# Rolling

# Content

- Terminology of rolled products
- Different kinds of rolling mills
- Rolling base on temperature
  - Hot Rolling
  - Cold rolling
  - Rolling of blooms billets, slabs, plates, strips, sheets, bars, rods & light section
- Lay out of different mills for rolling of above products
- Elementary roll pass design
- Forces and geometrical relationships in rolling
  - Deformation zone in rolling
  - Neutral point
  - Angle of bite
  - Forward slip
  - Roll flattening
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- Defects in rolled products

Rolling: The process of plastic deformation of metal by passing it between rolls.

- Widely used metal working process
  - high production
  - close control of the final product

- For deformation, high compressive stress is applied by rolls
  - Surface shear stresses due to friction between rolls and metal

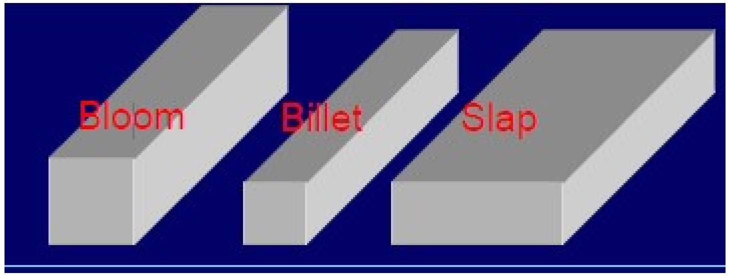
Stages of Rolling :

• Breakdown of ingots into blooms and billets by hot rolling.

• Blooms and billets →plate, sheet, rod, bar, pipe, rails and structural shape by hot or cold rolling.

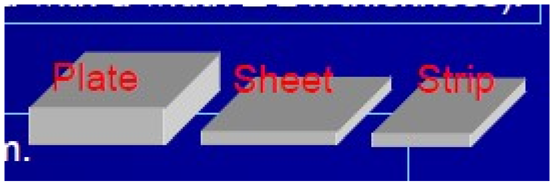
## Semi Finished Product

- Bloom is the product of first breakdown of ingot (cross sectional area > 230 $cm^2$).
- Billet is the product obtained from a further reduction by hot rolling (cross sectional area > 160 $mm^2$).
- Slab is the hot rolled ingot (cross sectional area > 100 $cm^2$ and with a width ≥ 2 x thickness).

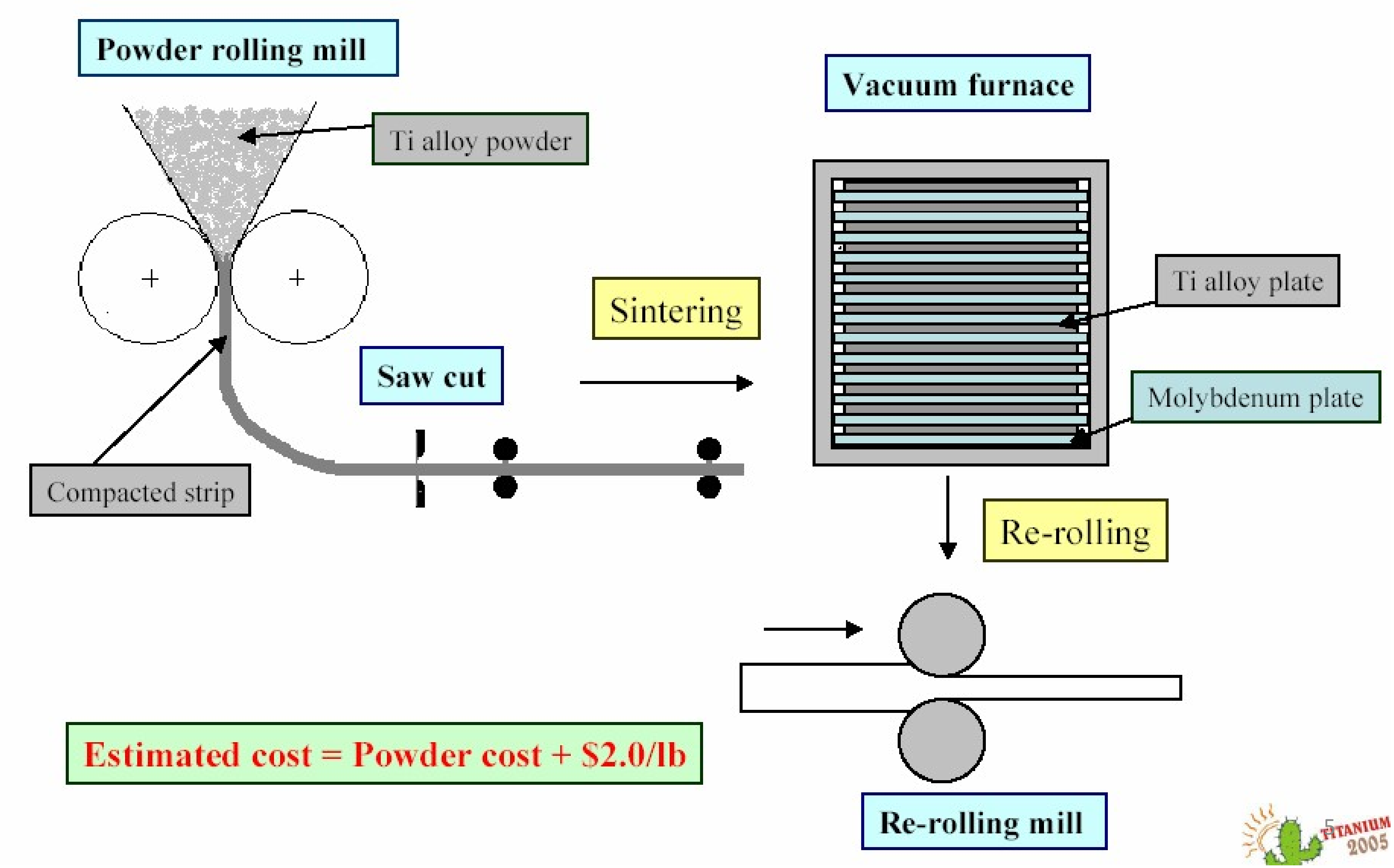



## Mill Products

- 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.



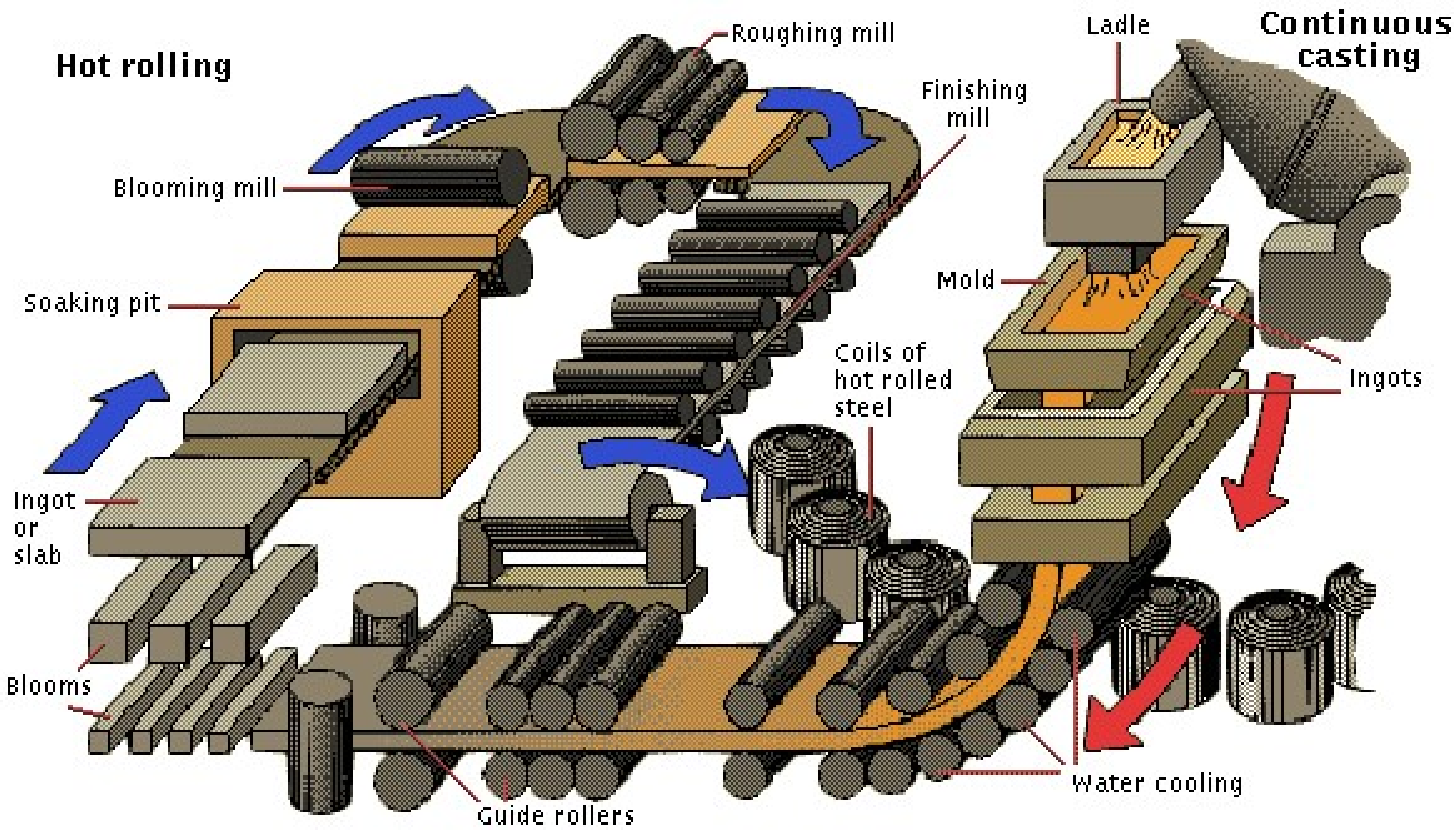
Powder Rolling: A metal powder is introduced between the rolls and compacted into a green strip, which is subsequently sintered and subjected to further hot and/or cold working and annealing cycles.



