2.1 Bulk deformation processes
Bulk deformation processes in metal working

Metal forming operations which causes significant shape change by deformation in metal parts whose initial form is bulk rather than sheet.

• Starting forms: cylindrical bars and billets, rectangular billets and slabs, and similar shapes.
• These processes work by stressing metal sufficiently to cause plastic flow into desired shape.
• Performed as cold, warm, and hot working operations.
Importance of bulk deformation

• When performed as hot working operations, they can achieve significant change in the shape of the work part.
• When performed as cold working operations, they can be used not only to shape the product, but also to increase its strength through strain hardening.
• These processes produce little or no waste as a byproduct of the operation. Since bulk deformation operations are near net shape or net shape processes.
Bulk deformation

Types of bulk deformation

1. Rolling; slab or plate is squeezed between opposing rolls
2. Forging: work is squeezed and shaped between opposing dies
3. Extrusion: work is squeezed through a die opening, thereby taking the shape of the opening
4. Wire and bar drawing: diameter of wire or bar is reduced by pulling it through a die opening
Types of bulk deformation

1. Rolling

Deformation process in which the thickness of the work is reduced by compressive forces exerted by two opposing rolls.

Figure 1.1  the rolling process (specifically, flat rolling)
Types of bulk deformation

Rolling

The functions of two rotating rolls:

✓ Pull the work into the gap between them by friction between workpart and rolls
✓ Simultaneously squeeze the work to reduce cross section
Rolling

Types of rolling

- By geometry of work:
  1. flat rolling: used to reduce thickness of a rectangular cross section.
  2. shape rolling: a square cross section is formed into a shape such as an I-beam

- By temperature of work
  1. hot rolling: most common due to the large amount of deformation required
  2. cold rolling: produces finished sheet and plate stock
Rolling

• Steel making provides the most common application of rolling mill operation.

The sequence of steps in steel rolling mill

• The work starts out as a cast steel ingot that has just solidified, while it is still hot, the ingot is placed in a furnace where it remains for many hours until it has reached a uniform temperature throughout, so that the metal will flow consistently during rolling.

• For steel, the desired temperature for rolling is around 1200°C. The heating operation is called soaking, and the furnaces in which it is carried out are called soaking pits.

• From soaking, the ingot is moved to the rolling mill, where it is rolled into one of the three intermediate shape called Blooms, Billets, or Slabs.
Rolling

- A bloom has a square cross section 150 mm × 150 mm or larger.
- A slab is rolled from an ingot or a bloom and has a cross section of width 250 mm or more and thickness 40 mm or more.
- A billet is rolled from a bloom and is square with dimensions 40 mm on a side or larger.
- These intermediate shapes are subsequently rolled into final product shapes.
Rolling

- Blooms are rolled into structural shapes and rails for railroad tracks.
- Billets are rolled into bars and rods. These shapes are the raw materials for machining, wire drawing, forging, and other metal working processes.
- Slabs are rolled into plates, sheets, and strips. Hot-rolled plates are used in shipbuilding, bridges, boilers, welded structures for various heavy machines, tubes and pipes, and many other products.
Figure 1.2: Some of the steel products made in a rolling mill.
Rolling

i. Flat rolling

- It involves the rolling of slabs, stripes, sheets, and plates. In flat rolling, the work is squeezed between two rolls so that its thickness is reduced by an amount called **Draft**.

\[ d = t_o - t_f \]

Where, \( d \) = draft (mm); \( t_o \) = starting thickness (mm);
\( t_f \) = final thickness (mm).

Draft is sometimes expressed as a fraction of the starting stock thickness, called the **reduction** (\( r \)).

\[ r = \frac{d}{t_o} \]
Rolling

Figure 1.3 side view of flat rolling

Roll speed, $v_r$

$R =$ roll radius

$p =$ roll pressure

$L =$ contact length

$\theta$

$t_o$

$t_f$

$v_o$

$v_f$

$v_r$
Flat rolling

- In addition to thickness reduction, rolling usually increases work width. This is called Spreading, and it tends to be most pronounced with low width-to-thickness ratios and low coefficients of friction.
- Conservation of matter is preserved, so the volume of metal exiting the rolls equals the volume entering.

\[ t_0 w_0 L_0 = t_f w_f L_f \]

Where, \( w_0 \) and \( w_f \) are the before and after work widths, mm: and \( L_0 \) and \( L_f \) are before and after work lengths, mm.
Flat rolling

• Similarly, before and after volume rates of material flow must be the same, so the before and after velocities can be related:

\[ t_0 w_0 v_0 = t_f w_f v_f \]

Where, \( v_o \) and \( v_f \) are the entering and exiting velocities of the work.

The rolls contact the work along a contact arc is defined by the angle \( \theta \). Each roll has radius \( R \), and its rotational speed gives it a surface velocity \( v_r \). This velocity is greater than the entering speed of the work \( v_o \) and less than its exiting speed \( v_f \).
Flat rolling

• Since the metal flow is continuous, there is a gradual change in velocity equals roll velocity. This is called the no-slip point, also known as the neutral point. On either side of this point, slipping and friction occur between roll and work.

• The amount of slip between the rolls and the work can be measured by means of the forward slip, a term used in rolling that is defined as:

\[ s = \frac{v_f - v_r}{v_r} \]

Where, \( s \) = forward slip; \( v_f \) = final (exiting) work velocity, m/s; and \( v_r \) = roll speed, m/s
Flat rolling

• The true strain experienced by the work in rolling is based on before and after stock thickness:

\[ \varepsilon = \ln \frac{t_0}{t_f} \]

The true strain can be used to determine the **average flow stress** applied to the work material in flat rolling:

\[ \bar{Y}_f = \frac{K \varepsilon^n}{1 + n} \]
Flat rolling

• Friction in rolling occurs with a certain coefficient of friction, and the compression force of the rolls, multiplied by this coefficient of friction, results in a friction force between the rolls and the work. On the entrance side of the no-slip point, friction force is in one direction, and on the other side it is in the opposite direction. However, the two forces are not equal.

