ROLLING

strip or plate

rollers
<table>
<thead>
<tr>
<th>S.No</th>
<th>Hot Working</th>
<th>Cold Working</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Working above recrystallization temperature</td>
<td>Working below recrystallization temperature</td>
</tr>
<tr>
<td>2</td>
<td>Formation of new crystals</td>
<td>No crystal formation</td>
</tr>
<tr>
<td>3</td>
<td>Surface finish not good</td>
<td>Good surface finish</td>
</tr>
<tr>
<td>4</td>
<td>No stress formation</td>
<td>Internal Stress formation</td>
</tr>
<tr>
<td>5</td>
<td>No size limit</td>
<td>Limited size</td>
</tr>
</tbody>
</table>
WHAT IS ROLLING??

The process of plastically deforming metal by passing it between rolls.
• The metal is subjected to high compressive stresses as a result of the friction between the rolls and the metal surface.
Bloom is the product of first breakdown of ingot (cross sectional area > 230 cm²).

Billet is the product obtained from a further reduction by hot rolling (cross sectional area > 40×40 mm²).

Slab is the hot rolled ingot (cross sectional area > 100 cm² and with a width ≥ 2 × thickness).
Plate is the product with a thickness $> 6$ mm.

Sheet is the product with a thickness $< 6$ mm and width $> 600$ mm.

Strip is the product with a thickness $< 6$ mm and width $< 600$ mm.
Flat-Rolling

(Top roll removed)

Workpiece

$V_0$, $V_f$

$h_0$, $w_0$, $L$, $R$, $w_f$, $h_f$
(a) Ingot with nonuniform grains

(b) Wrought product with large grains

- Hot rolling
- Deformed elongated grains
- New grains forming
- Recrystallization complete
- New grains growing
- Wrought product with small, uniform grains
Flat Rolling

- Initial thickness $h_o$
- Final thickness $h_f$
- Roll gap $L$
- Surface speed of rolls $V_r$
- Entry velocity of strip $V_o$
- Final velocity of the strip $V_f$

- Neutral point, no-slip point – point along contact length where velocity of the strip equals velocity of the roll
• Draft: $h_o - h_f$
• Maximum draft possible: $h_o - h_f = \mu^2 R$
  • Coefficient of friction $\mu$
  • Roll radius $R$

• The strip thickness is reduced at each rolling pass and the strip width increases slightly (around 2%)
• Roll Force: \( F = L w Y_{avg} \)
  - Roll-strip contact length \( L \)

• Contact length \( L = \sqrt{R (h_0 - h_f)} \)

• Average strip width \( w \) – despite the fact that spreading, or an increase in width, may actually occur if edger mills are not used

• Average true stress of the strip in the roll gap \( Y_{avg} \)

• Assumes no friction and thus predicts lower roll force than the actual value
Power per roll (SI units) = \( \pi FLN / 60,000 \ \text{kW} \)

Where F is in Newtons, L is in meters, and N is rpm of roll
1) The **arc of contact** between the rolls and the metal is a part of a circle.

2) The **coefficient of friction**, $\mu$, is constant in theory, but in reality $\mu$ varies along the arc of contact.

3) The metal is considered to **deform plastically** during rolling.

4) The **volume of metal** is constant before and after rolling. In practical the volume might decrease a little bit due to close-up of pores.

5) The **velocity of the rolls** is assumed to be constant.

6) The metal only extends in the rolling direction and **no extension in the width of the material**.