Advantage:

- Elimination of initial hot-ingot breakdown step which need large capital equipment
- Minimization of contamination in hot rolling
- production of sheet with very fine grain size or min. preferred orientation.

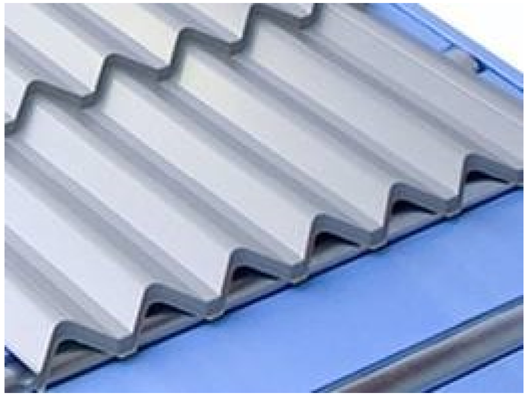
# Continuous casting and hot rolling



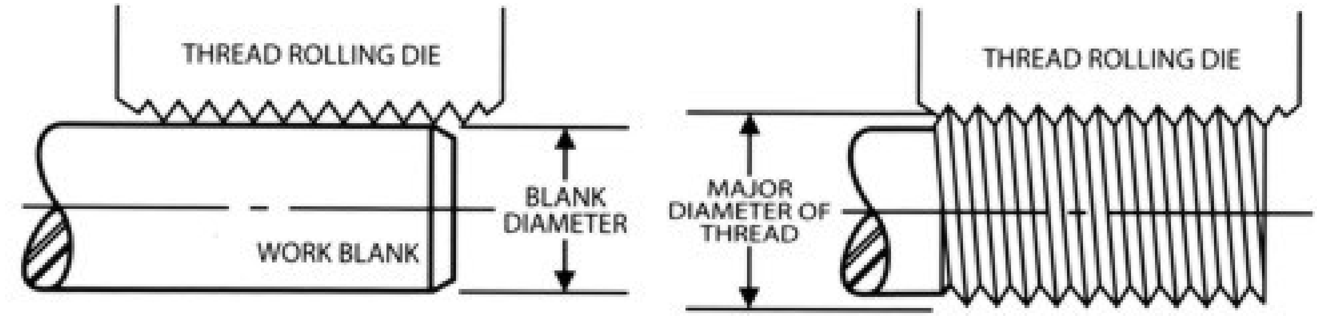

- Metal is melted, cast and hot rolled continuously through a series of rolling mills within the same process.
- Usually for steel sheet production.

Conventional rolling: to decreases the thickness of the metal which raise the length.

Roll forming: The strip is progressively bent into complex shapes by passing and by pressing through series of driven rolls. There won't be much change in thickness. It produces irregular shaped channels and trim.



Thread rolling: A blank is fed between two grooved die plates to form the threads.

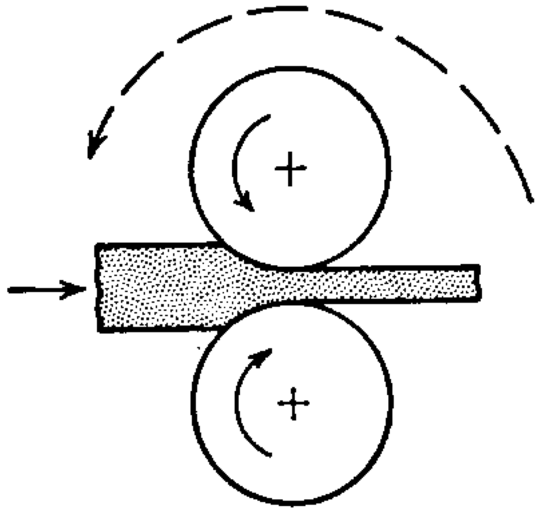



# Classification of Rolling

- Hot Rolling Mill
  - Two high or pullover mill
  - Two high reversing
  - Three high mill
  - Four high mill
  - Cluster mill
  - Sendzimir mill
  - Four stand continuous mill
  - Planetary mill
- Cold Rolling Mill
  - Pendulum mill
  - Contact Bend Stretch (CBS) rolling process

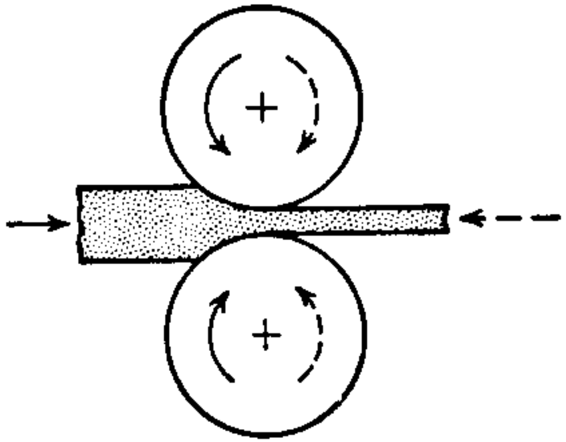
## Two high or pullover mill:

- simplest and common type mill
- Rolls of equal size are rotated only in one direction
- The stock is returned to the entrance or rear for further reduction



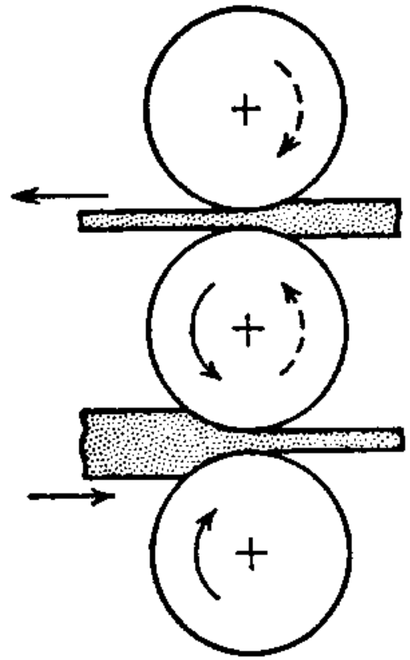
## Two high reversing:

- The work can be passed back and forth the rolls by reversing their direction of rotation
- It raises the productivity.



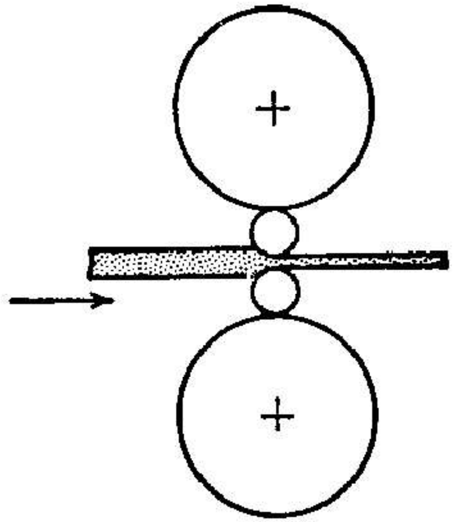
### Three high mill:

- Consists of an upper and lower driven roll and middle roll which rotates by friction.

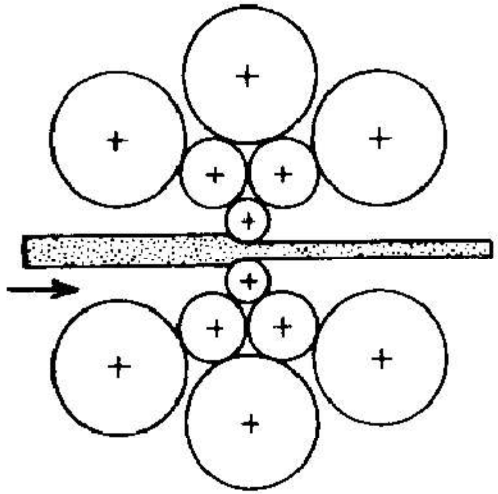


### Four high mill:

- Power requirement is less due to small diameter rolls.
- Because of small diameter rolls have less strength and rigidity than large rolls, they supported by larger-diameter backup rolls.
- Very thin sheet can be rolled to very close tolerances on  a mill with small-diameter work rolls.



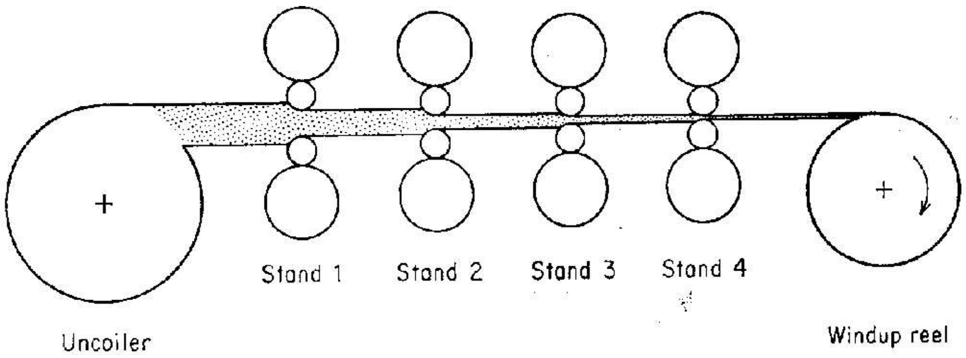
Cluster mill: the work rolls is supported by two backing rolls.