• The friction force on the entrance side is greater, so that the net force pulls the work through the rolls. If this were not the case, rolling would not be possible.
Flat rolling

- There is a limit to the maximum possible draft that can be accomplished in flat rolling with a given coefficient of friction:

\[ d_{max} = \mu^2 R \]

Where, \( d_{max} \) = maximum draft, mm; \( \mu \) = coefficient of friction; and \( R \) = roll radius, mm.

The equation indicates that if friction were zero, draft would be zero, and it would be impossible to accomplish the rolling operation.
Flat rolling

- Coefficient of friction in rolling depends on lubrication, work material, and working temperature. In cold rolling, the value is around 0.1; in warm working, a typical value is around 0.2; and in hot rolling, it is around 0.4.

- Hot rolling is often characterized by a condition called sticking, in which the hot work surface adheres to the rolls over the contact arc. This condition often occurs in the rolling of steels and high-temperature alloys.

- When sticking occurs, the coefficient of friction can be as high as 0.7.

- The consequence of sticking is that the surface layers of the work are restricted to move at the same speed as the roll speed $v_r$; and below the surface, deformation is more severe in order to allow passage of the piece through the roll gap.
Flat rolling

• Given a coefficient of friction sufficient to perform rolling, roll force $F$ required to maintain separation between the two rolls can be computed by integrating the unit roll pressure over the roll-work contact area:

$$F = w \int_{0}^{L} p \, dL$$

Where, $F$= rolling force, N; $w$= the width of the work being rolled, mm; $p$= roll pressure, MPa; and $L$= length of contact between rolls and work, mm.
Flat rolling

• The integration requires two separate terms, one for either side of the neutral point. Variation in roll pressure along contact length is significant. Pressure reaches a maximum at the neutral point, and trials off on either side to the entrance and exit points.

• As friction increases, maximum pressure increases relative to entrance and exit values.

• As friction decreases, the neutral point shifts away from the entrance and toward the exit in order to maintain a net pull force in the direction of rolling.

• Otherwise, with low friction, the work would slip rather than pass between the rolls. It can be calculated based on average flow stress:
Flat rolling

\[ F = \bar{y_f} w L \]

Where, \( \bar{y_f} = \text{average flow stress} \); and the product \( wL \) is the roll-work contact area, \( \text{mm}^2 \).

Fig. 1.4 Typical variation in pressure along the contact length in flat rolling.
Flat rolling

• The peak pressure is located at the neutral point. The area beneath the curve, representing the integration is the roll force.

• Contact length can be approximated by:

\[ L = \sqrt{R(t_0 - t_f)} \]

The torque in rolling can be estimated by assuming that the roll force is centered on the work as it passes between the rolls, and that it acts with a moment arm of one-half the contact length L. Thus, torque for each roll is:

\[ T = 0.5 FL \]
Flat rolling

• The power required to drive each roll is the product of torque and angular velocity. Angular velocity is $2\pi N$, where $N$ = rotational speed of the roll. Thus, the power for each roll is $2\pi NT$.

• The power can be calculated for rolling operations as follows:

$$P = 2\pi NFL$$

Where, $P$ = power, J/s or W; $N$ = rotational speed, rev/min; $F$ = rolling force, N; and $L$ = contact length, m.
Flat rolling

• In rolling process the power and force required to roll a strip of a given width and work material can be reduced through:

1. Using hot rolling rather than cold rolling to reduce strength and strain hardening \((K \text{ and } n)\) of the work material

2. Reducing the draft in each pass

3. Using a smaller roll radius \(R\) to reduce force

4. Using a lower rolling speed \(N\) to reduce power
ii. Shape rolling

• In shape rolling, the work is deformed into a contoured cross section rather than flat (rectangular)

• Products made by shape rolling include construction shapes such as I-beams, L-beams, and U-channels; rails for railroad tracks; and round and square bars and rods.

• The process is accomplished by passing the work through rolls that have the reverse of the desired shape.
Shape rolling

• Most of the principles that apply in flat rolling are also applicable to shape rolling. Shaping rolls are more complicated; and the work, usually starting as a square shape, requires a gradual transformation through several rolls in order to achieve the final cross section.

• Designing the sequence of intermediate shapes and corresponding rolls is called roll-pass design.

• Its goal is to achieve uniform deformation throughout the cross section in each reduction. Otherwise, certain portions of the work are reduced more than others, causing greater elongation in these sections.

• The consequence of non uniform reduction can be warping and cracking of the rolled product.
Figure 1.5: A rolling mill for hot flat rolling: the steel plate is seen as the glowing strip.
iii. Rolling mills

- Equipment is massive and expensive
- Rolling mill configurations:
  1. two-high: two opposing large diameter rolls
  2. three-high: work passes through both directions.
  3. four-high: backing rolls support smaller work rolls.
  4. cluster mill: multiple backing rolls on smaller rolls.
  5. tandem rolling mill: sequence of two-high mills
Rolling mills

- two-high rolling mill - the rolls in these mills have diameters in the range 0.6 – 1.4 m.
- The two-high configuration can be either reversing or non-reversing.
- In the non-reversing mill, the rolls are always rotate in the same direction, and the work always passes through from the same side.
- The reversing mill allows the direction of roll rotation to be reversed, so that the work can be passed through in either direction. This permits a series of reduction to be made through the same set of rolls, simply by passing through the work from opposite directions multiple times.
- The disadvantage of the reversing configuration is the significant angular momentum possessed by large rotating rolls and the associated technical problems involved in reversing the direction.
Rolling mills

(a) Figure 1.6 two-high rolling mill

(b) Figure 1.7 three-high rolling mill
Rolling mills

- In three-high configuration there are three rolls in a vertical column, and the direction of rotation of each roll remains unchanged.
- To achieve a series of reductions, the work can be passed through from either side by raising or lowering the strip after each pass.
- The equipment in a three-high rolling mill becomes more complicated, because an elevator mechanism is needed to raise and lower the work.
- By reducing roll diameter the roll-work contact length is reduced and this leads to lower forces, torque, and power.
- The four-high rolling mill uses two smaller-diameter rolls to contact the work and two backing rolls behind them owing to the high roll forces, these smaller rolls would deflect elastically between their end bearings as the work passes through unless the larger backing rolls were used to support them.
Rolling mills

Figure 1.8 four-high rolling mill

Figure 1.9 Cluster rolling mill
Rolling mills

• Another roll configuration that allows smaller working rolls against the work is the cluster rolling mill.