7) The **cross sectional area** normal to the rolling direction is not distorted.
Forces and geometrical relationships in rolling

- A metal sheet with a thickness $h_0$ enters the rolls at the entrance plane $xx$ with a velocity $v_0$.
- It passes through the roll gap and leaves the exit plane $yy$ with a reduced thickness $h_f$ and at a velocity $v_f$.
- Given that there is no increase in width, the vertical compression of the metal is translated into an elongation in the rolling direction.
- Since there is no change in metal volume at a given point per unit time throughout the process, therefore...
\[ bh_o v_o = bhv = bh_f v_f \]

Where \( b \) is the width of the sheet,

\( v \) is the velocity at any thickness \( h \) intermediate between \( h_o \) and \( h_f \).
From Eq. 1

\[ bh_o v_o = bh_f v_f \]

Given that \( b_o = b_f \)

\[ h_o \frac{L_o}{t} = h_f \frac{L_f}{t} \]

\[ v_o h_o = v_f h_f \]

\[ \frac{v_o}{v_f} = \frac{h_f}{h_o} \]
• At only one point along the surface of contact between the roll and the sheet, two forces act on the metal: 1) a radial force $P_r$ and 2) a tangential frictional force $F$.

• If the surface velocity of the roll $v_r$ equal to the velocity of the sheet, this point is called neutral point or no-slip point. For example, point $N$.

\[ N \text{ point : } v_{\text{roll}} = v_{\text{sheet}} \]
$P_r$ is the radial force, with a vertical component $P$ (rolling load - the load with which the rolls press against the metal).

The specific roll pressure, $p$, is the rolling load divided by the contact area.

$$p = \frac{P}{bL_p}$$

Where $b$ is the width of the sheet. $L_p$ is the projected length of the arc of contact.
ROLL PRESSURE DISTRIBUTION

Friction hill in rolling

Roll pressure vs Length of contact
• The distribution of roll pressure along the arc of contact shows that the pressure rises to a maximum at the neutral point and then falls off.

• The area in shade represents the force required to overcome frictional forces between the roll and the sheet.

• The area under the dashed line AB represents the force required to deform the metal in plane homogeneous compression.
Roll bite condition

The angle of bite or the angle of contact

\[ F \cos \alpha \geq P_r \sin \alpha \]

\[ \frac{F}{P_r} \geq \frac{\sin \alpha}{\cos \alpha} \geq \tan \alpha \]

\[ F = \mu P_r \]

Therefore \[ \mu = \tan \alpha \]

\[ F \] is a tangential friction force

\[ P_r \] is radial force
• **Average flow stress:**

\[ Y = k \varepsilon^n \]

\[ Y_{ave} = \frac{\int_0^{\varepsilon_f} k \varepsilon^n \, d\varepsilon}{\varepsilon_f} = \left[ \frac{k \varepsilon^{n+1}}{\varepsilon_f (n+1)} \right]_0^{\varepsilon_f} = k \frac{\varepsilon_f}{n+1} \]

• **In rolling:**

\[ \varepsilon_f = \ln \frac{h_0}{h_f} \]
PROBLEM

An annealed copper strip 228 mm wide and 25 mm thick is rolled to a thickness of 20 mm in one pass. The roll radius is 300 mm, and the rolls rotate at 100 rpm. Calculate the roll force and the power required.
For annealed copper, it has a true stress of about 80 Mpa in the unstrained condition and at a true strain of 0.223, true stress is 280 Mpa.
FOUR HIGH ROLLING MILL
Simplified analysis of rolling load

*The main variables in rolling are:*

- The roll diameter.
- The deformation resistance of the metal as influenced by metallurgy, temperature and strain rate.
- The friction between the rolls and the workpiece.
- The presence of the front tension and/or back tension in the plane of the sheet.
Relationship of $\mu$, rolling load and torque

$$\mu = \frac{M_T}{PR}$$

- We have known that the location of the neutral point $N$ is where the direction of the friction force changes.

- If back tension is applied gradually to the sheet, the neutral point $N$ shifts toward the exit plane.
Back and front tensions in sheet

Back tension, $\sigma_b$

Front tension, $\sigma_f$

Uncoiler

Coiler

$p$

$\sigma'_o$

$\sigma'_o = \sigma_b$

$\sigma'_o$

$\sigma'_o = \sigma_f$
• 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 ~ 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.
When high forces generated in rolling are transmitted to the workpiece through the rolls, there are two major types of elastic distortions:

1) The rolls tend to bend along their length because the workpiece tends to separate them while they are restrained at their ends. → thickness variation.