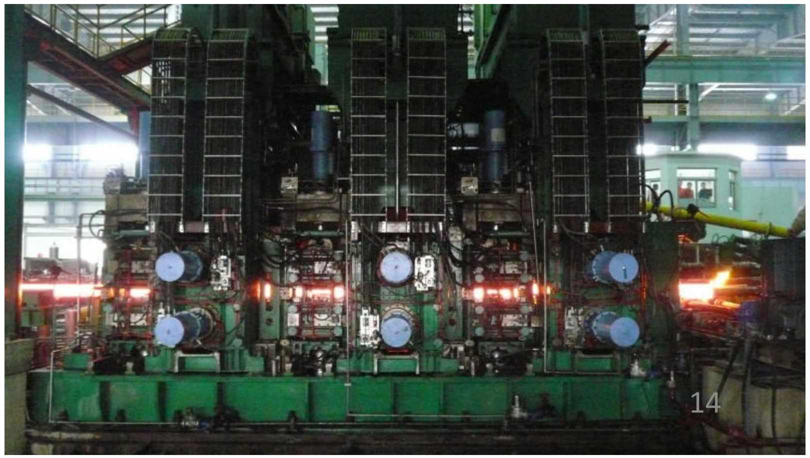


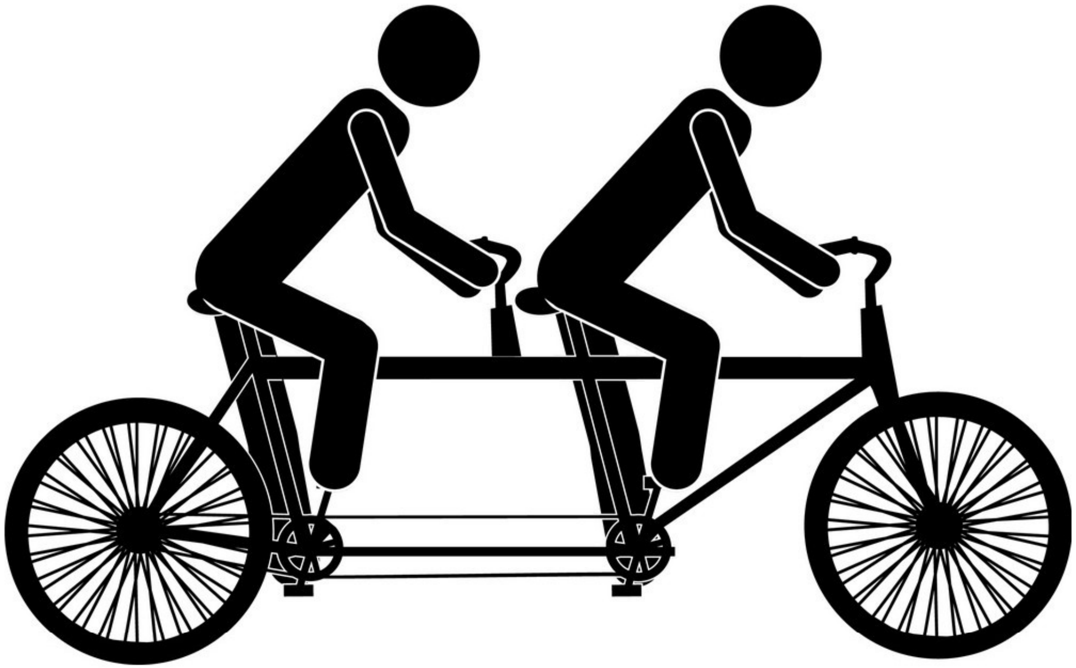
Sendzimir mill: is modification of cluster mill which is used for rolling thin sheet or foil from high strength alloys.

## Four stand continuous mill:

- For high production, a series of rolling mills one after another is connected like in tandem.
- Different reduction is taken at each stand, the strip will be moving a different velocities at each stage in the mill.
- The uncoiler and windup reel are feeding the stock to the rolls and coiling up the final product. In addition, supplies a back tension and a front tension to the strip which gives horizontal forces.

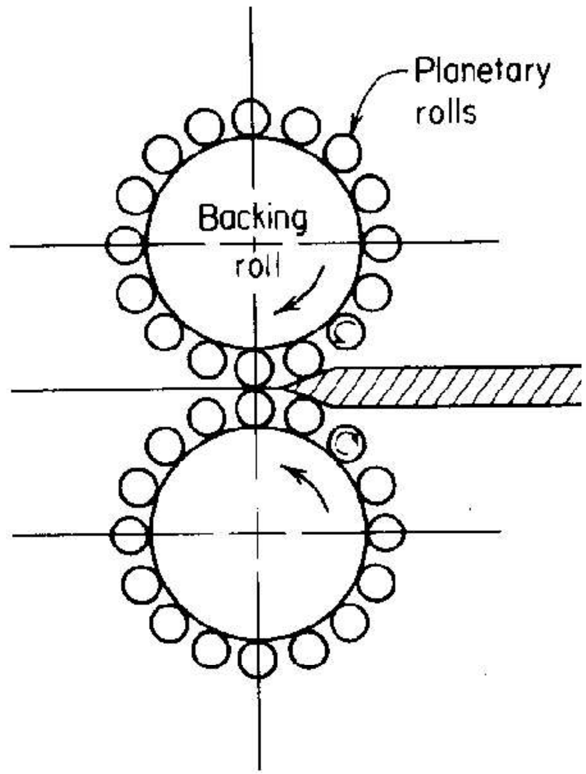




## Planetary mill:

- It has different rolling mill design.
- This mill consists of a pair of heavy backing rolls surrounded by a large number of small planetary rolls.
- The advantage of planetary mill is that it hot reduces a slab directly to strip in one pass through the mill.
- Each planetary roll gives an almost constant reduction to the slab as it sweeps out a circular path between the backing roll and the slab.
- As each pair of planetary rolls ceases to have contact with the work piece another pair of rolls makes contact and repeats that reduction.
- The overall reduction is the summation of series of small reductions by each pair of rolls in turn following each other in rapid succession.
- The action of planetary mill is more like forging than rolling.
- Feed rolls is used to introduce the slab into the mill and a pair of planishing roll at the exit side improve the surface finish.



## Cold Roll Mill

- Pendulum mill: uses small diameter work rolls which reciprocate over the arc of contact to cold reduce a slab to a thin sheet.
- Contact-bend-stretch (CBS) rolling process: uses four high mill with a small diameter floating bend roll.

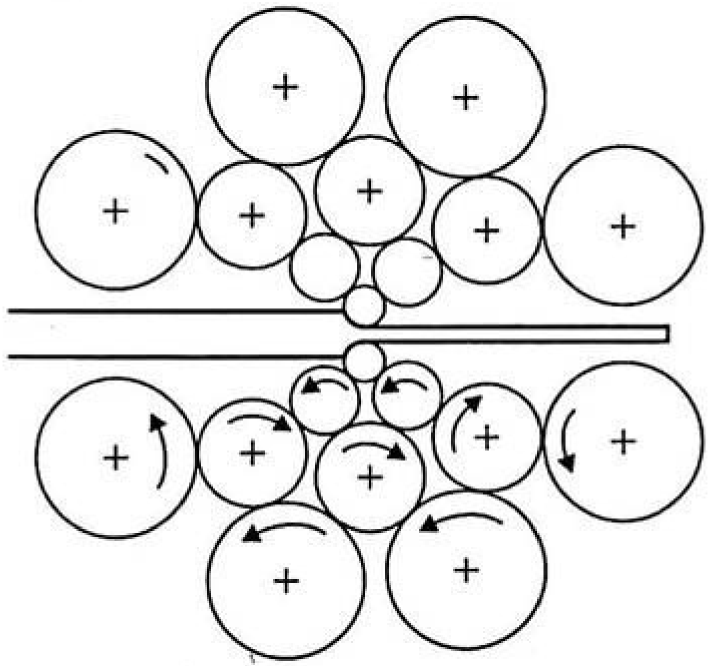
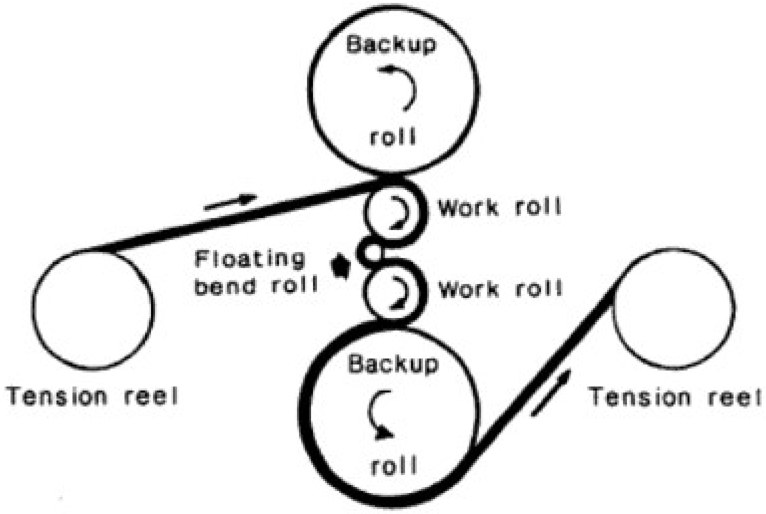
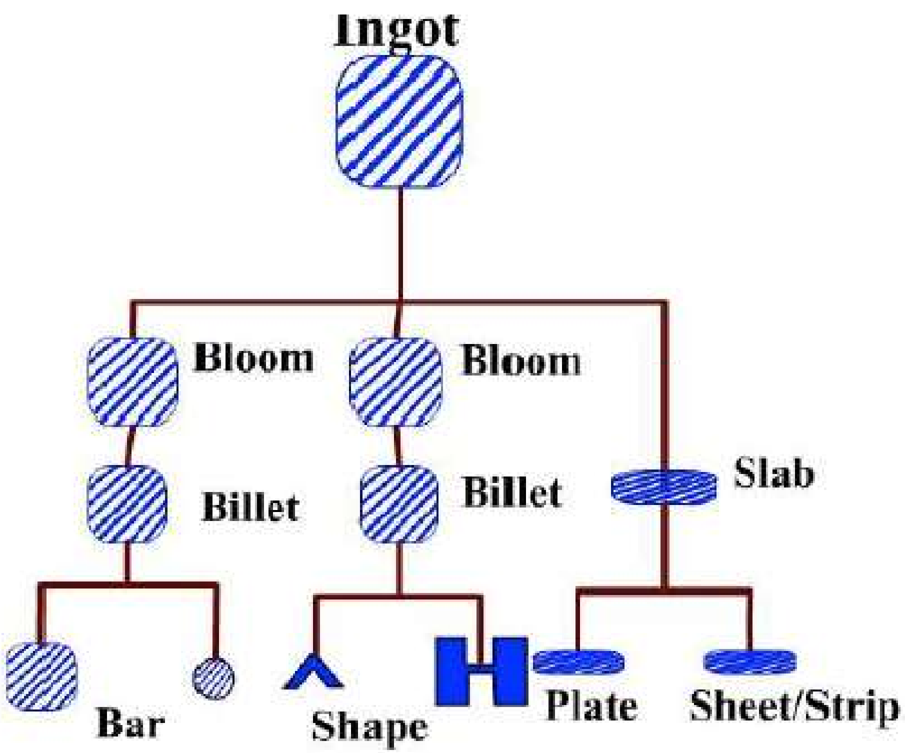


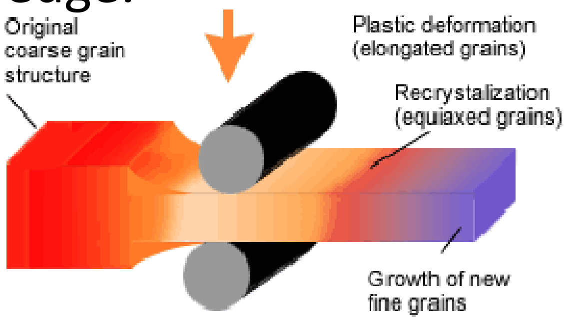
Fig. 6.1. Sendzimir mill.

