Continuous casting and hot rolling

• Metal is melted, cast and hot rolled continuously through a series of rolling mills within the same process.
• Usually for steel sheet production.
Hot-rolling

- The first hot-working operation for most steel products is done on the primary roughing mill (blooming, slabbing or cogging mills).
- These mills are normally two-high reversing mills with 0.6-1.4 m diameter rolls (designated by size).

- The objective is to breakdown the cast ingot into blooms or slabs for subsequent finishing into bars, plate or sheet.
- In hot-rolling steel, the slabs are heated initially at 1100 -1200 C. The temperature in the last finishing stand varies from 700 - 900 C, but should be above the upper critical temperature to produce uniform equiaxed ferrite grains.
Cold-rolling

Cold rolling is carried out under recrystallisation temperature and introduces work hardening.
- The starting material for cold-rolled steel sheet is pickled hot-rolled breakdown coil from the continuous hot-strip mill.
- The total reduction achieved by cold-rolling generally will vary from about 50%.
- The reduction in each stand should be distributed uniformly without falling much below the maximum reduction for each pass.
- Generally the lowest percentage reduction is taken place in the last pass to permit better control of flatness, gage, and surface finish.
Back and front tensions in sheet

- The presence of back and front tensions in the plane of the sheet reduces the rolling load.
  - Back tension may be produced by controlling the speed of the uncoiler relative to the roll speed.
  - Front tension may be created by controlling the coiler.
  - Back tension is \(\sim\) twice as effective in reducing the rolling load \(P\) as front tension.

- If a high enough back tension is applied, the neutral point moves toward the roll exit:
  - Rolls are moving faster than the metal.
- If the front tension is used, the neutral point will move toward the roll entrance.
Problems and defects in rolled products

- Defects from cast ingot before rolling.

  Defects other than cracks can result from defects introduced during the ingot stage of production.

- Porosity, cavity, blow hole occurred in the cast ingot will be closed up during the rolling process.

- Longitudinal stringers of non-metallic inclusions or pearlite banding are related to melting and solidification practices. In severe cases, these defects can lead to laminations which drastically reduce the strength in the thickness direction.
• **Defects after rolling:**

• **Flatness**

• The roll gap must be perfectly parallel to produce sheets/plates with equal thickness at both ends.
• The rolling speed is very sensitive to flatness. A difference in elongation of one part in 10,000 between different locations in the sheet can cause waviness.
Solutions to flatness problems

- Camber and crown can be used to correct the roll deflection (at only one value of the roll force). Or use rolling mill equipped with hydraulic jacks to permit the elastic distortion of the rolls to correct deflection.

(a) The use of cambered rolls to compensate for roll bending.
(b) Uncambered rolls give variation of thickness.
Possible effects when rolling with insufficient camber

Thicker center means the edges would be plastically elongated more than the center, normally called long edges.

- This induces the residual stress pattern of compression at the edges and tension along the centerline.
- This can cause centerline cracking (c), warping (d) or edge wrinkling or crepe-paper effect or wavy edge (e).
Possible effects when rolls are over-cambered.

- Thicker edges than the center means the center would be plastically elongated more than the edges, resulting in lateral spread.
- The residual stress pattern is now under compression in the centerline and tension at the edges (b).
- This may cause edge cracking (c), center splitting (d), centerline wrinkling (e).
Inhomogeneous Deformation

- Edging can also be caused by inhomogeneous deformation in the thickness direction.

- If only the surface of the work piece is deformed (as in a light reduction on a thick slab), the **edges are concaved** (a).

- With heavy reduction, the center tends to expand more laterally than the surface to produce **barrelled edges** (b).

- **Alligating** (c) will occur when lateral spread is greater in the center than the surface (surface in tension, center in compression) and with the presence of metallurgical weakness along the centerline.
Surface defects

- Surface defects are more easily in rolling due to high surface to volume ratio. Grinding, chipping or descaling of defects on the surface of cast ingots or billets are recommended before being rolled.
- Laps due to misplace of rolls can cause undesired shapes.

- Flakes or cooling cracks along edges result in decreased ductility in hot rolling such as blooming of extra coarse grained ingot.
- Scratches due to tooling and handling.
- Variation in thickness due to deflection of rolls or rolling speed.
Extrusion

- Extrusion is the process by which a block/billet of metal is reduced in cross section by forcing it to flow through a die orifice under high pressure.

- 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.

* The products obtained are also called extrusion.
Extrusion products

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

• **Example:** Aluminium extrusions are used in commercial and domestic buildings for window and door frame systems, prefabricated houses/building structures, roofing and exterior cladding, curtain walling, shop fronts, etc. Furthermore, extrusions are also used in transport for airframes, road and rail vehicles and in marine applications.
There are several ways to classify metal extrusion processes:

- **By Direction**
  - Direct and Indirect Extrusion.

