Deformation Process

• Permanent (plastic) deformation of a material under tension, compression, shear or a combination of loads.

• Types of Deformation
  – Bulk flow in (3) dimensions
  – Simple shearing of material
  – Compound to simple bending
  – Combination of above
Deformation Process

- Stresses used to produce change
  - Tension
  - Compression
  - Shear
  - Combination in multiple axis

- (2) Classifications
  - Bulk = Significant change in surface area, thickness and cross section reduced, and overall geometry changed.
  - Sheet = Some deforming of material, but initial material thickness remains the same
### TABLE 15-2 Classification of Some Forming Operations

<table>
<thead>
<tr>
<th>Process</th>
<th>Schematic Diagram</th>
<th>State of Stress in Main Part During Forming $^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rolling</td>
<td><img src="image" alt="Rolling Diagram" /></td>
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<td>Forging</td>
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<td>Extrusion</td>
<td><img src="image" alt="Extrusion Diagram" /></td>
<td>9</td>
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<tr>
<td>Shear spinning</td>
<td><img src="image" alt="Shear Spinning Diagram" /></td>
<td>12</td>
</tr>
</tbody>
</table>
Deformation Process

Tube spinning

Swaging or kneading

Deep drawing

Wire and tube drawing

In flange of blank, 5
In wall of cup, 1
Deformation Process

- Stretching
- Straight bending
- Contoured flanging

(a) Convex
At bend, 2 and 7
At outer flange, 6
At bend, 2 and 7

(a) Concave
At bend, 2 and 7
At outer flange, 1
At bend, 2 and 7

*Numbers correspond to those in parentheses in Table 15-1.*
Work Ranges

- Types of mechanical work where material undergoes plastic deformation
  - Hot Working (HW)
  - Cold Working (CW)
Definition of HW vs. CW

- HW is performed above the recrystallization temp of the material and CW is done below the recrystallization temp of the material.
- Recrystallization Temp: “The approximate minimum temp at which complete recrystallization of a cold worked metal occurs within a specified time.”
Hot Working

• When HW a metal is in a plastic state and is easily formed. The forces required to deform the metal are less than CW. Some mechanical properties of the metal are improved due to process characteristics.

• At elevated temperatures, metal microstructures are rebuilding continually through the recrystallization process which allows for much higher deformation.
Advantages to HW

• Porosity in metal is largely eliminated
• Impurities (inclusions) are broken up and distributed through the metal
• Coarse grains are refined
• Due to grain refinement, the physical properties are generally improved
  • Ductility and resistance to impact are improved
  • Strength is increased
Advantages to HW

**Figure 15-3** Cross section of a 4-in.-diameter case copper bar polished and etched to show the as-cast grain structure.

**Figure 15-4** Flow structure of a hot-forged gear blank. Note how flow is parallel to all critical surfaces. (*Courtesy of Bethlehem Steel Corporation, Bethlehem, PA.*)
Advantages to HW

• Amount of energy necessary to change the shape of the raw material in a plastic state is far less than if the material was “cold.”

• Economical compared to CW
Disadvantages to HW

• High working temp. can result in rapid oxidation/scaling of surface = poor surface finish
• Generally, close tolerances are hard to control
• Equipment and tool maintenance costs are high
Primary HW Processes

- Rolling
- Forging
- Extrusion
- Pipe & tube manufacturing
- Drawing
Introduction

Practically all metals, which are not used in cast form are reduced to some standard shapes for subsequent processing.

- Manufacturing companies producing metals supply metals in form of ingots which are obtained by casting liquid metal into a square cross section.
  - Slab (500-1800 mm wide and 50-300 mm thick)
  - Billets (40 to 150 sq mm)
  - Blooms (150 to 400 sq mm)

Sometimes continuous casting methods are also used to cast the liquid metal into slabs, billets or blooms.