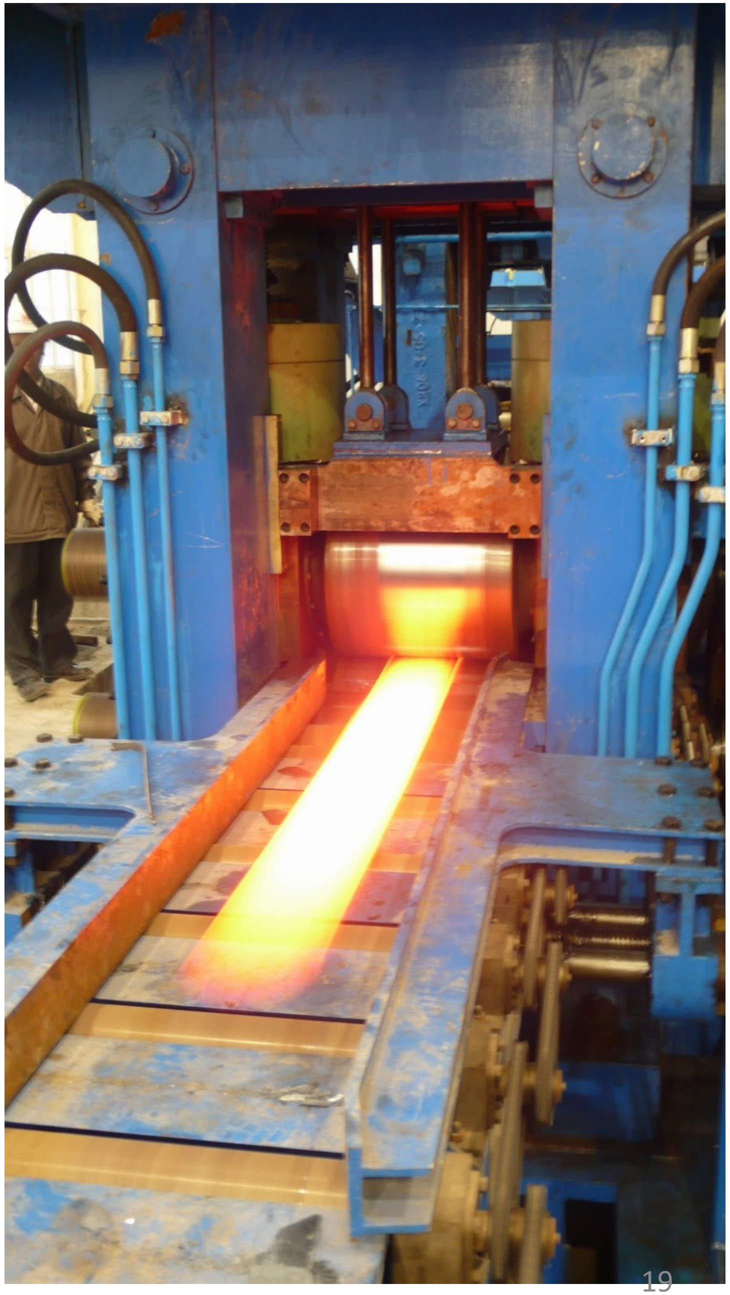



Ingot
Bloom
Bloom
Billet
Billet
Slab
Bar
Shape
Plate
Sheet/Strip

# Hot Rolling

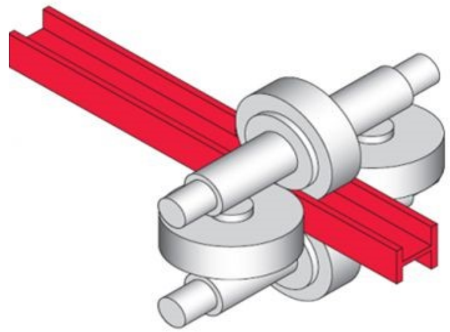
- The cast ingot converted into blooms or slabs by hot working operation are called as primary roughing mill (also called as blooming, slabbing or cogging mills).
- These mills are normally two high reversing mills with 0.6 to 1.4m diameter rolls.
- Ingot → blooms/slabs → bars → plate → sheet
- The initial breakdown passes often involve only small reduction. Heavy scale is removed initially by rolling the ingot while lying on edge.

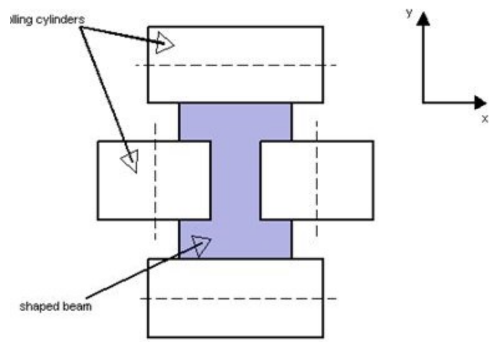


## Slap Production:

- Reversing Mills
  - (low production and edging)
- Universal Mills
  - high production
  - 2 rolling mills + 2 vertical mills)
- Continuous casting
  - The elimination of ingot molds, stripping equipment, soaking pits and primary (bloom, billet, slab) mills
  - 60 to 75% less generation of scrap in the production of billets and slabs
  - Faster solidification which gives uniform structure
  - Smaller initial and operating costs
- Bottom pressure casting

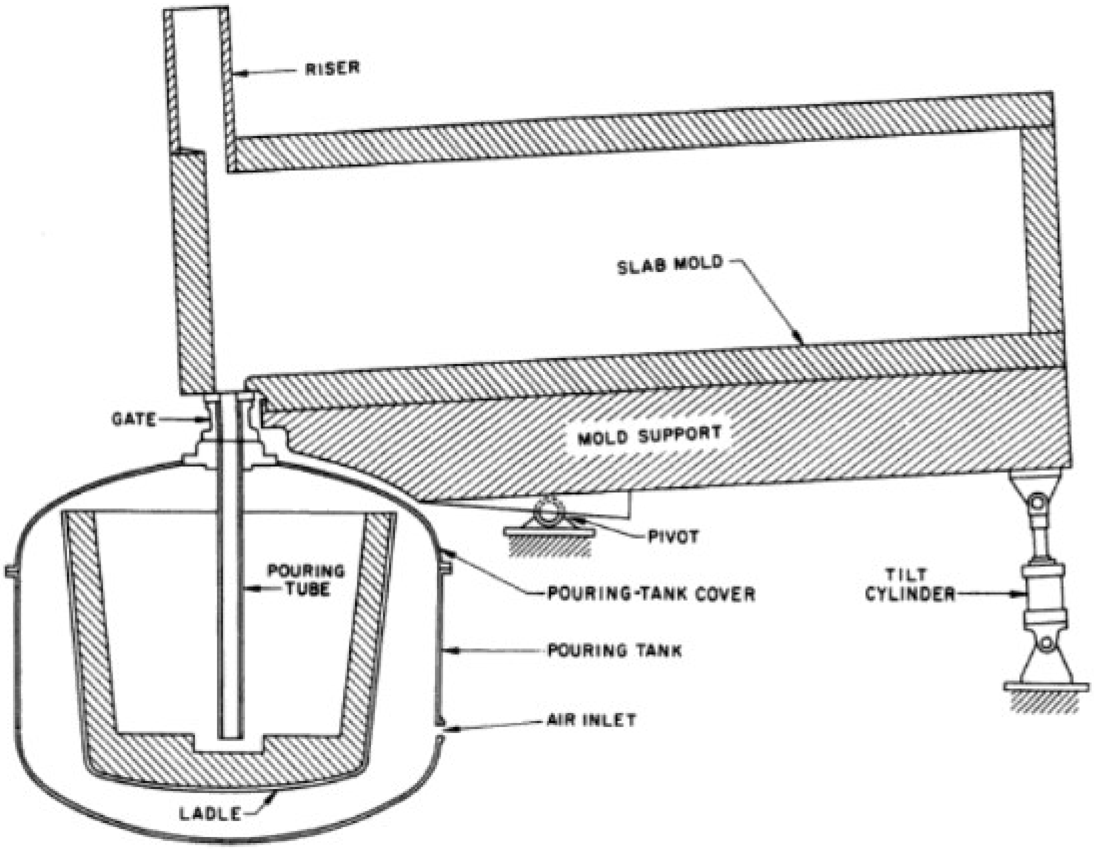





Universal mill

# Bottom Pressure Casting

- Eliminates the ingot and primary mill stages
- Products cast by this method include 2.5 square billets, 8-inch diameter rounds and slabs 6 inches by 30 inches edges by 17 feet long.
- Even larger slabs (150 x 1050 x 7600mm) of stainless steel are being cast by this method in Japan for rolling into plate and strip



## Plate Production:

- Sheared plate: Straight horizontal mill --> trimming of edges
- Universal mill plates: Universal mill + trimming of edges

## Sheet/Strip Production: (Strip < 600mm & sheet > 600mm wide)

- Continuous hot strip mill

Slabs → Scale breaker mill → Roughing train (4 four high mills) → Finishing train (6 four high mills) → strip

Slabs → Scale breaker mill → broadside mill → Finishing train → sheet

(width of slab is increased by cross rolling)

- In hot-rolling steel, the slabs are heated initially at 1100 - 1300$^{o}$C. The temperature in the last finishing stand varies from 700 - 900$^{o}$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 to 90%.
- 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, gauge, and surface finish.
- Cold rolling provide products with superior surface finish (due to low temperature  no oxide scales)
- Better dimensional tolerances compared with hot-rolled products due to less thermal expansion.
- Cold-rolled nonferrous sheet may be produced from hot-rolled strip, or in the case of certain copper alloys it is cold-rolled directly from the cast state.