• To achieve higher throughout rates in standard products, a tandem rolling mill is often used.

• This configuration consists of a series of rolling stands, a typical tandem rolling mill can have eight to ten stands, each making a reduction in thickness or a refinement in shape of the work passing through. With each rolling step, work velocity increases and the problem of synchronizing the roll speeds at each stand is a significant one.

• Modern tandem rolling mills are often supplied directly by continuous casting operations. These setups achieve a high degree of integration among the processes required to transform starting raw materials into finished products. Advantages include elimination of soaking pits, reduction in floor space, and shorter manufacturing lead times. These technical advantages translate into economic benefits for a mill that can accomplish continuous casting and rolling.
Rolling mills

Figure 1.10 tandem rolling mill
iv. Other deformation processes related to rolling

The operations include thread rolling, ring rolling, and gear rolling.

a) **Thread rolling:** bulk deformation process used to form threads on cylindrical parts by rolling them between two dies.

- Most important commercial process for mass producing external threaded component (bolt and screws).
- Performed by cold working in thread rolling machines, these machines are equipped with special dies that determine the size and the form of the thread.
Thread rolling

Advantages over thread cutting (machining)

- Higher production rates
- Better material utilization
- Stronger threads due to work hardening
- Better fatigue resistance due to compressive stresses introduced by rolling
Thread rolling

Figure 1.11  thread rolling with flat dies: (1) start of cycle, (2) end of cycle
Ring rolling

b) **Ring rolling**: deformation process in which a thick-walled ring of smaller diameter is rolled into a thin-walled ring of larger diameter.

- As thick-walled ring is compressed, deformed metal elongates, causing diameter of ring to be enlarged.
- Hot working process for large rings and cold working process for smaller rings.
- Application: ball and roller bearing races, steel tires, for railroad wheels, and rings for pipes, pressure vessels, and rotating machinery.
Ring rolling

Figure 1.12  ring rolling: (1) start, (2) completion of process

Advantages of ring rolling

- Material savings, ideal grain orientation, strengthening through cold working, for rolling of complex shapes.
Gear rolling

c) Gear rolling: a cold working process which used to produce gears.

✓ The automotive industry is an important user of these products.

✓ The setup in gear rolling is similar to thread rolling, except that the deformed features of the cylindrical blank or disk are oriented parallel to its axis (at an angle in the case of helical gears) rather than spiraled as in thread rolling.
Gear rolling

Advantages of Gear rolling

• Higher production rates
• Strong thread due to work hardening
• better fatigue resistance due to resistance
• less material waste
2. **Forging**: deformation process in which the work is compressed between two dies.

- oldest of the metal forming operations, dating from about 5000 BC.
- Components: engine crankshafts, connecting rods, gears, aircraft structural components, jet engine turbine parts.
- In addition, basic metal industries use forging to establish basic form of large components that are subsequently machined to final shape & dimensions.
Forging

Figure.2.1  forging machine
Forging

Classification of forging operations

• Cold vs. hot forging

✓ Hot or warm forging - most common, due to the significant deformation and the need to reduce strength and increase ductility of work metal.

✓ Cold forging - used to increase the strength which results from strain hardening

• Impact vs. press forging

➤ Forge hammer - applies an impact load

➤ Forge press - applies gradual pressure
Forging

Classification of forging process based on the degree to which the flow of the work metal is constrained by the dies:

A. **Open-die forging**: work is compressed b/n two flat dies, allowing metal to flow laterally without constraint.

B. **Impression-die forging**: die surface contain a cavity or impression that is imparted to workpart, thus constraining metal flow- flash is created. Flash is excess metal that must be trimmed.

C. **Flashless forging**: work part is completely constrained in die & no excess flash is produced.
Figure 2.2  *types of forging: (a) open-die forging, (b) impression-die forging, and (c) flashless forging*
Forging

A. **Open-die forging**: compression of a work part of cylindrical cross section between two flat dies.

- Deformation operation reduces height and increases diameter of work.
- Common names include upsetting or upset forging.
Analysis of open-die forging

• If no friction occurs between work and die surfaces, then homogeneous deformation occurs, so that radial flow is uniform throughout workpart height. Under ideal conditions the true strain is given by:

\[ \epsilon = \ln \frac{h_o}{h} \]

Where, \( h_o \) = starting height; and \( h \) = height at some point during compression.
At \( h \) = final value \( h_f \), true strain reaches maximum value
Open-die forging

Fig. 2.3 Homogeneous deformation under ideal conditions in an open-die forging operation: (1) start of process with work piece at its original length and diameter, (2) partial compression, and (3) final size.
Open-die forging

Estimates of force to perform upsetting can be calculated. The force required to continue the compression at any given height \( h \) during the process can be calculated:

\[
F = Y_f A
\]

Where, \( F \) = force; \( A \) = cross sectional area of the part, mm\(^2\); and \( Y_f \) = flow stress corresponding to the strain, MPa

**Open-die forging with friction**

✓ Friction between work and die surfaces constrains lateral flow of work, resulting in barrel effect.
✓ In hot open-die forging, effect is even more pronounced due to heat transfer at and near die surfaces, which cools the metal and increases its resistance to deformation.
Analysis of open-die forging

- The hotter metal in the middle of the part flows more readily than the cooler metal at the ends. These effects are more significant as the diameter-to-height ratio of the work part increases, due to the greater contact area at the work-die interface.