2) The rolls flatten in the region where they contact the workpiece. The radius of the curvature is increased $R \rightarrow R'$. (roll flattening)
Roll flattening
Example: Determine the maximum possible reduction for cold-rolling a 300 mm-thick slab when $\mu = 0.08$ and the roll diameter is 600 mm. What is the maximum reduction on the same mill for hot rolling when $\mu = 0.5$?
**Example:** Determine the maximum possible reduction for cold-rolling a 300 mm-thick slab when $\mu = 0.08$ and the roll diameter is 600 mm. What is the maximum reduction on the same mill for hot rolling when $\mu = 0.5$?

From Eq.7,

$$ (\Delta h)_{\text{max}} = \mu^2 R $$

For cold-rolling

$$ (\Delta h)_{\text{max}} = (0.08)^2 (300) = 1.92\text{mm} $$

For hot-rolling

$$ (\Delta h)_{\text{max}} = (0.5)^2 (300) = 75\text{mm} $$

Alternatively, we can use the relationship below

$$ \sin \alpha = \frac{L_p}{R} = \frac{\sqrt{R \Delta h}}{R}, \alpha = \tan^{-1}(\mu) $$

$$ \Delta h = 1.92\text{mm} $$
PROBLEMS AND DEFECTS IN ROLLED PRODUCTS

Porosity, Cavity, Blow Holes occurred in the cast ingot will be closed up during the rolling processes.

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

There are **two aspects** to the problem of the shape of a sheet.

1) **Uniform thickness** over the width and thickness – can be precisely controlled with modern gage control system.

![Diagram of uniform thickness](image1)

2) **Flatness** – difficult to measure accurately.

![Diagram of flatness](image2)
Perfectly flat

More elongated along edges

More elongated in the centre
Possible effects when rolling with insufficient camber

- Thicker centre means the edges would be plastically elongated more than the centre, normally called **long edges**.
- This induces the residual stress pattern of compression at the edges and tension along the centreline.
- This can cause **centreline 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 centre means the centre would be plastically elongated more than the edges, resulting in **lateral spread**.

- The *residual stress pattern* is now under compression in the centreline and tension at the edges (b).

- This may cause **edge cracking** (c), **centre splitting** (d), **centreline wrinkling** (e).
Residual Stresses Developed in Rolling

(a) Residual stresses developed in rolling with small-diameter rolls or at small reductions in thickness per pass. (b) Residual stresses developed in rolling with large-diameter rolls or at high reductions per pass. Note the reversal of the residual stress patterns.
Production of Steel Balls

(a) Production of steel balls by the skew-rolling process. (b) Production of steel balls by upsetting a cylindrical blank. Note the formation of flash. The balls made by these processes subsequently are ground and polished for use in ball bearings.
Ring-Rolling

(a) Schematic illustration of a ring-rolling operation. Thickness reduction results in an increase in the part diameter. (b-d) Examples of cross-sections that can be formed by ring-rolling.
Thread-rolling processes: (a) and (c) reciprocating flat dies; (b) two-roller dies. (d) Threaded fasteners, such as bolts, are made economically by these processes at high rates of production. Source: Courtesy of Central Rolled Thread Die Co.
Machined and Rolled Threads

(a) Features of a machined or rolled thread. Grain flow in (b) machined and (c) rolled threads. Unlike machining, which cuts through the grains of the metal, the rolling of threads imparts improved strength because of cold working and favorable grain flow.
Cavity formation in a solid, round bar and its utilization in the rotary tube-piercing process for making seamless pipe and tubing.

**Mannesmann Process**
Tandem Rolling
Schematic illustration of various tube-rolling processes: (a) with fixed mandrel; (b) with moving mandrel; (c) without mandrel; and (d) pilger rolling over a mandrel and a pair of shaped rolls. Tube diameters and thicknesses can also be changed by other processes, such as drawing, extrusion, and spinning.