Cold rolled metals are rated as ‘temper’

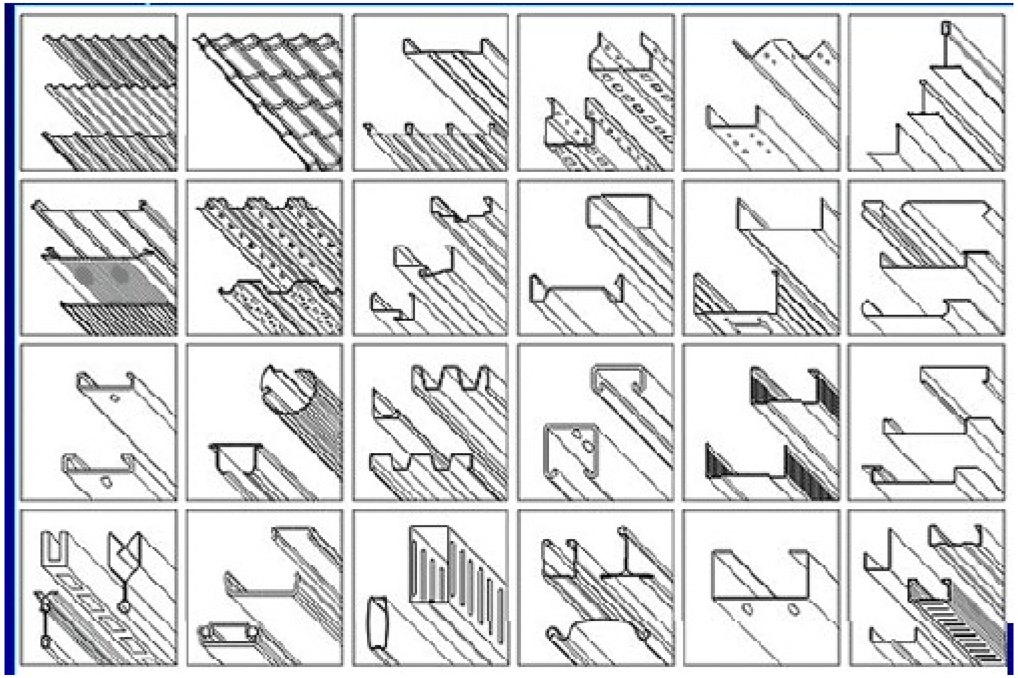
- Skin rolled : Metal undergoes the least rolling ~ 0.5-1% harden, still more workable.
- Quarter hard : Higher amount of deformation. Can be bent normal to rolling direction without fracturing
- Half hard : Can be bent up to $90^{o}$.
- Full hard : Metal is compressed by 50% with no cracking. Can be bent up to $45^{o}$.

# Roll Forming

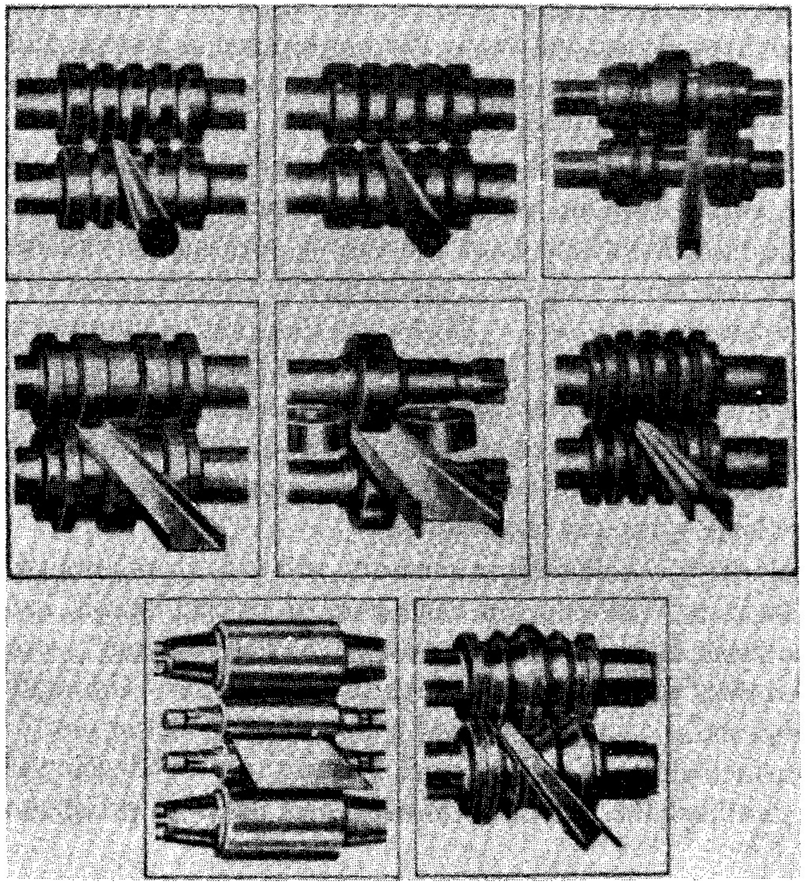
A variety of sections can be produced by roll forming process using a series of forming rollers in a continuous method to roll the metal ingot or sheet to a specific shape

**Applications:**

- construction materials
- partition beam
- ceiling panel
- roofing panels
- steel pipe
- automotive parts
- household appliances
- metal furniture,
- door and window frames
- other metal products.

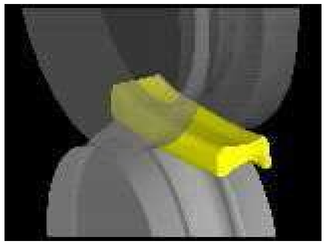


# Rolling of Bars and Shapes



Hot rolling with grooved rolls

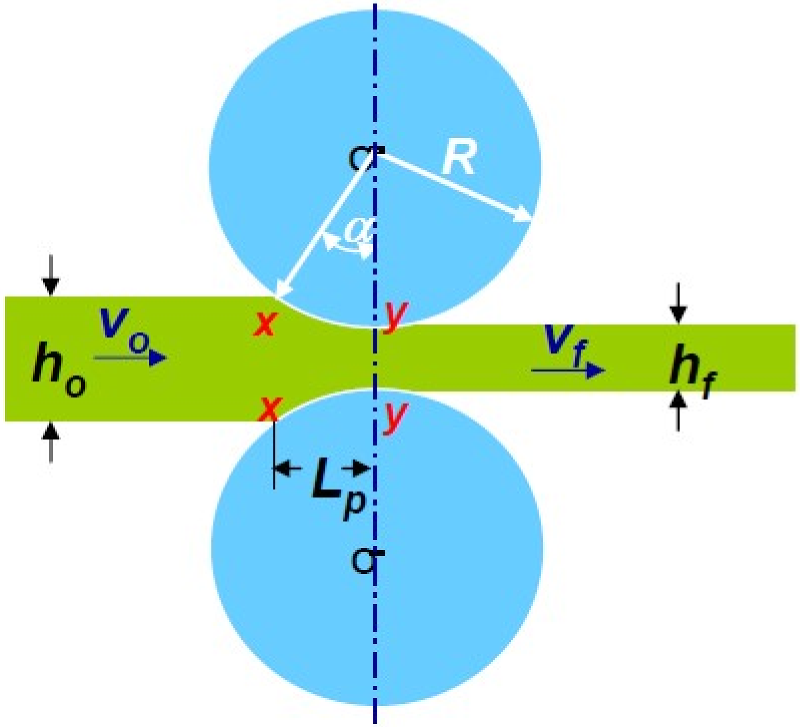
- Bars shape
  - Circular
  - Hexagonal
- Structural shaped beams
  - Channels
  - Railroad rails



- In rolling of bars and shapes, the cross section is metal is reduced in two direction for that it is rotated $90^0$.
- Spreading of metal in hot working is more than cold working.
  - In designing, allowance for spreading has to be considered
  - Other possibility is passes through oval and square shaped grooves.
- Bars produced by rolling mill
  - Called as bar mill or merchant mill
  - Generally have two or three high rolling mill
  - Continuous stand (rolls ) are used

# Fundamental of Metal Rolling

- The arc of contact between the rolls and the metal is a part of a circle.
- The coefficient of friction, μ is constant in theory, but in reality μ varies along the arc of contact.
- The metal is considered to deform plastically during rolling.
- 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.
- The velocity of the rolls is assumed to be constant.
- The metal only extends in the rolling direction and no extension in the width of the material.
- The cross sectional area normal to the rolling direction is not distorted.



