IE 309 Manufacturing Processes I
Bulk Forming Processes

Dr. Adnan Kefal
Faculty of Engineering and Natural Sciences
Sabanci University
adnankefal@sabanciuniv.edu
Spatial work pieces
Large changes in cross-section/thickness
Material flows in all directions
Generally multi-axial compressive stress states
Larger relative forces

Planar work pieces (sheets, plates)
Hollow pieces with almost constant thickness
Generally two-axial stress states: tensile-tensile or tensile-compressive
Bulk Deformation

**Bulk Forming Processes**

- **Steady-state Processes**
  - Deformation patterns are independent of time
  - All parts of the workpiece are subjected to same mode of deformation
  - Example: Extrusion, rolling, drawing

- **Non-steady-state Processes**
  - Deformation patterns are dependent of time
  - Geometry of the part changes continually
  - Example: Upsetting, forging, extrusion
<table>
<thead>
<tr>
<th>Process</th>
<th>General Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forging</td>
<td>Production of discrete parts with a set of dies; some finishing operations usually necessary; similar parts can be made by casting and powder-metallurgy techniques; usually performed at elevated temperatures; dies and equipment costs are high; moderate to high labor costs; moderate to high operator skill.</td>
</tr>
<tr>
<td>Rolling</td>
<td></td>
</tr>
<tr>
<td>Flat</td>
<td>Production of flat plate, sheet, and foil at high speeds, and with good surface finish, especially in cold rolling; requires very high capital investment; low to moderate labor cost.</td>
</tr>
<tr>
<td>Shape</td>
<td>Production of various structural shapes, such as I-beams and rails, at high speeds; includes thread and ring rolling; requires shaped rolls and expensive equipment; low to moderate labor cost; moderate operator skill.</td>
</tr>
<tr>
<td>Extrusion</td>
<td>Production of long lengths of solid or hollow products with constant cross-sections, usually performed at elevated temperatures; product is then cut to desired lengths; can be competitive with roll forming; cold extrusion has similarities to forging and is used to make discrete products; moderate to high die and equipment cost; low to moderate labor cost; low to moderate operator skill.</td>
</tr>
<tr>
<td>Drawing</td>
<td>Production of long rod, wire, and tubing, with round or various cross-sections; smaller cross-sections than extrusions; good surface finish; low to moderate die, equipment and labor costs; low to moderate operator skill.</td>
</tr>
<tr>
<td>Swaging</td>
<td>Radial forging of discrete or long parts with various internal and external shapes; generally carried out at room temperature; low to moderate operator skill.</td>
</tr>
</tbody>
</table>
Bulk Deformation Processes

ROLLING
- Flat
- Shape
- Ring
- Tube

DRAWING
- Wire, bar
- Tube

EXTRUSION
- Solids
- Tube

FORGING
- Open die
- Impression die
- Closed die

Steady state
Non steady state

Hot and cold
Primary and secondary
Large and small scale
Forging process is where workpiece is shaped by compressive forces applied through dies and tooling

Oldest metal forming process

Forging operations produce discrete parts

Forged parts have good strength and toughness, and are reliable for highly stressed and critical applications

Forging can carry out at room temperature (cold forging) or at elevated temperatures (warm or hot forging) depending on the homologous temperature

Types of forging

- Open-die forging (upsetting)
- Closed-die forging
- Impression-die forging
Open-die forging is where a solid workpiece is placed between two flat dies and reduced in height by compressing it.

Also called upsetting or flat die forging.

Workpiece is deformed uniformly under frictionless conditions.

Increases the diameter of a material by compressing its length.

Both cold and hot upsetting.
Impression-die Forging

Workpiece acquires the shape of the die cavity while deformed between the closing dies.

