemming
Flanging Operations

- **Flanging**
  - Process of bending the edge of a sheet
  - Figure (a)

- **Dimpling**
  - A hole is punched and then expanded into the flange
  - Figure (b)

**Figure 16.25 Various flanging operations.**

(a) Flanges on a flat sheet.
(b) Dimpling.
(c) The piercing of sheet metal to form a flange. In this operation, a hole does not have to be pre-punched before the punch descends. Note, however, the rough edges along the circumference of the flange.
(d) The flanging of a tube. Note the thinning of the edges of the flange.
Roll-Forming Process

- Roll Forming
  - Also called contour roll forming, cold roll forming
  - Metal is bent in stages by passing it through a series of rolls
  - Used to make
    - Gutters, door and picture frames, pipes and tubing with lock seams
Tube bending and forming

- How do you avoid the tube from buckling when you bend it?
  - Pack the inside with loose particles (sand) before bending.
  - Sand is shaken out after bend has been completed.
- Thick walls with a large bend radius can be bent without filling.
Bulging

- Place a tubular, conical, curvilinear part (plug) into a split female die
- Expand the plug
  - Commonly polyurethane plug
- Retract the plug
- Open the die and remove the plug
- Used in making
  - Coffee / water pitchers
  - Barrels
- Internal fluid pressure
  - Replaces the plug
  - Ends are sealed mechanically
  - Exhaust pipes
Segmented dies

- Individual segments are placed inside the tube
- Expanded in the radial direction
- Retracted
- Sheet metal is clamped along its edges then stretched over a die.
- Used in making wing-skin panels for aircrafts.
- Material will shrink in width as it is stretched.
- Disadvantage:
  - Can’t produce parts with sharp corners
  - Re-entrant corners
- Advantages:
  - Little (or no) lubrication is necessary
  - Versatile
  - Economical
- Used for low production runs.
Deep drawing can be used to make cylindrical and box shaped parts using deep drawing
- Kitchen sinks

Process
- A sheet metal blank is placed over a die opening and is held in place with a blank holder (hold-down ring)
- A punch forces the blank into the cavity
  - Forming a cup
- Cup wall may be subjected to a tensile stress in order to elongate the wall

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

- Important variables
  - Sheet metal properties
  - Blank diameter / punch diameter
  - Clearance
  - Punch radius
  - Die corner radius
  - Blank holder force
  - Friction
  - Lubrication

- Deep drawability
  - Failure typically occurs from thinning of the cup walls under high tensile stresses
  - Tensile tests are performed to determine the deep drawability of the material

- Earing
  - Edges of the cups may be wavy called earing

- Due to anisotropy of the material
  - 2, 4, 8 ears
Drawbeads

- Controls the flow of the blank into the cavity

Ironing

- Ensuring the wall thickness is constant
- Cup is pushed through ironing rings
<table>
<thead>
<tr>
<th>Process</th>
<th>Process illustration</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Blanking</td>
<td><img src="image1" alt="Blanking Diagram" /></td>
<td><img src="image2" alt="Blanking Result" /></td>
</tr>
<tr>
<td>2. Deep drawing</td>
<td><img src="image3" alt="Deep Drawing Diagram" /></td>
<td><img src="image4" alt="Deep Drawing Result" /></td>
</tr>
<tr>
<td>3. Redrawing</td>
<td><img src="image5" alt="Redrawing Diagram" /></td>
<td><img src="image6" alt="Redrawing Result" /></td>
</tr>
<tr>
<td>4. Ironing</td>
<td><img src="image7" alt="Ironing Diagram" /></td>
<td><img src="image8" alt="Ironing Result" /></td>
</tr>
<tr>
<td>5. Domeing</td>
<td><img src="image9" alt="Domeing Diagram" /></td>
<td><img src="image10" alt="Domeing Result" /></td>
</tr>
<tr>
<td>6. Necking</td>
<td><img src="image11" alt="Necking Diagram" /></td>
<td><img src="image12" alt="Necking Result" /></td>
</tr>
<tr>
<td>7. Seaming</td>
<td><img src="image13" alt="Seaming Diagram" /></td>
<td><img src="image14" alt="Seaming Result" /></td>
</tr>
</tbody>
</table>

**Can Manufacture**
Aluminum Beverage Cans

(a)

(b)

- Scored region
- Integral rivet
- Pop-top cantilever
Figure 16.37 An embossing operation with two dies. Letters, numbers, and designs on sheet-metal parts can be produced by this process.
Rubber Forming

- One of the dies in a set are made of a flexible material (polyurethane)
- Female die is replaced with a rubber pad
  - Protects the outer surface of the sheet from scratches
Hydroform Process

- Also called fluid-forming process
  - Pressure over the rubber membrane is controlled by a fluid
  - Close control of the part during forming
  - Deeper draws can be obtained with the hydroform process than with conventional deep drawing techniques
    - since the pressure around the rubber membrane aids in reducing the longitudinal tensile stresses in the sheet
Tube-Hydroforming

Diagram showing components of a hydroforming process:
- Top die
- Bottom die
- Seal punch
- Slide plate
- Centering
- Die holder plate
- Horizontal cylinder
- Cylinder holder bracket
- Bed plate
- Hydroformed part

Image (b) showing a hydroformed part.
Forming of axisymmetric parts over a mandrel

- **Conventional**
  - Sheet metal is held against the mandrel and rotated
  - Conical and curvilinear shapes

- **Shear**
  - Rollers are used during the forming process
  - Conical or curvilinear shapes
  - Max diameter is maintained
  - Thickness is reduced

- **Tube spinning**
  - Thickness is reduced resulting in thinner tubes
Dent Resistance

- Dynamic forces causes localized dents
- Static forces spreads the dent
- Dent resistance
  - Increases with
    - Increased yield strength
    - Increased thickness
  - Decreases with
    - Increased elastic modulus
Structures Made by Diffusion Bonding and Superplastic Forming of Sheet Metals

Before

After

Product

Stop-off

Clamp

Stop-off (no bonding)

Mold

(a)

(b)
Explosive Forming

(a) Diagram showing the components of an explosive forming process:
- Explosive
- Water level
- Standoff
- Hold-down ring
- Die
- Vacuum line
- Tank

(b) Diagram showing the setup:
- Cartridge
- Forming die
- Workpiece (tube)
Magnetic-Pulse Forming Process

(a) Diagram showing the process with labels:
- After forming
- Mandrel
- Before
- Coil
- *Coil current
- • Eddy current
- Tube

(b) Image of the formed object.
Manufacturing Honeycomb Structures

(a) Roll → Sheet → Block → Expanded panel

(b) Roll → Corrugating rolls → Corrugated sheet → Corrugated block

(c) Adhesive-impregnated scrim cloth (optional) → Expanded honeycomb core → Face sheet
Efficient Part Nesting for Optimum Material Utilization

Poor

Better

43.2 mm

13.2 mm

39.6 mm

11.4 mm
Control of Defects in a Flange

(a)

- Poor: Closed corner
- Better: 3 & 3 sheet thickness
- Best: Relief notch

(b)

- Closed corner
- 3 & 3 sheet thickness
- Relief notch
Application of Notches

(a) Poor: Tearing, Good: Notch

(b) Poor, Good

(c) Poor, Good: Notch
Thank you