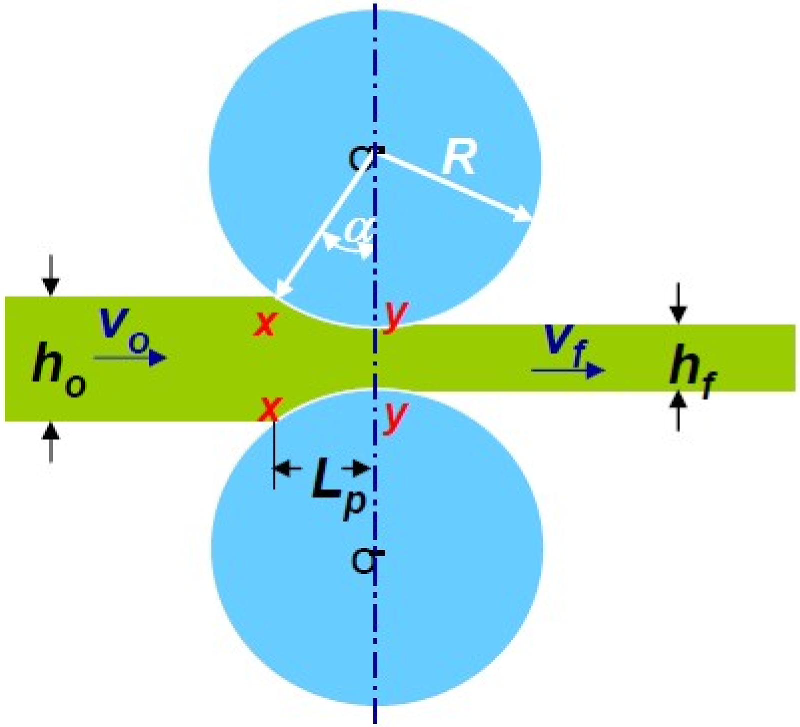
# Forces and geometrical relationships in rolling

- A metal sheet with a thickness $h_o$ enters the rolls at the entrance plane xx with a velocity $v_o$.
- 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 of throughout the process, therefore

$$bh_o v_o = bhv = bh_f v_f$$

Where b is the width of the sheet

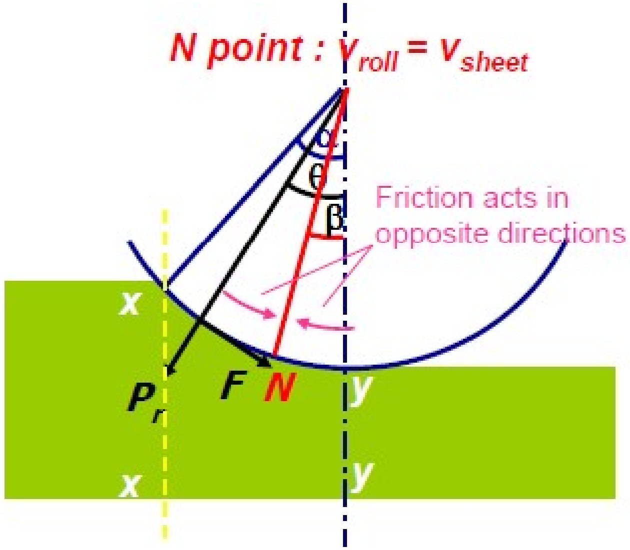
v is the velocity at any thickness h intermediate between $h_o$ and $h_f$.



- Note that, $V_f > V_i$.
- 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.
- At any point along the surface of contact between the roll and the sheet, two forces act on the metal:

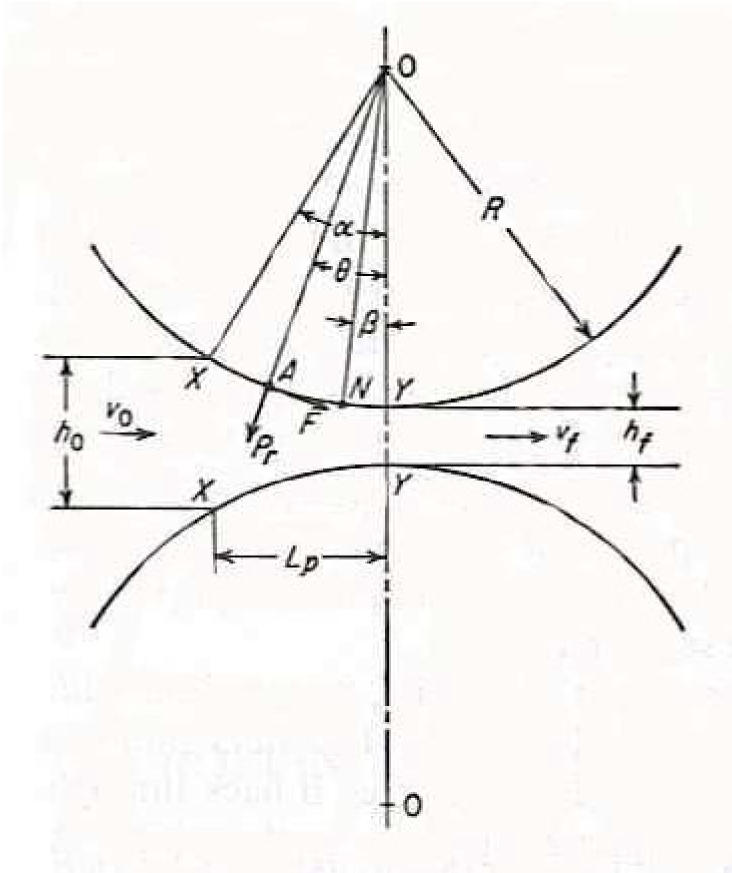
  1) a radial force $P_r$ and

  2) a tangential frictional force F.
- Between the entrance plane (xx) and the neutral point the sheet is moving slower than the roll surface, and the tangential frictional force, F, act in the direction (see Fig) to draw the metal into the roll.
- On the exit side (yy) from the neutral point, the sheet moves faster than the roll surface. The direction of the frictional force is then reversed and oppose the delivery of the sheet from the rolls.



- The vertical component $P_r$ is also called as rolling load P (rolling load is the load with which the rolls press against the metal which is equal to the force exerted by the metal two separate the roll [separating force]).
- The specific roll pressure 'p' is the rolling load divided by the contact area.

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

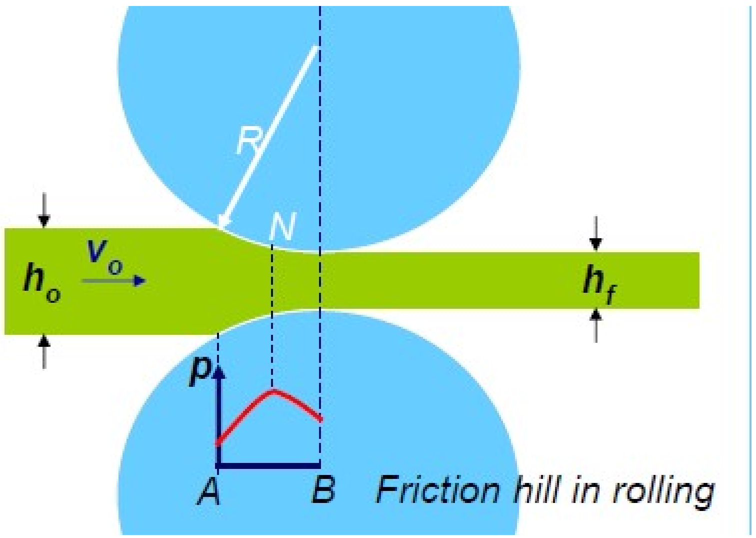


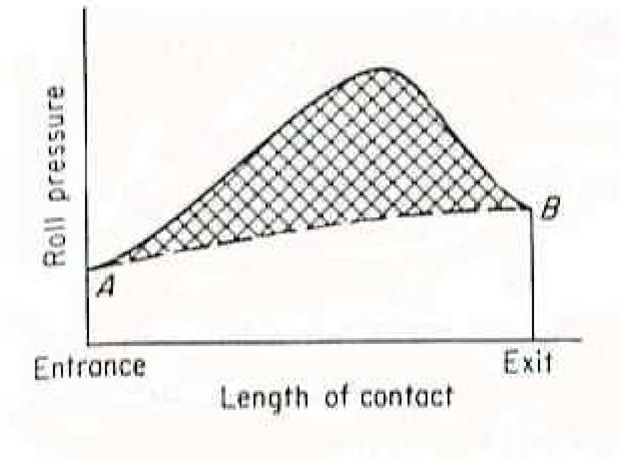

Where b is the width of the sheet

$L_p$ is the projected length of the arc of contact.

$$L_p = \left[ R\left(h_0 - h_f\right) - \frac{(h_o - h_f)^2}{4} \right]^{1/2} \approx \left[ R\left(h_o - h_f\right) \right]^{1/2}$$

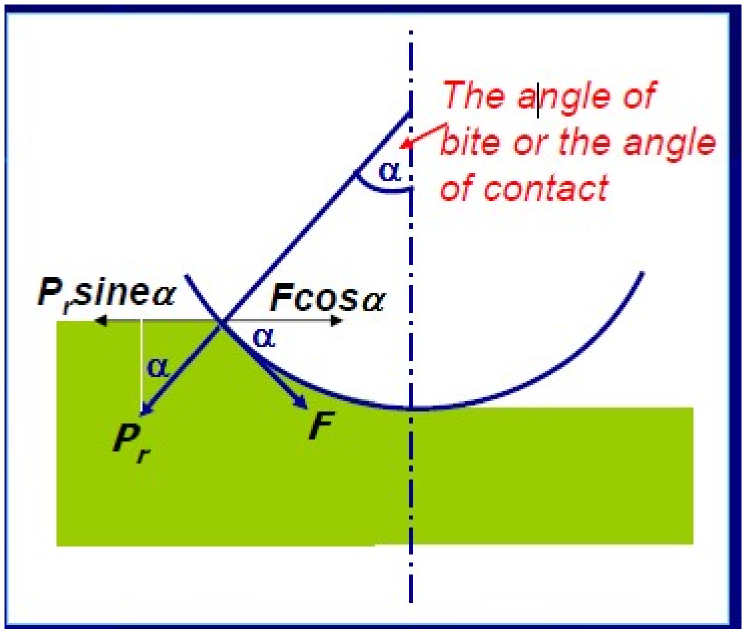
- The distribution of roll pressure along the arc of contact shows that the pressure rises to a maximum at the neutral point and then falls off.
- The pressure distribution does not come to a sharp peak at the neutral point, which indicates that the neutral point is not really a line on the roll surface but an area.
- The area under the curve is proportional to the rolling load.
- 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 'α' between entrance plane and the centerline of the rolls is called as angle of contact or angle of bite.
- For the workpiece to enter the throat of the roll, the component of the friction force must be equal to or greater than the horizontal component of the normal force.




$$F \cos\alpha \geq P_r \sin\alpha$$

$$\frac{F}{P_r} \geq \frac{\sin\alpha}{\cos\alpha} \geq \tan\alpha$$

We know that, $F = \mu P_r$

Therefore,

$$\mu = \tan\alpha$$

Note

- if tan α > μ, the work piece cannot be drawn
- If μ = 0, rolling cannot occur

Therefore Free engagement will occur when $\mu > \tan \alpha$

Increase the effective values of $\mu$ , for example grooving the rolls parallel to the roll axis.