Quality, dimensional tolerances, and surface finish of forging depend on operations performance and control.

\[ F = K_p Y_f A \]

**Range of \( K_p \) Values in Eq. (6.22) for Impression-Die Forging**

- Simple shapes, without flash: 3–5
- Simple shapes, with flash: 5–8
- Complex shapes, with flash: 8–12

*Load-stroke Curve*
## Comparison of Forging Processes

Open-die forging is the simplest forging operation

<table>
<thead>
<tr>
<th>General Characteristics of Forging Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Process</strong></td>
</tr>
<tr>
<td>Open die</td>
</tr>
<tr>
<td>Closed die</td>
</tr>
<tr>
<td>Blocker</td>
</tr>
<tr>
<td>Conventional</td>
</tr>
<tr>
<td>Precision</td>
</tr>
</tbody>
</table>
Grain Flow

Grain flow lines in upsetting a solid, steel cylindrical specimen at elevated temperatures between two flat cool dies. Note the highly inhomogeneous deformation and barreling, and the difference in shape of the bottom and top sections of the specimen. The latter results from the hot specimen resting on the lower die before deformation proceeds. The lower portion of the specimen began to cool, thus exhibiting higher strength and hence deforming less than the top surface.

Schematic illustration of grid deformation in upsetting: (a) original grid pattern; (b) after deformation, without friction; (c) after deformation, with friction. Such deformation patterns can be used to calculate the strains within a deforming body.
Relevance of forming forces:
• To design the tools (tool pressures, stresses)
• To select the appropriate forming press
• To evaluate the elastic deformations in the forming system

Maximum possible frictional shear stress is \( \tau_{\text{yield}} \)

\[
\tau_{\text{yield}} = \frac{1}{2} Y \ (\text{Tresca})
\]

\[
\tau_{\text{yield}} = \frac{1}{\sqrt{3}} Y \ (\text{von Mises})
\]

Methods of Force Computation
• Empirical
• Experimental
• Analytical
• Numerical

\textbf{Coulomb Model:}

\[
F_{\text{friction}} = \mu \cdot F_{\text{normal}}
\]

\[
\tau_{\text{friction}} = \mu \cdot \sigma_{\text{normal}}
\]

Friction coefficient \( \mu \) is

\[0 \leq \mu \leq 0.5 \ (0.577)\]

Best suited for \textit{cold forming}. 
Friction in Metal Forming

Metal working lubricants are used to prevent die/workpiece adhesion, control surface finish, prevent heat loss in hot working.
Mean Flow Stress

Flow stress is defined as the stress needed to maintain plastic deformation at the temperature, strain, and strain-rates prevailing in the process.

For non-steady state processes (like forging), instantaneous flow stress at the end of deformation is utilized in the computations.

For steady state processes (such as rolling and extrusion) mean flow stress is often-times employed.

Average value of the flow stress in cold-forming

\[
\sigma_{fm} = \frac{1}{\varepsilon_{eq}} \int_{0}^{\varepsilon_{eq}} K \varepsilon^n d\varepsilon = \frac{K \varepsilon_{eq}^n}{n + 1}
\]
**Equilibrium**

\[ \sum F_x = 0 \]

\[ \sigma_x h - (\sigma_x + d\sigma_x)h - 2\mu\sigma_y dx = 0 \]

\[ d\sigma_x + \frac{2\mu\sigma_y}{h} dx = 0 \]

**Distortion-energy criterion for plane strain**

\[ \sigma_y - \sigma_x = \frac{2}{\sqrt{3}} Y = \bar{Y} \rightarrow d\sigma_y = d\sigma_x \]

\[ \int \frac{1}{\sigma_y} d\sigma_y = -\frac{2\mu}{h} \int dx \rightarrow \sigma_y(x) = Ce^{\frac{2\mu x}{h}} \]

**Boundary conditions**

\[ x = a, \sigma_x = 0 \]

\[ \sigma_y = Ce^{\frac{-2\mu a}{h}} = \bar{Y} \]

\[ \sigma_y = C = \bar{Y} e^{\frac{2\mu a}{h}} \]

**Resulting die pressure**

\[ \sigma_y(x) = \bar{Y} e^{\frac{2\mu (a-x)}{h}} \]
The pressure at $x=0$ \[ \sigma_y = \bar{Y} e^{2\mu a/h} \]

The pressure at $x=a$ \[ \sigma_y = \bar{Y} \]