- A shape factor can be calculated to account for effects of the diameter-to-height ratio and friction:

\[ F = K_f Y_f A \]

Where, \( K_f \) is the forging shape factor, which defined as:

\[ K_f = 1 + \frac{0.4 \mu D}{h} \]

Where, \( \mu \)=coefficient of friction; \( D \)= workpart diameter or other dimension representing contact length with die surface, mm; and \( h \)= workpart height, mm.
Open-die forging

Figure 2.4 Actual deformation of a cylindrical work part in open-die forging, showing barreling effect: (1) start of the process, (2) partial deformation, and (3) final shape.
Open-die forging practice

- Open-die forging operations produce rough forms, and subsequent operations are required to refine the parts to final geometry and dimensions.
- An important contribution of open-die hot forging is that it creates a favorable grain flow and metallurgical structure in the metal.
- Operations classified as open-die forging or related operations include fullering, edging, and cogging.
- **Fullering** is a forging operation performed to reduce the cross section and redistribute the metal in a workpart in preparation for subsequent shape forging. It is accomplished by dies with convex surfaces.
- Fullering die cavities are often designed into multi-cavity impression dies, so that the starting bar can be rough formed before final shaping.
Open-die forging practice

• **Edging** is similar to fullering, except that the dies have concave surfaces.

• A **cogging** operation consists of a sequence of forging compressions along the length of a workpiece to reduce cross section and increase length. It is used in the steel industry to produce blooms and slabs from cast ingots.

• It is accomplished using open dies with flat or slightly contoured surfaces. The term incremental forging is sometimes used for this process.
Open-die forging

Figure. 2.5 Several open-die forging operations: (a) fullering, (b) edging, and (c) cogging
B. impression-die forging

- Impression-die forging, sometimes called **closed-die forging**, is performed with dies that contain the inverse of the desired shape of the part.

- Flash is formed by metal that flows beyond die cavity into small gap between die plates.

- Flash must be later trimmed from part, but it serves an important function during compression:
  - As flash forms, friction resists continued metal flow into gap, constraining material to fill die cavity.
  - In hot forging, metal flow is further restricted by cooling against die plates.
Impression-die forging

Figure. 2.6 Sequence in impression-die forging: (1) just prior to initial contact with raw workpiece, (2) partial compression, and (3) final die closure, causing flash to form in gap between die parts.
Impression-die forging practice

• Several forming steps often required, with separate die cavities for each step

✓ Beginning steps redistribute metal for more uniform deformation and desired metallurgical structure in subsequent steps

✓ Final steps bring the part to its final geometry

✓ Impression-die forging is often performed manually by skilled operator under adverse conditions.
Impression-die forging

- Because of flash formation in impression die forging and the more complex part shapes made with these dies, forces in this process are significantly greater and more difficult to analyze than in open-die forging.
- Relatively simple formulas and design factors are often used to estimate forces in impression-die forging.

\[ F = K_f Y_f A \]

Where, \( F \) = maximum force in the operation, \( A \) = projected area of the part including flash, \( \text{mm}^2 \); \( Y_f \) = flow stress of the material, \( \text{MPa} \); and \( K_f \) = forging shape factor.
Impression-die forging

• In hot forging, the appropriate value of $Y_f$ is the yield strength of the metal at the elevated temperature.
• $K_f$ in above equation is a factor intended to account for increases in force required to forge part shapes of various complexities.

<table>
<thead>
<tr>
<th>Part shape</th>
<th>$K_f$</th>
<th>Part shape</th>
<th>$K_f$</th>
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<tbody>
<tr>
<td>Impression-die forging:</td>
<td></td>
<td>Flashless forging:</td>
<td></td>
</tr>
<tr>
<td>Simple shapes with flash</td>
<td>6.0</td>
<td>Coining (top &amp; bottom surfaces)</td>
<td>6.0</td>
</tr>
<tr>
<td>Complex shapes with flash</td>
<td>8.0</td>
<td>Complex shapes</td>
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</tr>
<tr>
<td>Very complex shapes with flash</td>
<td>10.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table. 1 typical $K_f$ values for various part shapes in impression-die and flashless forging
Advantages of impression-die forging

• Higher production rates
• Conservation of metal (less waste)
• Greater strength
• Favorable grain orientation in the metal

Disadvantages of impression die forging

▪ Not capable of close tolerances
▪ Machining often required to achieve accuracies and features needed, such as holes, threads, and mating surfaces that fit with other components.
C. Flashless forging

- Flashless forging imposes requirements on process control that are more demanding than impression-die forging.
- Most important is that the work volume must equal the space in the die cavity within a very close tolerance.
- If the starting blank is too large, excessive pressures may cause damage to the die or press.
- If the blank is too small, the cavity will not be filled.
- Best suited to part geometries that are simple and symmetrical
- Often classified as a precision forging process.
Flashless forging

Figure 2.7 Flashless forging: (1) just before partial contact with workpiece, (2) partial compression, and (3) final punch and die closure.
Flashless forging

- Forces in flashless forging reach values comparable to those in impression die forging.
- Estimates of these forces can be computed using the same methods as for impression die forging.
- Coining is a special application of closed-die forging in which fine details in the die are impressed into the top and bottom surface of the workpart.
- There is little flow of metal in coining, yet the pressures required to reproduce the surface details in the die cavity are high.
Flashless forging

Figure 2.8 coining operation: (1) start of cycle, (2) compression stroke, and (3) ejection of finished part.
Forging hammers (drop hammers)

• operate by applying an impact loading against the work.
• Drop hammers are most frequently used for impression-die forging.
• The upper portion of the forging die is attached to the **ram**, and the lower portion is attached to the **anvil**.
• In the operation, the work is placed on the lower die, and the ram is lifted and then dropped.
• When the upper die strikes the work, the impact energy causes the part to assume the form of the die cavity.
Forging hammer

Figure 2.9  details of drop hammer for impression-die forging
Forging hammer

Drop hammers can be classified as gravity and power drop hammers.