- These shapes are further processed through hot rolling, forging or extrusion, to produce materials in standard form such as plates, sheets, rods, tubes and structural sections.
Sequence of operations for obtaining different shapes

Ingot → Hot rolling → Billet → Hot rolling → Blooms → Hot rolling → Structural sections

Slab → Hot rolling → Plates Sheets

Cold rolling → Plates Sheets

Bars → Drawing → Bars Wires

Rods →
Primary Metal Forming Processes

- Rolling
- Forging
- Extrusion
- Tube and wire drawing
- and Deep drawing
- Although Punching and Blanking operations are not metal forming processes however these will be covered due to similarity with deep drawing process.
Rolling
Diagram of rolling process

- $v_r$: Roll speed
- $R$: Roll radius
- $p$: Roll pressure
- $t_o$: Thickness before rolling
- $t_f$: Thickness after rolling

$\theta$: Angle

$L$: Contact length
• $P \sin \alpha = P \mu \cos \alpha$

• $\mu = \tan \alpha \Rightarrow \alpha = \tan^{-1} \mu$

Where $\alpha =$ angle of contact or bite
$\mu =$ coefficient of friction between the metal and roll surfaces

If $\alpha > \tan^{-1} \mu$, metal would not enter b/w rolls automatically
Change in grains structure in rolling
Salient points about rolling

- Rolling is the most extensively used metal forming process and its share is roughly 90%.
- The material to be rolled is drawn by means of friction into the two revolving roll gap.
- The compressive forces applied by the rolls reduce the thickness of the material or changes its cross sectional area.
- The geometry of the product depend on the contour of the roll gap.
- Roll materials are cast iron, cast steel and forged steel because of high strength and wear resistance requirements.
- Hot rolls are generally rough so that they can bite the work, and cold rolls are ground and polished for good finish.
In rolling the crystals get elongated in the rolling direction. In cold rolling crystal more or less retain the elongated shape but in hot rolling they start reforming after coming out from the deformation zone.

The peripheral velocity of rolls at entry exceeds that of the strip, which is dragged in if the interface friction is high enough. $v_0 > v_r$ (Lagging zone)

In the deformation zone the thickness of the strip gets reduced and it elongates. This increases the linear speed of the at the exit. $v_r < v_1$ (Leading zone)

Thus there exist a neutral point where roll speed and strip speeds are equal. At this point the direction of the friction reverses. (Neutral zone)

When the angle of contact $\alpha$ exceeds the friction angle $\lambda$ the rolls cannot draw fresh strip

Roll torque, power etc. increase with increase in roll work contact length or roll radius
Roll passes to get a 12 mm rod from 100 x 100 mm billet
Roll configurations in rolling mills

- Two-high and three-high mills are generally used for initial and intermediate passes during hot rolling, while four-high and cluster mills are used for final passes.
- Last two arrangements are preferred for cold rolling because roll in these configurations are supported by back-up rolls which minimize the deflections and produce better tolerances.
Various Roll Configurations (a) Two-high (b) Three-high (c) Four-high (d) Cluster mill (e) Tandem mill
Other deformation processes related to rolling

(1) Starting blank
(2) Finished part

(1) Fixed die
Moving die

(1) Idler roll
Edging rolls

(2) Main roll
Feed

(2) Rolls
Mandrel

(b) Starting cylinder
Finished tube
Defects in Rolling

Schematic illustration of typical defects in flat rolling: (a) wavy edges; (b) zipper cracks in the center of the strip; (c) edge cracks; and (d) alligatoring.
Forging

Forging is perhaps oldest metal working process and was known even during prehistoric days when metallic tools were made by heating and hammering.

Forging is basically involves plastic deformation of material between two dies to achieve desired configuration. Depending upon complexity of the part forging is carried out as open die forging and closed die forging.

In open die forging, the metal is compressed by repeated blows by a mechanical hammer and shape is manipulated manually.

In closed die forging, the desired configuration is obtained by squeezing the workpiece between two shaped and closed dies.
• On squeezing the die cavity gets completely filled and excess material comes out around the periphery of the die as flash which is later trimmed.
• Press forging and drop forging are two popular methods in closed die forging.
• In press forging the metal is squeezed slowly by a hydraulic or mechanical press and component is produced in a single closing of die, hence the dimensional accuracy is much better than drop forging.
• Both open and closed die forging processes are carried out in hot as well as in cold state.
• In forging favorable grain orientation of metal is obtained
Open and closed die forging
Grain orientation in forging