- **By Temperature**
  - Hot and cold Extrusion.

- **By Equipment**
  - Horizontal and Vertical Extrusion.
Direct Extrusion

Schematic illustration of the direct extrusion process.
Direct Extrusion

Friction increases the extrusion force.
Hollow section is formed using a mandrel.
Indirect Extrusion

Schematic illustration of the indirect extrusion process.
Indirect Extrusion

Metal is forced to flow through the die in an opposite direction to the ram’s motion.

Lower extrusion force as the work billet metal is not moving relative to the container wall.
Comments on Direct Extrusion

• Also called *forward extrusion*
• As ram approaches die opening, a *small portion* of billet remains that cannot be forced through die opening (dead metal zone…..DMZ)
• This *extra portion*, called the *DMZ*, must be separated from *extrudate* by cutting it just beyond the die exit
• Starting billet cross section usually *round*
• Final shape of extrudate is determined by die opening
Comments on Indirect Extrusion

• Also called **backward extrusion**
• **Lower extrusion force** as the work billet metal is not moving relative to the container wall.
• Limitations of indirect extrusion are imposed by
  – Lower rigidity of hollow ram
  – Difficulty in supporting extruded product as it exits die
Variation of Ram Force with ram stroke

Note that in direct extrusion the ram pressure decreases as the billet is extruded further because $L$ decreases, whereas in indirect extrusion the ram pressure is not a function of the billet length.

1- upsetting
2- metal starts to flow
3- extrusion
4- pipe
5- DMZ
Extrusion Die Features

- **Low die angle** - surface area is large, which increases friction at die-billet interface
  - Higher friction results in larger ram force
- **Large die angle** - more turbulence in metal flow during reduction
  - Turbulence increases ram force required
- **Optimum angle** depends on work material, billet temperature, and lubrication
Hydrostatic Extrusion

Using hydrostatic system to reduce the friction and lower the power requirement.

Sealing is the major problem.
Cold and Hot Extrusion

Cold Extrusion

- Cold extrusion is the process done at room temperature or slightly elevated temperatures. This process can be used for most materials-subject to designing robust enough tooling that can withstand the stresses created by extrusion.
- Examples of the metals that can be extruded are lead, tin, aluminium alloys, copper, titanium, molybdenum, vanadium, steel. Examples of parts that are cold extruded are collapsible tubes, aluminium cans,
- cylinders, gear blanks.
- Advantages
  - No oxidation takes place.
  - Good mechanical properties due to severe cold working as long as the temperatures created are below the re-crystallization temperature.
  - Good surface finish with the use of proper lubricants.
Cold and Hot Extrusion

- **Hot extrusion**
- Hot extrusion is done at fairly high temperatures, approximately 50 to 75% of the melting point of the metal. The pressures can range from 35-700 MPa.
- The most commonly used extrusion process is the hot direct process. The cross-sectional shape of the extrusion is defined by the shape of the die.
- Due to the high temperatures and pressures and its detrimental effect on the die life as well as other components, good lubrication is necessary. Oil and graphite work at lower temperatures, whereas at higher temperatures glass powder is used.
Horizontal and Vertical Machines.

- **Horizontal extrusion presses**
  - (15-50 MN capacity or up to 140 MN)
  - Used for most commercial extrusion of bars and shapes.
- **Disadvantages:**
  - Deformation is non-uniform due to different temperatures between top and bottom parts of the billet.
Horizontal and Vertical Machines

- **Vertical extrusion presses (3-20 MN capacity)**
  - Chiefly used in the production of thin-wall tubing.
  - **Advantages:**
    - Easier alignment between the press ram and tools.
    - Higher rate of production.
    - Require less floor space than horizontal presses.
    - Uniform deformation, due to uniform cooling of the billet in the container.
  - **Requirements:**
    - Need considerable headroom to make extrusions of appreciable length.
    - A floor pit is necessary.
Deformation in extrusion, lubrication

- (a) Low container friction and a well-lubricated billet nearly homogeneous deformation.
- b) Increased container wall friction, producing a dead zone of stagnant metal at corners which undergoes little deformation.
- c) For high friction at the container-billet interface, metal flow is concentrated toward the center and an internal shear plane develops – due to cold container. In the sticky friction, the metal will separate internally along the shear zone. A thin skin will be left in a container and a new metal surface is obtained.
- d) Low container friction and a well lubricated billet in indirect extrusion.
Dead Metal Zone

Dead-Metal Zone-Flowing Metal Interface. The dead-metal zone occurs when a material is extruded through square dies. In such geometry, the material in the corners no longer takes part in the flow but adheres to the die face, forming a conical die-like channel through which the billet passes in a still-converging kind of flow. Friction between the dead-metal zone and the flowing material is no more than the shear stress of the material.