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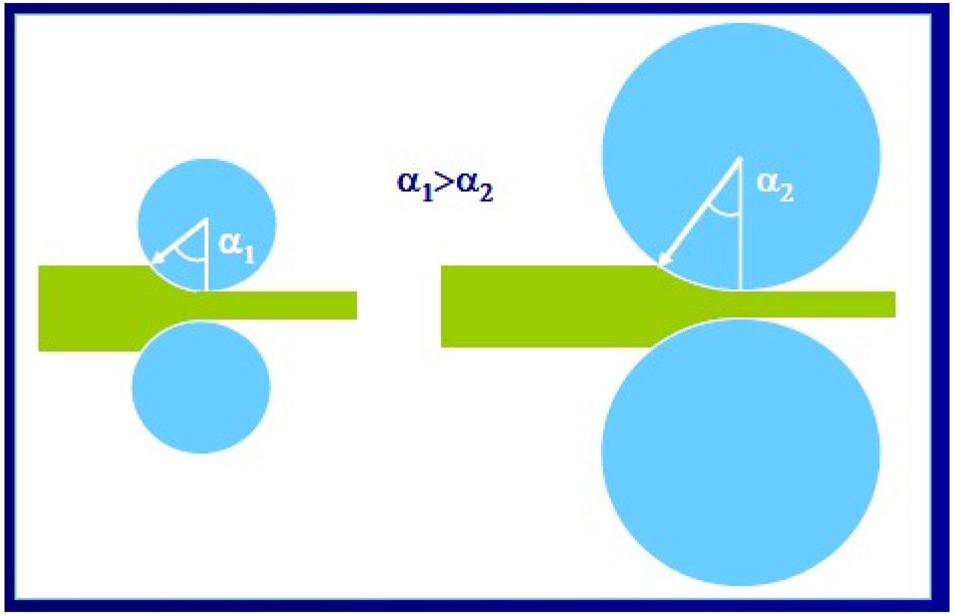
Using big rolls to reduce $\tan \alpha$ or if the roll diameter is fixed, reduce the $h_o$



# Maximum Reduction

From triangle ABC,

$$R^2 = L_p^2 + (R-a)2$$

$$L_p^2 = R^2 - \left(R^2 - 2Ra + a^2\right)$$

$$L_p^2 = 2Ra - a^2$$

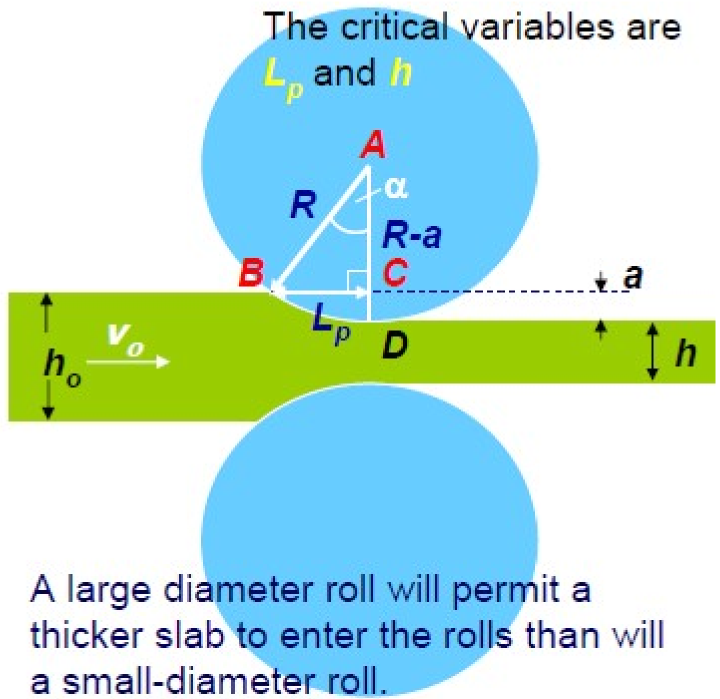
If a<<R, ignore $a_2$.

$$L_p \approx \sqrt{2Ra} \approx \sqrt{R\Delta h}$$

Where $\Delta h = h_o - h_f = 2a$

$$\mu = \tan\alpha = \frac{L_p}{R - \Delta h/2} \approx \frac{\sqrt{R\Delta h}}{R - \Delta h/2} \approx \sqrt{\frac{\Delta h}{R}}$$

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

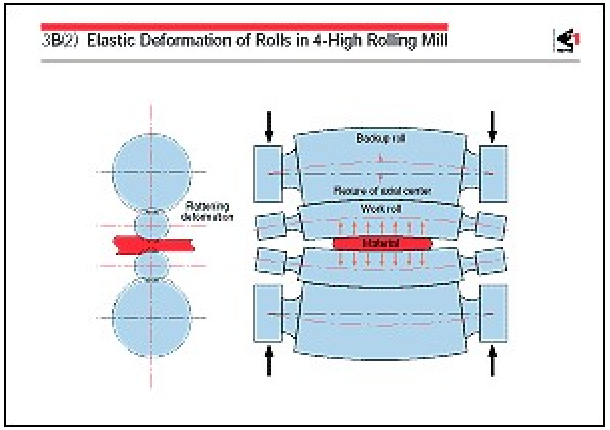


# Problem with roll flattening

When high forces generated in rolling are transmitted to the workpiece through the rolls, there are two major types of elastic distortions:

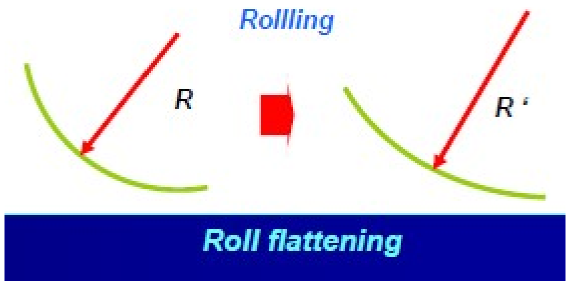
1) The rolls tends to bend along their length because the workpiece tends to separate them while they are restrained at their ends. (Thickness variation)

2) The rolls flatten in the region where they contact the workpiece. The radius of the curvature is increased R to R'. (roll flattening).




According to analysis by Hitchcock,

$$R' = R\left[1 + \frac{CP'}{b\left(h_o - h_f\right)}\right]$$




Where $C=16(1-v^2)E=2.16\times10^{-11}\ Pa^{-1}$ for steel rolls

P'=rolling load based on the deformed roll radius

Problem: Determine the maximum possible reduction for coldrolling a 300 mm-thick slab when μ = 0.08 and the roll diameter is 600 mm. What is the maximum reduction on the same mill for hot rolling when μ = 0.5?

R=300mm μ= 0.08 for cold rolling → Δh=?

μ=0.5 for hot rolling → Δh=?

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

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

$$(\Delta h)_{\max} = (0.05)^2 (300) = 75 mm$$

We can also use, tanα=μ→ get α

$$\sin\alpha = \frac{\mathrm{L_p}}{\mathrm{R}} = \frac{\sqrt{R\Delta h}}{R} = \sqrt{\frac{\Delta h}{R}} \quad \rightarrow \Delta h$$

# 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.

We consider in three conditions:

1) No friction condition

2) Normal friction condition

3) Sticky friction condition

## No Friction Condition:

In the case of no friction situation, the rolling load (P) is given by the roll pressure (p) times the area of contact between the metal and the rolls ($bL_p$).

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

$$P = pbL_p = \sigma'_o b\sqrt{R\Delta h}$$

Where the roll pressure (p) is the yield stress in plane strain when there is no change in the width (b) of the sheet.

## Normal Friction Condition:

In the normal case of friction situation in plane strain, the average pressure $\overline{p}$ can be calculated as:

$$\frac{\overline{p}}{\overline{\sigma}} = \frac{1}{Q}(e^{Q} - 1)$$

Where $Q = \mu L_p / \overline{h}$ and $\overline{h}$ is the mean thickness between entry and exit from the roller.

$$P = \overline{p} b L_p$$

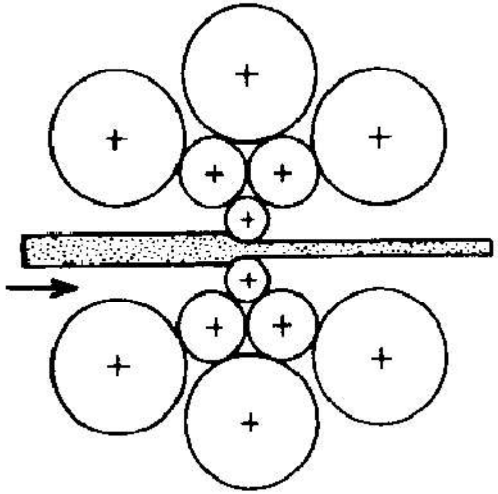
$$P = \frac{2}{\sqrt{3}}\overline{\sigma}_o\left[\frac{1}{Q}\left(e^{Q} - 1\right)b\sqrt{R\Delta h}\right]$$

Roll diameter ↑ Rolling load ↑

- Therefore the rolling load P increases with the roll radius $R^{1/2}$, depending on the contribution from the friction hill.
- The rolling load also increases as the sheet entering the rolls becomes thinner (due to the term $e^Q$).
- At one point, no further reduction in thickness can be achieved if the deformation resistance of the sheet is greater than the roll pressure. The rolls in contact with the sheet are both severely elastically deformed.
- Small-diameter rolls which are properly stiffened against deflection by backup rolls can produce a greater reduction before roll flattening become significant and no further reduction of the sheet is possible.
- Example: the rolling of aluminium cooking foil. Roll diameter < 10 mm with as many as 18 backing rolls.