- **Gravity drop hammers** achieve their energy by the falling weight of a heavy ram.
- The **force** of the blow is determined by the **height of the drop** and the weight of the ram.
- **Power drop hammers** accelerate the ram by pressurized air or steam.
- One of the disadvantages of drop hammers is that a large amount of the impact energy is transmitted through the anvil and into the floor of the building.
Forging presses

Apply gradual pressure, rather than sudden impact, to accomplish the forging operation.
• Forging presses include mechanical presses, hydraulic presses, and screw presses.
• Mechanical presses converts rotation of drive motor into linear motion of ram.
• Hydraulic presses use a hydraulically driven piston to actuate the ram.
• Screw presses apply force by a screw mechanism that drives the vertical ram.
• These machines are therefore suitable for forging (and other forming) operations that require a long stroke.
Other deformation processes related to Forging

i. Upsetting and Heading

• Upset forging is widely used in the fastener industry to form heads on nails, bolts, and similar hardware products.
• More parts produced by upsetting than any other forging operation.
• Performed cold, warm, or hot on machines called headers or formers
• Wire or bar stock is fed into machine, end is headed, then piece is cut to length
• For bolts and screws, thread rolling is then used to form threads
Figure 2.10  upset forging operation to form a head on a bolt or similar hardware item. The cycle is as follows:
(1) wire stock is fed to the stop; (2) gripping dies close on the stock and the stop is retracted, (3) punch moves forward, and (4) bottom to form the head.
• There are limits on the amount of deformation that can be achieved in upsetting, usually defined as the maximum length of stock to be forged.

Figure 2.11 examples of heading (upset forging) operations: (a) heading a nail using open dies, (b) round head formed by punch, (c & d) heads formed by dies, and (e) carriage bolt head formed by punch and die.
ii. Swaging

Accomplished by means of rotating dies that hammer a workpiece radially inward to taper it as the piece is fed into the dies.

- used to reduce the diameter of a tube or solid rod.
- Swaging is often performed on the end of a workpiece to create a tapered section.
- A mandrel is sometimes required to control the shape and size of the internal diameter of tubular parts that are swaged.
swaging

Figure.2.12  swaging process to reduce solid rod stock; the dies rotate as they hammer the work. In radial forging, the workpiece rotates while the dies remain in a fixed orientation as they hammer the work.
Figure 2.13 examples of parts made by swaging: (a) reduction of solid stock, (b) tapering a tube, (c) Swaging to form a groove or tube, (d) pointing of a tube, and (e) swaging of neck on a gas cylinder.
iii. Trimming

Cutting operation to remove flash from workpart in impression-die forging

- Usually done while work is still hot, so as a separate trimming press is included at the forging station.
- Trimming can also be done by alternative methods, such as grinding or sawing.
Figure 2.14 Trimming operation (shearing process): to remove the flash after impression-die forging.
Types of bulk deformation process

3. Extrusion

Compression process in which the work metal is forced to flow through a die opening to produce a desired cross-sectional shape.

- Process is similar to squeezing a toothpaste out of a toothpaste tube.
- In general, extrusion is used to produce cylindrical bars or hollow tubes or for the starting stock for drawn rod, cold extrusion or forged products.
- Most metals are hot extruded due to large amount of forces required in extrusion. Complex shape can be extruded from the more readily extrudable metals such as Aluminium.
Extrusion

Extrusion products

Typical parts produced by extrusion are trim parts used in automotive and construction applications, window frame members, railing, aircraft structural parts.

Example: Al extrusions are used in commercial and domestic buildings for window and door frame systems, prefabricated houses/ building structures, roofing and exterior cladding, curtain walling, etc.
Extrusion

Types of extrusion:

✓ Classification based on physical configuration
   i. direct extrusion
   ii. Indirect extrusion

✓ Classification based on working temperature:
   cold, warm and hot extrusion

✓ Classification based on working process:
   I. continuous process
   II. discrete process
Types of Extrusion

✓ **Direct extrusion** (forward extrusion):
  
  • The metal billet is placed in a container and driven through the die by the ram.
  
  • The dummy block or pressure plate, is placed at the end of the ram in contact with the billet.
  
  • Friction is at the die and container wall.
  
  Requires higher pressure than indirect extrusion.
Extrusion

• As ram approaches die opening, a small portion of billet remains that cannot be forced through die opening.

• This extra portion, called the butt, must be separated from extruded product by cutting it just beyond the die exit.

• Starting billet cross section usually round, but final shape is determined by die opening.
Extrusion

Figure 3.2 Direct extrusion
Direct Extrusion

- Hollow sections (e.g. tubes) are possible in direct extrusion. The starting billet is prepared with a hole parallel to its axis, this allows passage of a mandrel that is attached to the dummy block. As the billet is compressed, the material is forced to flow through the clearance between the mandrel and the die opening.

- The clearance between the mandrel and the die wall determines the **wall thickness of the tube**.

- Tubes are produced either by starting with a hollow billet or by a two step extrusion in which a solid billet is first **pierced** and then **extruded**.
Direct extrusion

Figure 3.4 (a) Direct extrusion to produce a hollow or semi-hollow cross section, (b) hollow, and (c) semi-hollow cross sections.
Extrusion

Indirect extrusion:

- Also called backward or reverse extrusion.
- the die is mounted to the ram rather than at the opposite end of the container.
- As the ram penetrates into the work, the metal is forced to flow through the clearance in a direction opposite to the motion of the ram.
- Friction is at the die only (no relative movement at the container wall) \( \Rightarrow \) Requires roughly constant pressure, lower force.
- Limitations of indirect extrusion are imposed by the lower rigidity of the hollow ram and the difficulty in supporting the extruded product as it exits the die.
Indirect Extrusion

Figure 3.5 indirect extrusion to produce: (a) a solid cross section, and (b) a hollow cross section

There are practical limitations on the length of the extruded part that can be made by this method. Support of the ram becomes a problem as work length increases.
Types of extrusion

**Cold vs. Hot extrusion**

- Extrusion can be performed either hot or cold, depending on work metal and amount of strain to which it is subjected during deformation.
- Hot extrusion involves prior heating of the billet to a temperature above its re-crystallization temperature. This reduces strength and increases ductility of the metal, permitting more extreme size reductions and more complex shapes to be achieved in the process.
- Another advantage of hot extrusion is reduction of ram force, increased ram speed, and reduction of grain flow characteristics in the final product.
Extrusion

Disadvantage of hot extrusion:

• Cooling of the billet as it contacts the container walls is a problem, and isothermal extrusion is sometimes used to overcome this problem.