Compare between Direct and Indirect Extrusion
Extrusion of tubing

To produce tubing by extrusion from a solid billet, the ram may also be fitted with a piercing mandrel. As the ram moves forward, the metal is forced over the mandrel and through the hole in the die, causing a long hollow tube. Just like toothpaste, only hollow.

If the billets are hollow, a rod that matches the diameter of the cast hole in the billet (but slightly smaller than the hole in the die at the opposite end of the chamber) are used.

Note: the bore of the hole will become oxidized resulting in a tube with an oxidized inside surface.
Extrusion tubing with a porthole die

• The metal is forced to flow into separate streams and around the central bridge, which supports a short mandrel.
• The separate streams of metal which flow through the ports are brought together in a welding chamber surrounding the mandrel, and the metal exits from the die as a tube.
• Since the separate metal streams are jointed within the die, where there is no atmosphere contamination, a perfectly sound weld is obtained.
• Porthole extrusion is used to produce hollow unsymmetrical shapes in aluminium alloys.

Example: pyramid porthole dies
Production of seamless pipe and tubing

Extrusion is suited for producing seamless pipe and tubing, especially for metals which are difficult to work.

- The red-hot billet is rotated and drawn by rolls over a piercing rod, or mandrel. The action of the rolls causes the metal to flow over and about the mandrel to create a hollow pipe shell.

- After reheating, the shell is moved forward over a support bar and is hot-rolled in several reducing/sizing stands to the desired wall thickness and diameter.

Stainless steel seamless pipes

Titanium seamless pipes
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 0.5 mm (on flat dies) or 0.7 mm (on hollow dies) can be made for aluminium extrusion.
- Heat treatments such as nitriding are required (several times) to increase hardness (1000-1100 Hv or 65-70 HRC).

This improves die life is avoiding unscheduled press shutdown.

There are two general types of extrusion dies:

1) Flat-faced dies
2) Dies with conical entrance angle.
Extrusion dies

1) Flat-faced dies

• 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.

2) Dies with conical entrance angle

• requires good lubricants.
• decreasing die angle, increasing homogeneity, lower extrusion pressure (but beyond a point the friction in the die surfaces becomes too great.
• for most operation, $45^\circ < \alpha < 60^\circ$
Impact Extrusion

Impact extrusion is performed at higher speeds and shorter strokes than conventional extrusion.

Schematic illustration of the impact-extrusion process. The extruded parts are stripped by the use of a stripper plate, because they tend to stick to the punch.
Sheathing

Extrusion was originally applied to the making of lead pipe and later to the lead sheathing on electrical cable.

Extrusion of lead sheath on electrical cable.
Effects of temperature on hot extrusion

- Decreased flow stress or deformation resistance due to increasing extrusion temperature.

- Use minimum temperature to provide metal with suitable plasticity.

- The top working temperature should be safely below the melting point.
- Oxidation of billet and extrusion tools.

- Softening of dies and tools.

- Difficult to provide adequate lubrication.

The temperature of the work piece in metal working depends on:

1) The initial temperature of the tools and the materials

2) Heat generated due to plastic deformation

3) Heat generated by friction at the die/material interface (highest)

4) Heat transfer between the deforming material and the dies and surrounding environment.
Extrusion Ratio

Also called the *reduction ratio*, it is defined as

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

where \( r_x \) = extrusion ratio; \( A_o \) = cross-sectional area of the starting billet; and \( A_f \) = final cross-sectional area of the extruded section

- Applies to both direct and indirect extrusion
Extrusion Analysis

Extrusion ratio, \( r_x = \frac{A_o}{A_f} \)

Assuming all sections are circular, ideal deformation, no friction, no redundant work:

\( \varepsilon = \ln r_x \)

Ram pressure

\( p = \bar{Y}_f \ln r_x \)
Extrusion Analysis

For direct extrusion, additional pressure, $p_f$, required by the extruder to overcome the wall friction is related as follows:

The additional pressure:
$$ p_f = P \frac{4\mu L}{D_o} $$

The total ram pressure:
$$ p = P \left( 1 + \frac{4\mu L}{D_o} \right) $$

The power required:
$$ P = F v $$
Extrusion Analysis

For the case of non-circular extruded section, a shape factor has to be introduced:

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

where \( K_x \) = shape factor
\( C_x \) = perimeter of the non-circular extruded section
\( C_c \) = perimeter of a circle that has the same cross-sectional area as the extruded section.

The extrusion pressure,

For direct

\[ pT = K_x P \left( 1 + \frac{4 \mu L}{D_o} \right) \]

For Indirect

\[ p = K_x Y_f \varepsilon_x \]
Extrusion Defects

a) **Centre-burst: internal crack** due to excessive tensile stress at the centre possibly because of high die angle, low extrusion ratio.

b) **Piping**: sink hole at the end of billet under direct extrusion.

c) **Surface cracking**: High part temperature due to low extrusion speed and high strain rates.