The average interface pressure

\[ \sigma_{av} = \frac{1}{a} \int_0^a \sigma_y(x) dx = \frac{\bar{Y}}{a} \int_0^a e^{2\mu(a-x)/h} dx \]

\[ \sigma_{av} = \frac{\bar{Y} - h}{a} e^{2\mu(a-x)/h} \bigg|_0^a = \frac{\bar{Y}h}{2\mu a} \left( e^{2\mu a/h} - 1 \right) \]

Taylor series expansion of $e^x$ including the quadratic term yields

\[ e^{2\mu a/h} \approx 1 + \frac{2\mu a}{h} + \frac{2\mu^2 a^2}{h^2} \]

\[ \sigma_{av} = \bar{Y} \left( 1 + \mu \frac{a}{h} \right) \]
Slab Analysis of Forging

Resulting die pressure for axisymmetric forging

\[
\sigma_z (r) = \bar{Ye}^{2\mu(R-r)/h}
\]

The average interface pressure

\[
\sigma_{av} = \frac{1}{\pi R^2} \int_0^R \sigma_z (r) 2\pi rdr
\]

\[
\sigma_{av} = \bar{Y} \left( \frac{h}{2\mu R} \right)^2 \left( e^{2\mu R/h} - \frac{2\mu R}{h} - 1 \right)
\]

Taylor series expansion of \( e^{\mu x} \) including the cubic term yields

\[
e^{2\mu R/h} \approx 1 + \frac{2\mu R}{h} + \frac{2\mu^2 R^2}{h^2} + \frac{4\mu^3 R^3}{3h^3}
\]

\[
\sigma_{av} = \bar{Y} \left( 1 + \frac{2\mu R}{3h} \right)
\]
Various Forging Operations

Coining

A closed-die forging process used in the minting of coins, medallions and jewellery

Marking parts with letters and numbers can be done rapidly through coining
Various Forging Operations

Examples of piercing operations.

Forming the heads of fasteners, such as bolts and rivets, by the *heading* process.
Various Forging Operations

(a)  
(b)  
(c)  

Die  
Workpiece  
Die  
Workpiece  
Die

---

[Images of forging operations and examples of forged parts]
Forging Process

1. Blank (bar stock)
2. Edging
3. Blocking
4. Finishing
5. Trimming

Stages in forging a connecting rod for an internal combustion engine. Note the amount of flash developed, which is important in properly filling die cavities.

Standard terminology for various features of a typical forging die.
Forging Press

Schematic illustration of various types of presses used in metalworking. The choice of a press is an important consideration in the overall operation and productivity.

8,000 ton Forging Press (9,200 kN)
Forming Economics
Forging Defects

Web buckle and laps

Internal cracks
- Excess material flows over already forged portions

Grain flow pattern
- Grain flow line reach surface perpendicularly

Anisotropic properties
- Metal flow in various directions
- Temperature variation within the forging
- Ductility varies in different locations and along different directions
Rolling

The process of reducing thickness or changing cross-section of a long workpiece by compressive forces applied through a set of rolls.

Often the first process that is used to convert material into a finished wrought product

Thick stock can be rolled into blooms, billets, or slabs
  • Blooms have a square or rectangular cross section (>36 sq. in.)
  • Billets are usually smaller than a bloom and can have a square or circular cross section
    ➤ Can be further rolled into structural shapes
  • Slabs are a rectangular solid with a width greater than twice the thickness
    ➤ Can be used to produce plates, sheets, or strips

Rolling accounts for 90% of all metals produced by metalworking
Different Rolling Operations

Classification by Die (Roll) Geometry
- Flat rolling
- Shape rolling

Kinematic Classification
- Longitudinal Rolling
- Transverse Rolling
- Oblique Rolling
Two illustrations of roll forging (*cross-rolling*) operations. Tapered leaf springs and knives can be made by this process using specially designed rolls.
Oblique Rolling

(a) Production of steel balls for bearings by skew rolling.  (b) Production of steel balls by upsetting of a short cylindrical blank; note the formation of flash. The balls are subsequently ground and polished to be used as ball bearings and similar components.
Flat Rolling

The process of reducing the thickness of a slab to produce a thinner and longer but only slightly wider product is referred to as flat rolling.