• Lubrication is critical in hot extrusion for certain metals (e.g. steels), and special lubricants have been developed that are effective under the harsh conditions in hot extrusion. Glass powder is sometimes used as a lubricant in hot extrusion; in addition to reducing friction, it also provides effective thermal insulation between the billet and the extrusion container.

• Advantages of cold extrusion include increased strength due to strain hardening, close tolerances, improved surface finish, absence of oxide layers, and high production rates, also eliminates the need for heating the starting billet.
Tube Extrusion

• Examples of metals that can be cold extruded are: Pb, Sn, Al alloys, Cu, Ti, Mb, V, steel. Parts that are cold extruded are: collapsible tubes, aluminium cans, cylinders, gear blanks, etc.
Impact extrusion

• Produce short lengths of hollow shapes, such as collapsible toothpaste or spray cans.

• Requires soft materials such as Aluminium, Lead, Copper and Tin.

• A small shot of solid material is placed in the die and is impacted by a ram, which causes cold flow in the material.

• It is performed on a high speed mechanical press.
Extrusion

Continuous vs. Discrete processing:

• A true continuous process operates in steady state mode for an indefinite period of time. Some extrusion operations approach this ideal by producing very long sections in one cycle, but these operations are ultimately limited by the size of the billet that can be loaded into the extrusion container. These processes are more accurately described as semi-continuous operations.

• In nearly all cases, the long section is cut into smaller lengths in a subsequent sawing or shearing operation.
• In a discrete extrusion operation, a single part is produced in each extrusion cycle. Impact extrusion is an example of the discrete processing case.
Analysis of extrusion

One important parameter is the extrusion ratio, also called the **reduction ratio**. The ratio is defined:

\[ r_x = \frac{A_o}{A_f} \]

Where, \( r_x \) = extrusion ratio, \( A_o \) = cross sectional area of the starting billet, mm\(^2\), and \( A_f \) = final cross sectional area of the extruded section, mm\(^2\).

The ratio applies for both direct and indirect extrusion.
Analysis of extrusion

The value of $r_x$ can be used to determine true strain in extrusion, given that ideal deformation occurs with no friction and no redundant work:

$$
\varepsilon = \ln r_x = \ln \frac{A_o}{A_f}
$$

Under the assumption of ideal deformation (no friction and no redundant work), the pressure applied by the ram to compress the billet through the die opening depicted in figure below can be computed as follows:

$$
P = \bar{Y}_f \ln r_x
$$

Where, $\bar{Y}_f$ = average flow stress during deformation, MPa.
Analysis of extrusion

In fact, extrusion is not a frictionless process; friction exists between the die and the work as the billet squeezes down and passes through the die opening.

- In **direct extrusion**, friction also exists between the container wall and the billet surface. The effect of friction is to increase the strain experienced by the metal.
Analysis of extrusion

As a result of friction force in extrusion the actual true strain and ram pressure in an extrusion operation can be calculated:

$$\varepsilon_x = a + b \ln r_x$$

Where, $\varepsilon_x$ = extrusion strain; and $a$ and $b$ are empirical constants for a given die angle.

Typical values of these constants are: $a= 0.8$ and $b=1.2$ to $1.5$.

Values of $a$ and $b$ will increase as the die angle increases.
Analysis of extrusion

• The ram pressure to perform indirect extrusion can be estimated based on Johnson’s extrusion strain formula as follows:

\[ P = \bar{Y}_f \varepsilon_X \]

Where, \( \bar{Y}_f \) is calculated based on ideal strain rather than extrusion strain.
Analysis of extrusion

• In **direct** extrusion, the effect of friction between the container walls and the billet causes the ram pressure to be greater than for indirect extrusion. We can write the following expression which isolates the friction force in the direct extrusion container:

\[
\frac{p_f \pi D_o^2}{4} = \mu p_c \pi D_o L
\]

Where, \( p_f \) = additional pressure required to overcome friction, MPa; \( \pi D^2 / 4 \) is billet cross sectional area; \( \mu \) = coefficient of friction at the container wall; \( p_c \) = pressure of the billet against the container wall; \( \pi D_o L \) = area of the interface between the billet and container wall.
Analysis of extrusion

• If sticking occurs at the container wall so that friction stress equals shear yield strength of the work metal:

\[ \mu p_c \pi D_0 L = Y_s \pi D_0 L \]

Where, \( Y_s \) = shear yield strength, Mpa

If we assume that \( Y_s = \bar{Y}_s / 2 \), then \( P_f \) reduces to the following:

\[ P_f = \bar{Y}_f \frac{2L}{D_0} \]
Analysis of extrusion

• Based on the above reasoning, the ram pressure in direct extrusion can be calculated:

\[ p = \bar{Y_f} \left( \epsilon_x + \frac{2L}{D_o} \right) \]

Where, \( \frac{2L}{D_o} \) accounts for additional pressure due to friction at the container-billet interface, \( L= \) is the portion of the billet length remaining to be extruded, and \( D_o= \) the original diameter of the billet.

**NB:** \( P \) is reduced as the remaining billet length decreases during the process.
Figure 3.8 typical plots of ram pressure versus ram stroke (and remaining billet length) for direct and indirect extrusion.

✓ The higher values in direct extrusion result from friction at the container wall.