Forging

Machining
Flash less forging or precision forging
Forging

- Process disadvantages:
  - Possible scale inclusions in forging
  - Tooling cost can be high
  - Usually not used for short production runs
Forging Methods

- Open-Die Drop Hammer - heated metal is placed between dies—a force is delivered with a steam hammer.
  - Accuracy is not good
  - Complicated shapes are difficult to produce
Forging Methods

Open-Die Drop Hammer - Steam Hammer

1. Preform mounted on saddle/mandrel.
2. Metal displacement - reduce preform wall thickness to increase diameter.
3. Progressive reduction of wall thickness to produce ring dimensions.
4. Machining to near net shape.
Forging Methods
Forging Methods

• Upset forging
  – Grip a bar—heat the end—forge into desired shape
  • Product examples
    – Bolts
    – Engine valves
Forging Methods

• Impression Die Drop Hammer Forging - Hot pliable metal is forces into the shape of closed impression dies. This process is typically performed in a progressive method through a series of dies to control the flow.
  - 2 Types of drop forge hammers
    • Steam
    • Gravity
Forging Methods

**Impression Die Drop Hammer Forging**
Forging Methods

Figure 16-12
Impression drop forging dies and the product resulting from each impression. The flash is trimmed from the finished connecting rod in a separate trimming die. The sectional view shows the grain flow resulting from the forging process. (Courtesy of Forging Industry Association, Cleveland, OH.)
Forging Methods

• Press Forging
  – Large….thick work
  – Slow Squeezing action penetrates entire work piece producing uniform deformation
  – Dies are typically heated to:
    • Assist surface flow
    • Reduce surface heat loss
    • Assist in obtaining close tolerances and surface finish
  – Two types of presses -- mechanical and hydraulic
Forging Methods

• Press Forging
Defects in forging

(a) Blocked forging

(b) Forging begins

Examples of defects in forged parts. (a) Laps formed by web buckling during forging; web thickness should be increased to avoid this problem. (b) Internal defects caused by oversized billet; die cavities are filled prematurely, and the material at the center flows past the filled regions as the dies close.
Extrusion

- It is a relatively new process and its commercial exploitation started early in the nineteenth century with the extrusion of lead pipes. Extrusion of steels became possible only after 1930 when extrusion chambers could be designed to withstand high temperature and pressure.

- In extrusion, the material is compressed in a chamber and the deformed material is forced to flow through the die. The die opening corresponds to the cross section of the required product.

- It is basically a hot working process, however, for softer materials cold extrusion is also performed.
Extruded product examples
Direct and Indirect Extrusion

In direct extrusion metal flows in the same direction as that of the ram. Because of the relative motion between the heated billet and the chamber walls, friction is severe and is reduced by using molten glass as a lubricant in case of steels at higher temperatures. At lower temperatures, oils with graphite powder is used for lubrication.

In indirect extrusion process metal flows in the opposite direction of the ram. It is more efficient since it reduces friction losses considerably. The process, however, is not used extensively because it restricts the length of the extruded component.
Impact Extrusion

It is similar to indirect extrusion. Here the punch descends rapidly on to the blank which gets indirectly extruded on to the punch and to give a tubular section. The length of the tube formed is controlled by the amount of metal in the slug or by the blank thickness. Collapsible tubes for pastes are extruded by this method.
Hydrostatic Extrusion

In this process the friction between container wall and billet is eliminated, however, this process has got limited applications in industry due to specialized equipment & tooling and low production rate due to high set up time.
Defects in extrusion

- Surface cracking
- Piping
- Internal cracking
Drawing

- Large quantities of wires, rods, tubes and other sections are produced by drawing process which is basically a cold working process. In this process the material is pulled through a die in order to reduce it to the desired shape and size.