- Primary forming process.
- Hot rolling (not tight tolerances)
- Cold rolling (tight tolerances)
- Normal anisotropy is induced in the sheet or band

Changes in the grain structure of metals during hot rolling. This is an effective method to reduce grain size and refine the microstructure in metals, resulting in improved strength and good ductility. In this process cast structures of ingots or continuous castings are converted to a wrought structure.
Initial rolling steps (breaking down) of the material is done by hot rolling

A cast structure is dendritic and is brittle and porous

Hot rolling converts the cast structure to a wrought structure with finer grains and enhanced ductility

Product of the first hot-rolling operation is called a bloom, a slab, or a billet

To improve flatness, the rolled strip goes through a series of leveling rolls
Spreading

Increase in width is called spreading

Spreading increases with:
• Decreasing width-to-thickness ratio of the entering strip
• Increasing friction
• Decreasing ratio of the roll radius to the strip thickness
Roll Configuration

(a) 2-high mill;
(b) 3-high mill;
(c) 4-high mill;
(d) tandem rolling, with three stands;
(e) planetary mill
(f) cluster
Straight and long structural shapes are formed at elevated temperatures by shape rolling.
Ring Rolling

A thick ring is expanded into a large-diameter thinner one

Thickness is reduced by bringing the rolls closer together as they rotate

Short production times, material savings and close dimensional tolerances
Thread rolling is a cold-forming process by which straight or tapered threads are formed on round rods or wire. Threads are formed with rotary dies at high production rates.
Thread rolling process has the advantages of generating threads with good strength without any loss of material.

Internal thread rolling can be carried out with a fluteless forming tap, produces accurate internal threads with good strength.
Diameter and thickness of pipes and tubing can be reduced by tube rolling, which utilizes shaped rolls.
Also known as the Mannesmann process

It is a hot-working operation for making long, thick-walled seamless pipe and tubing

The round bar is subjected to radial compressive forces while tensile stresses develop at the center of the bar
As the surface speed of the rigid roll is constant, there is relative sliding between the roll and the strip along the arc of contact in the roll gap, $L$

At neutral point or no-slip point, the velocity of the strip is the same as that of the roll

The maximum possible draft is defined as the difference between the initial and final strip thicknesses

From the relationship, higher the friction and the larger the roll radius, the greater the maximum possible draft becomes

\[ h_o - h_f = \mu^2 R \]
Friction is important

Neutral point

- $V_r = V_f$ (no slip point)
- Direction of friction is different across the neutral point
- Desired to be close to exit

Forward slip $= \frac{V_f - V_r}{V_r}$

Relative velocity distribution between roll and strip surfaces. The arrows represent the frictional forces acting along the strip-roll interfaces. Note the difference in their direction in the left and right regions.
Roll Forces

Roll Forces: \( P_r = s_f L w p_{av} \) (sf is the safety factor, 1.15)

High frictional conditions, **average rolling stress**

\[
p_{av} = \bar{Y} \frac{h}{\mu L} \left( e^{\mu L/h_{av}} - 1 \right) \approx \bar{Y} \left( 1 + \frac{\mu L}{2h_{av}} \right)
\]

\[
\bar{Y} = \frac{2}{\sqrt{3}} \sigma_{fm}, \quad h_{av} = \frac{h_o + h_f}{2}
\]

L is the length of contact \( L = \sqrt{R(h_o - h_f)} \)

**Cold mean flow stress**

\[
\sigma_{fm} = \frac{K \varepsilon_{eq}^n}{n+1}, \quad \varepsilon_{eq} = \ln \left( \frac{h_o}{h_f} \right)
\]
Remark: The torque is obtained from the normal forces alone since frictional forces can be considered to cancel each other.

Torque per roll:

\[ T = Pr \frac{L}{2} \]

Total Power Requirement:

\[ \text{Power} = 2T \omega_{roll} \]

\[ \omega_{roll} = \frac{v_{roll}}{R} \]
Cold Rolling – $\mu \approx 0.02-0.3$
Hot Rolling – $\mu \approx 0.3-0.7$
Max Possible Draft, $\Delta h_{\text{max}} = \mu^2 R$
Max Angle of Acceptance, $\alpha_{\text{max}} = \tan^{-1}(\mu)$
Roll Bending

Roll forces will bend the rolls elastically during rolling.