✓ The shape of the initial pressure buildup at the beginning of the plot depends on die angle (higher die angle causes steeper pressure buildups). The pressure increase at the end of the stroke is related to formation of the butt.
Analysis of extrusion

• Ram force in **direct** and **indirect** extrusion can be calculated as follows:

\[ F = p A_o \]

Where, \( P = \) ram pressure; \( A_o = \) billet area

✓ Power required in extrusion operation can be calculated as follows:

\[ P = F v \]

Where, \( F = \) ram force in extrusion, \( N; P = \) power, \( J/s \); and \( V = \) ram velocity, \( m/s \)
Extrusion Equipment

Extrusion equipment mainly includes: Presses, dies and tooling.

1. Extrusion Presses
   • Most extrusions are made with hydraulic presses.
   • This can be classified based on the direction of travel of the ram.
     i. Horizontal presses
     ii. Vertical presses
Extrusion Presses

**Horizontal extrusion presses**
- Used for most commercial extrusion of bars and shapes.
- Deformation is non-uniform due to different temperatures between top and bottom parts of the billet.

**Vertical extrusion Presses**
- Chiefly used in the production of thin-wall tubing.
- Uniform deformation, due to uniform cooling of the billet in the container.
- Requires less floor space than horizontal presses.
- Higher rate of production
- Easier alignment between the press ram & tools.
Extrusion dies

1. Extrusion Dies
   • Important factors in die are Die angle and orifice shape.
   • For low angle the surface area of the die is large, leading to increased friction at the die-billet interface. Higher friction results in larger ram force.
   • Large die angle causes more turbulence in the metal flow during reduction, increasing the ram force required.
   • The effect of die angle on the ram force is a U-shaped function.
Optimum angle depends on **work material, billet temperature** and **lubrication**. Die designers rely on rules of thumb and judgment to decide the appropriate angle.
Extrusion dies

Die design
• Die design is at the heart of efficient extrusion production.
• Dies must withstand considerable amount of stresses, thermal shock, and oxidation.

Die design considerations:
✓ Wall thickness: different wall thicknesses in one section should be avoided.
✓ Simple shape: the more simple shapes the more cost effective.
✓ Symmetrical: more accurate
✓ Sharp or rounded corners: sharp corners should be avoided
✓ Size to weight ratio
Extrusion dies

Die materials

• Dies are made from highly alloy tools steels or ceramics (Zirconia, Si₃N₄).
  For cold extrusion offering longer tool life and reduced lubricant used, good wear resistance.

• **Wall thickness** as small as 0.5mm (on flat dies) or 0.7mm (on hollow dies) can be made for Aluminium extrusion.

• **Heat treatments** such as nitriding are required (several times) to increase hardness (65-70 HRC) this improves die life avoiding unscheduled press shutdown.
Types of extrusion dies

a) Flat-faced dies
b) Dies with conical entrance angle

a, Flat faced dies

• When metal entering the die will form a dead zone and shears internally to form its own die angle

• A parallel land on the exit side of the die helps strengthen the die and allow for reworking of the flat face on the entrance side of the die without increasing the exit diameter.

Figure 3.10 Flat-faced dies
Extrusion dies

b, Dies with conical entrance angle

• Requires good lubricants
• Decreasing die angle increasing homogeneity, lower extrusion pressure.
• For most operation, $45^\circ < \alpha < 60^\circ$.

Figure 3.11 dies with conical entrance angle
Extrusion dies

- The shape of the die orifice affects the ram pressure required to perform the extrusion operation.
- A complex cross section such as the one in figure 3.10, requires a higher pressure and greater force than a circular shape.
- The effect of the die orifice shape can be assessed by the die shape factor.
Extrusion dies

Figure 3.12  a complex extruded cross section for a heat sink
**Die shape factor** is the ratio of the pressure required to extrude a cross section of a given shape relative to the extrusion pressure for round cross section of the same area.

\[
K_x = 0.98 + 0.02 \left( \frac{C_x}{C_c} \right)^{2.25}
\]

Where, \( K_x \) = die shape factor in extrusion; \( C_x \) = perimeter of the extruded cross section, mm; and \( C_c \) = perimeter of a circle of the same area as the extruded shape, mm.

✓ A circular shape is the simplest shape with \( K_x \) value of 1.
✓ Hollow, thin-walled sections have higher shape factors and are more difficult to extrude.
Extrusion

- For shapes other than round, for indirect extrusion the pressure can be calculated:

\[ p = K_x \overline{Y_f} \epsilon_x \]

- It can be calculated for direct extrusion as follows:

\[ p = K_x \overline{Y_f} \left( \epsilon_x + \frac{2L}{D_0} \right) \]

Where, \( P \) = extrusion pressure, MPa; \( K_x \) = shape factor.
Other extrusion processes

**Hydrostatic extrusion**

- One of the problems in direct extrusion is friction along the billet-container interface.
- The problem of friction can be addressing by surrounding the billet with fluid inside the container and pressurizing the fluid by the forward motion of the ram.
- It can be carried out at room temperature or at elevated temperatures.
- Special fluids and procedures must be used at elevated temperatures.
- Hydrostatic extrusion is an adaptation of direct extrusion.
Extrusion

✓ hydrostatic pressure on the work increases the materials ductility.
✓ This process can be used on metals that would be too brittle for convention extrusion operations.
✓ The starting work billet must be formed with a taper at one end to fit snugly into the die entry angle, to act as a seal for prevention fluid from squirting out the die hole when the container is initially pressurized.
Defects in extruded products

There are different types of defects which occur in extruded products:

a. **Surface cracking**: results from high workpart temperatures that cause cracks to develop at the surface. It often occur when extrusion speed is too high, leading to high strain rates and associated heat generation. Other factors contributing to surface cracking are high friction and surface chilling of high temperature billets in hot extrusion.

b. **Piping**: is a defect associated with direct extrusion. It is a formation of a sink hole in the end of the billet. The use of a dummy block whose diameter is slightly less than that of the billet helps to avoid piping. Other names called **tailpipe, fishtailing**.
Defects in extruded products

c. Centerburst: is an internal crack that develops as a result of tensile stresses along the centerline of the workpart during extrusion. If stresses are great enough, bursting occurs.