- In a typical wire drawing operation, once end of the wire is reduced and passed through the opening of the die, gripped and pulled to reduce its diameter.
• By successive drawing operation through dies of reducing diameter the wire can be reduced to a very small diameter.
• Annealing before each drawing operation permits large area reduction.
• Tungsten Carbide dies are used to for drawing hard wires, and diamond dies is the choice for fine wires.
Tube drawing

- Tube drawing is also similar to wire drawing, except that a mandrel of appropriate diameter is required to form the internal hole.
- Here two arrangements are shown in figure (a) with a floating plug and (b) with a moving mandrel.
- The process reduces the diameter and thickness of the tube.
## Comparison of metal forming processes

<table>
<thead>
<tr>
<th>Metal Forming Process</th>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open-die forging</td>
<td>• Inexpensive tooling and equipment.</td>
<td>• Can be used for simple shapes only.</td>
</tr>
<tr>
<td></td>
<td>• Simple to operate.</td>
<td>• Fairly skilled operators are required.</td>
</tr>
<tr>
<td></td>
<td>• Wide range of workpiece sizes can be used.</td>
<td>• Production rate is low.</td>
</tr>
<tr>
<td></td>
<td>• Suitable for low production volume.</td>
<td>• Dimensional accuracy and surface finish achieved are poorer.</td>
</tr>
<tr>
<td>Closed-die forging</td>
<td>• Suitable for high production rate.</td>
<td>• Finishing required for achieving final shape.</td>
</tr>
<tr>
<td></td>
<td>• Can be used for production of complex shapes.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Good dimensional accuracy and reproducibility</td>
<td></td>
</tr>
<tr>
<td>Hot rolling</td>
<td>• High production rate.</td>
<td>• High equipment and tooling cost.</td>
</tr>
<tr>
<td></td>
<td>• Suitable for large reduction.</td>
<td>• Appropriate die set for production of each component.</td>
</tr>
<tr>
<td></td>
<td>• Wide range of shapes (Billets, blooms, slabs, sheets, bars, tubes, structural sections, etc.) can be produced</td>
<td>• More than one step required for each forging.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Finishing required for achieving final shape.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• High equipment cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Suitable for production of large sections.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Poor dimensional accuracy and finish.</td>
</tr>
<tr>
<td>Metal Forming Process</td>
<td>Advantages</td>
<td>Limitations</td>
</tr>
<tr>
<td>-----------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Cold rolling</td>
<td>• High production rate.</td>
<td>• High equipment cost.</td>
</tr>
<tr>
<td></td>
<td>• Suitable for production of plates, sheets, foils, etc.</td>
<td>• Deformation limited to small reductions.</td>
</tr>
<tr>
<td></td>
<td>• Good dimensional accuracy and finish.</td>
<td></td>
</tr>
<tr>
<td>Hot extrusion</td>
<td>• Moderate cost of equipment and toolings.</td>
<td>• Only constant cross-section can be produced.</td>
</tr>
<tr>
<td></td>
<td>• Suitable for large reduction.</td>
<td>• Components with thin walls are difficult to produce.</td>
</tr>
<tr>
<td></td>
<td>• Complex sections and long products can be produced.</td>
<td>• Lubrication is necessary.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Dimensional accuracy and finish achieved are not good.</td>
</tr>
<tr>
<td>Impact extrusion</td>
<td>• High production rate.</td>
<td>• Suitable for production of light components from softer materials.</td>
</tr>
<tr>
<td></td>
<td>• Good finish and dimensional accuracy.</td>
<td>• Deformation limited to small reductions.</td>
</tr>
<tr>
<td></td>
<td>• Generally no finishing is required.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Suitable for production of thin sections.</td>
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</tr>
<tr>
<td>Metal Forming Process</td>
<td>Advantages</td>
<td>Limitations</td>
</tr>
<tr>
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</tr>
</tbody>
</table>
| **Drawing**           | - Low equipment and tooling cost.  
- Good surface finish and dimensional accuracy.  
- High production rate.  
- Long lengths of rounds, tubings, square, angles, etc. can be produced. | - Deformation limited to small reductions.  
- Production of constant cross-sections only.  
- Lubrication is necessary. |
| **Deep drawing**      | - High production rate.  
- Moderate equipment and tooling cost.  
- Good surface finish. | - Limited to forming of thin sheets.  
- Forming of shallow or deep parts of simple shapes only.  
- Finishing required |
| **Punching and blanking** | - High production rate.  
- Low cost of labour.  
- Almost any shape can be obtained.  
- Moderate equipment cost. | - Limited to thin sheet applications.  
- Cost of tooling can be high. |