When the roll bends, the strip has a constant thickness along its width.

The heat generated by plastic deformation cause the rolls to be slightly barrel shaped (thermal camber).

Roll forces also tend to flatten the rolls elastically.
Defects in Rolled Plates and Sheets

Defects may be present on the surfaces or there may be internal structural defects.

They are undesirable as they compromise surface appearance and adversely affect strength, formability, and other manufacturing characteristics.

Surface defects may be caused by inclusions and impurities in the original cast material.

Wavy edges on sheets are the result of roll bending.

Cracks are due to poor material ductility at the rolling temperature.
Other Characteristics of Rolled Metals

Residual Stresses

Residual stresses develop in rolled plates and sheets due to non-uniform deformation of materials in roll gap.
Other Characteristics of Rolled Metals

Dimensional Tolerances

Thickness tolerances for cold-rolled sheets range from ±0.1~0.35 mm

Flatness tolerances are within ±15 mm/m for cold rolling and ±55 mm/m for hot rolling

Surface Roughness

Cold rolling can produce a very fine surface finish

Cold-rolled sheets products may not require additional finishing operations
Extrusion and drawing is used for continuous manufacture of discrete products from metals and alloys.

In extrusion, large deformations can take place without fracture as the material is under high triaxial compression.

Products made by extrusion are railings for sliding doors and window frames.
Types of Extrusion

Direct Extrusion

Indirect Extrusion

Hydrostatic Extrusion

Impact Extrusion
Cold extrusion is a general term for a combination of operations, such as direct and indirect extrusion and forging.

Used widely for components in automobiles.
Advantages over hot extrusion:

• Improved mechanical properties
• Good control of dimensional tolerances
• Improved surface finish
• Production rates and costs that are competitive
Cold Extrusion

EXAMPLE: Cold-extruded Part

Investigating material flow during the deformation of the slug helps avoid defects

Part is sectioned in the mid-plane, polished and etched to display the grain flow
Cold Extrusion: Impact Extrusion

Similar to indirect extrusion
Cold Extrusion: Hydrostatic Extrusion

Pressure required in the chamber is supplied through an incompressible fluid medium

Brittle materials can be extruded successfully as the hydrostatic pressure increases the ductility of the material
Extrusion Ratio

Also called the reduction ratio, it is defined as

\[ R = \frac{A_0}{A_f} \]

Ao : cross-sectional area of the starting billet

Af : final cross-sectional area of the extruded section

Applies to both direct and indirect extrusion

10 < R < 1000

- Hard steel <20
- Steel ~40
- Pb, Al ~400
Optimum Die Angle
Metal flow pattern in extrusion is important as it influences the quality and mechanical properties of the extruded product.

Types of metal flow in extruding with square dies:

In the dead-metal zones, the metal at the corners essentially is stationary. This situation is similar to the stagnation of fluid flow in channels that have sharp angles or turns.
**Cold Extrusion Mechanics**

**Case 1:** Ideal deformation (perfectly plastic material, no friction)

\[ p = Y \ln(R) \]

For strain hardening materials, replace \( Y \) with average flow stress

\[ F = pA_0 \]

**Case 2:** Ideal force with friction (by slab method)

\[ p = Y \left( 1 + \frac{\tan \alpha}{\mu} \right) \left[ R^{\mu \cot \alpha} - 1 \right] \quad \bar{Y} = \frac{K \varepsilon^n}{n + 1} \]

**Case 3:** Practical empirical formula

\[ p = Y \left( a + b \ln R \right), \ a \approx 0.8, b=1.2-1.5 \]
Metals and alloys do not have ductility at room temperature.

To reduce the forces required, extrusion is carried out at elevated temperatures.