- Increases with die angle
- Increases with increasing amounts of impurities
- Decreases with increasing extrusion ratio & friction.
- Other names called arrowhead fracture, center cracking, and chevron cracking.
Extrusion Defects

Figure 3.14 some common defects in extrusion:
- (a) centerburst, (b) Piping, and (c) surface cracking
Types of bulk deformation processes

4. Wire and bar drawing

• Drawing is an operation in which the cross section of a bar, rod, or wire is reduced by pulling it through a die opening.

• Similar to extrusion except work is pulled through die in drawing (it is pushed through in extrusion)

• Although drawing applies tensile stress, compression also plays a significant role since metal is squeezed as it passes through die opening.
Wire and bar drawing

Figure 4.1 drawing of bar, rod, or wire
Wire vs. Bar drawing

• The basic difference between bar drawing and wire drawing is the **stock size** that is processed.
• Bar drawing- used for large diameter bar, rod stock.
• Wire drawing- used for small diameter stock. Wire sizes down to 0.03mm are possible.
• Although the mechanics are the same, the methods, equipment, and even terminology are different.
Analysis of drawing

• In a drawing operation, the change in the size of the work is usually given by the area reduction.

\[ r = \frac{A_o - A_f}{A_o} \]

Where, \( r \) = area reduction in drawing; \( A_o \) = original cross-sectional area of work; and \( A_f \) = final area, mm\(^2\).

✓ In *Bar drawing*, *rod drawing*, and in drawing of large diameter wire for upsetting and heading operations, the term draft is used to denote the before and after difference in the size of the processed work.

\[ d = D_o - D_f \]

Where, \( d \) = draft; \( D_o \) = original diameter; and \( D_f \) = final diameter of work.
Analysis of drawing

**Mechanics of drawing**: if no friction or redundant work occurred in drawing, true strain can be calculated:

\[ \varepsilon = \ln \frac{A_o}{A_f} = \ln \frac{1}{1 - r} \]

The stress that results from this ideal deformation is given by:

\[ \sigma = \bar{Y}_f \varepsilon = \bar{Y}_f \ln \frac{A_o}{A_f} \]
Analysis of drawing

• In reality friction is present in drawing and the work metal experiences inhomogeneous deformation.

• The draw stress can be calculated:

\[
\sigma_d = Y_f \left(1 + \frac{\mu}{\tan \alpha}\right) \phi \ln \frac{A_o}{A_f}
\]

Where, \( \sigma_d \) = draw stress, MPa; \( \mu \) = die-work coefficient of friction; \( \alpha \) = die angle; and \( \Phi \) = is a factor that accounts for inhomogeneous deformation which is determined as follows for round cross section:

\[
\phi = 0.88 + 0.12 \frac{D}{L_c}
\]

Where, \( D \) = average diameter of work during drawing; and \( L_c \) = contact length of the work with the draw die.
Analysis of drawing

The average diameter of the work and contact length can be calculated as follows:

\[ D = \frac{D_o + D_f}{2} \]

\[ L_c = \frac{D_o - D_f}{2 \sin \alpha} \]

The corresponding draw force (F) can be calculated:

\[ F = A_f \sigma_d = A_f \bar{Y}_f \left(1 + \frac{\mu}{\tan \alpha}\right) \phi \ln \frac{A_o}{A_f} \]
**Drawing practice and products**

- Drawing is usually performed as a cold-working operation.
- Most frequently used to produce round cross sections, but squares and other shapes are also drawn.

**Products:**

- **Wire**: electrical wire and cable; wire stock for fences, coat hangers, and shopping carts. Road stock to produce nails, screws, rivets and springs.
- **Bar**: used to produce metal bars for machining, forging, and other processes.
Bar drawing

• Accomplished as a single-draft operation- the stock is pulled through one die opening.
• Beginning stock has a large diameter and it is in the form of straight cylindrical piece rather than coiled, which limits the length of the work to be drawn.
• Accomplished on a machine called a draw bench, consisting of an entry table, die stand (which contain the draw die), carriage, and exit rack.
• The carriage is used to pull the stock through the draw die, it is powered by hydraulic cylinders or motor driven chains.
• The die stand is often designed to hold more than one die, so that several bars can be pulled simultaneously through their respective dies.
Bar drawing

Figure 4.2 hydraulically operated draw bench for drawing metal bars
Wire drawing

✓ Continuous drawing machines consisting of multiple draw dies (typically 4 to 12) separated by accumulating drums.
  ▪ Each drum (capstan) provides proper force to draw wire stock through upstream die.
  ▪ Each die provides a small reduction, so desired total reduction is achieved by the series.
  ▪ Annealing sometimes required between dies.
Figure.4.3 continuous drawing of wire
Features of draw die

• Entry region- funnels lubricant into the die to prevent scoring of work and die surfaces.
• Approach- cone shaped region where drawing occurs. Approach angle ranges from 6 to 20.
• Bearing surface (land)- determines final stock size
• Back relief (exit zone)- provided with a back relief angle (half-angle) about 30°
• Die materials: tool steels or cemented carbides. Dies for high speed wire drawing use inserts made of diamond (both synthetic and natural) for the wear surfaces.
Figure 4.4 draw die for drawing of round rod or wire
Preparation of the work for wire or bar drawing

✓ Prior to drawing, the beginning stock must be properly prepared. This involves three stages:

- **Annealing** - to increase ductility of stock to accept deformation during drawing.

- **Cleaning** - to prevent damage to work surface & draw die. It involves removal of surface contaminants (e.g. scale & rust) by means of chemical pickling or shot blasting.

- **Pointing** - to reduce diameter of starting end to allow insertion through draw die to start the process.

✓ This is usually accomplished by swaging, rolling, or turning.

✓ The pointed end of the stock is then gripped by the carriage jaws or other device to initiate the drawing process.