### Typical Extrusion Temperature Ranges for Various Metals and Alloys

<table>
<thead>
<tr>
<th>Material</th>
<th>°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead</td>
<td>200–250</td>
</tr>
<tr>
<td>Aluminum and its alloys</td>
<td>375–475</td>
</tr>
<tr>
<td>Copper and its alloys</td>
<td>650–975</td>
</tr>
<tr>
<td>Steels</td>
<td>875–1300</td>
</tr>
<tr>
<td>Refractory alloys</td>
<td>975–2200</td>
</tr>
</tbody>
</table>
Hot Extrusion

As the billet is hot, it develops an oxide film, unless it is heated in an inert-atmosphere furnace.

Die Design

Die design requires considerable experience.
Hot Extrusion

Die Design

Square dies (shear dies) are used in extruding nonferrous metals.

Tubing is extruded from a solid or hollow billet.
Hot Extrusion

Die Design

Hollow cross sections can be extruded by welding-chamber and using various dies known as a porthole die, spider die, and bridge die.
Die Design

Guidelines for proper die design in extrusion:

- Symmetry of cross section
- Avoidance of sharp corners
- Avoidance of changes in die dimensions

![Diagram of die designs](image)
Lubrication

Lubrication is important as it has effects on
- Material flow during extrusion
- Surface finish and product quality
- Extrusion forces

Glass is an excellent lubricant for steels, stainless steels and high-temperature metals and alloys
EXAMPLE: Manufacture of Aluminum Heat Sinks

Hot extrusion of aluminum is preferred for heat sink applications.

Tooling for hot extrusion can be produced through electrical-discharge machining.
Hot Extrusion Mechanics

Process variables in direct extrusion

- The die angle, reduction in cross section, extrusion speed, billet temperature, and lubrication all affect the extrusion pressure.

Extrusion Force: \[ F = A_0 k \ln(R) \]

R is the extrusion ratio

k is the extrusion constant for varying temperature
Extrusion Defects

Extruded products can develop defects that affect their strength and product quality. Some defects are visible to the naked eye while others can be detected only by some techniques.

**Surface Cracking**

High surface temperatures can cause surface cracking and tearing. Cracks are intergranular caused by hot shortness. Can be avoided by lowering the billet temperature and the extrusion speed.

**Pipe**

Type of metal-flow pattern in extrusion will draw surface oxides and impurities toward the center of the billet. Defect is known as pipe defect, tailpipe, or fishtailing. Reduced by having more uniform flow pattern.
Internal Cracking

Center of the extruded product can develop cracks, called center cracking, center-burst, arrowhead fracture, or chevron cracking.
Extrusion Equipment

Basic equipment for extrusion is a horizontal hydraulic press
The Drawing Process

Cross section of a long rod or wire is reduced by pulling it through a draw die.
Rod or Wire Drawing

Variables in drawing round rod or wire.
The Drawing Process

Drawing of Other Shapes

Selection of reduction sequence is required to reduce internal / external defects and improve surface quality

Wall thickness, diameter or shape of tubes can be reduced further by tube-drawing processes

(a) Die

(b) Stationary mandrel

(c) Floating mandrel

(d) Moving mandrel
Bundle Drawing

Increase productivity by drawing many wires simultaneously as a bundle

Wires are separated by a metallic material with similar properties but lower chemical resistance

Wires are used in electrically conductive plastics, heat-resistant and electrically conductive textiles
Mechanics: Drawing

• Ideal deformation (perfectly plastic material no friction)
  \[ \sigma_d = Y \varepsilon = Y \ln(A_0/A_f) \]
  \[ F = \sigma_d A_f \]

• For strain hardening materials, replace \( Y \) with average flow stress

• Ideal deformation and friction
  \[ \sigma_d = Y (1 + \frac{\tan \alpha}{\mu}) \left[ 1 - \left( \frac{A_f}{A_o} \right) \frac{\mu \cot \alpha}{\Phi} \right] \]

• Friction and redundant work of deformation included

\[ \sigma_d = \Phi Y \left( 1 + \frac{\mu}{\alpha} \right) \ln \left( \frac{A_o}{A_f} \right) \]

\[ \Phi = 1 + 0.12 \left( \frac{h}{L} \right) \]