$$P = \frac{2}{\sqrt{3}}\bar{\sigma}_o\left[\frac{1}{Q}\left(e^Q - 1\right)b\sqrt{R\Delta h}\right]$$

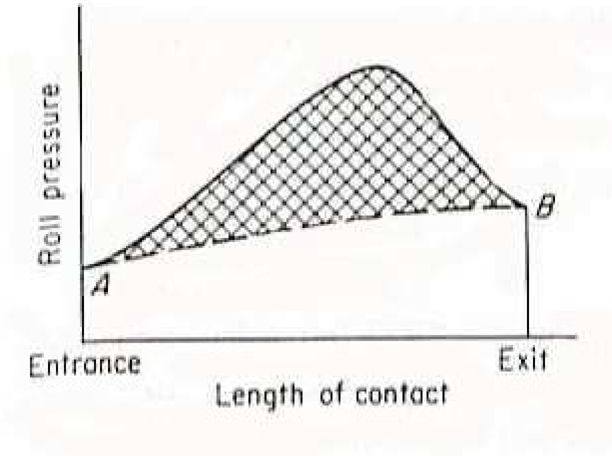
$$Q = \mu L_p / \bar{h}$$



- Frictional force is needed to pull the metal into the rolls and responsible for a large portion of the rolling load.
- High friction results in high rolling load, a steep friction hill and great tendency for edge cracking.
- The friction varies from point to point along the contact arc of the roll. However it is very difficult to measure this variation in μ, all theory of rolling are forced to assume a constant coefficient of friction.
- For cold-rolling with lubricants,

  μ ~ 0.05 – 0.10.
- For hot-rolling ,

  μ ~ 0.2 up to sticky condition.



Example: Calculate the rolling load if steel sheet is hot rolled 30% from a 40 mm-thick slab using a 900 mm-diameter roll. The slab is 760 mm wide. Assume μ = 0.30. The plane-strain flow stress is 140 MPa at entrance and 200 MPa at the exit from the roll gap due to the increasing velocity.

$$\frac{h_o - h_f}{h_o} X100 = 30\%$$

$$\frac{(40) - h_f}{(40)} X100 = 30\%$$

$$h_f = 28mm$$

$$\Delta h = h_o - h_f$$

$$\Delta h = (40) - (28) = 12mm$$

$$\bar{h} = \frac{ho + hf}{2} = \frac{(40) + (28)}{2} = 34mm$$

$$Q = \frac{\mu L_p}{\bar{h}} = \frac{\mu\sqrt{R\Delta h}}{\bar{h}}$$

$$Q = \frac{(0.30)\sqrt{450x12}}{(34)} = 0.65$$

$$\bar{\sigma}'o = \frac{\sigma'_{entrance} + \sigma'_{exit}}{2}$$

$$\bar{\sigma}'o = \frac{140 + 200}{2} = 170MPa$$

$$P = \sigma'_o \left[ \frac{1}{Q}\left(e^Q - 1\right) b\sqrt{R\Delta h} \right]$$

$$P = 170\left[ \frac{1}{(0.65)}\left(e^{0.65} - 1\right)(0.76)\sqrt{0.45x0.012} \right]$$

$$P = 13.4MN$$

For sticky friction situation

Continuing the analogy with compression in plane strain

$$\overline{p} = \sigma_o' \left( \frac{a}{2\overline{h}} + 1 \right) = \sigma_o' \left( \frac{L_p}{4\overline{h}} + 1 \right)$$

$$L_p = \sqrt{R \Delta h}$$

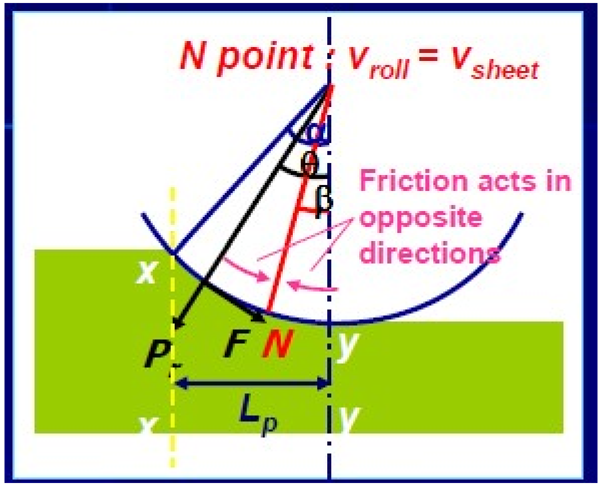
$$P = \overline{p} b L_p$$

$$P = \sigma_o' \left( \frac{\sqrt{R \Delta h}}{4\overline{h}} + 1 \right) b \sqrt{R \Delta h}$$

$$P = 170 \left( \frac{\sqrt{0.45x0.012}}{4x0.034} + 1 \right) (0.76) \sqrt{0.45x0.012}$$

$$P = 14.6 MN$$

# Relationship of μ, rolling load and torque




- 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.
- The total rolling load P and torque MT (per unit of width b) is given by

$$\frac{P}{b} = \int_0^{L_p} p\,dx$$

$$\frac{M_T}{b} = \int_o^{L_p} (\mu p\,dx) R = \mu R \frac{P}{b}$$

*thus*

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

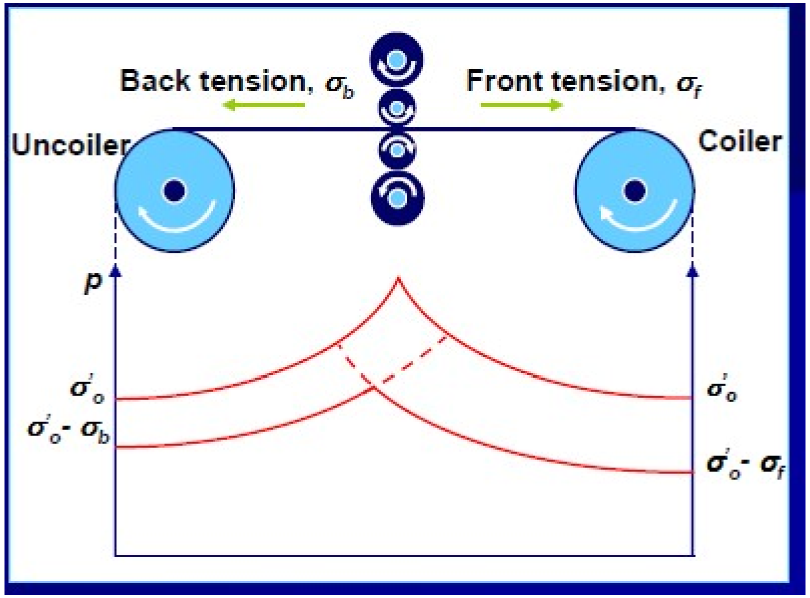
Where μ is obtained by measuring the torque and the rolling load at constant roll speed and reduction with the proper back tension.

# Back and front tensions in sheet

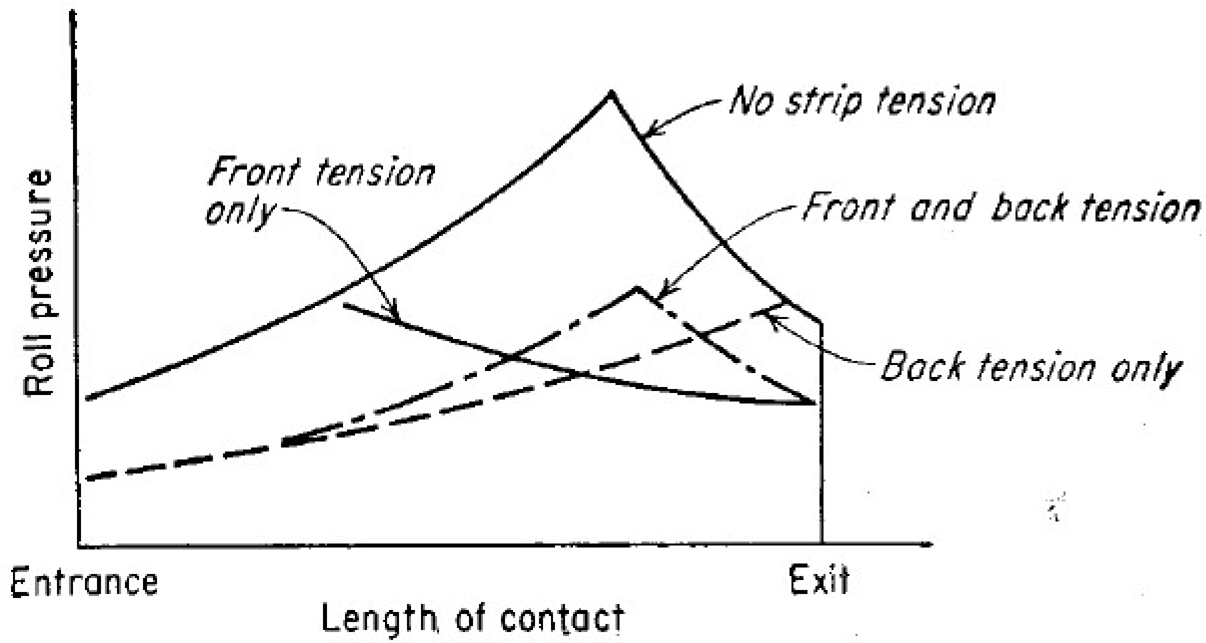
- The presence of back and front tensions in the plane of the sheet reduces the rolling load.
- Back tension may be produced by controlling the speed of the uncoiler relative to the roll speed.
- Front tension may be created by controlling the coiler.
- The effect of sheet tension on reducing rolling pressure p can be shown simply by

$$p = \sigma'_o - \sigma_h = \frac{2}{\sqrt{3}}\bar{\sigma}o - \sigma_h$$

Where $\sigma_h$ = horizontal sheet 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.


No strip tension
Front tension only
Front and back tension
Back tension only
Roll pressure
Entrance
Exit
Length of contact

# Defects in rolled Products

## Classification :

- Defects from cast ingot i.e. before rolling
- Defects due to rolling

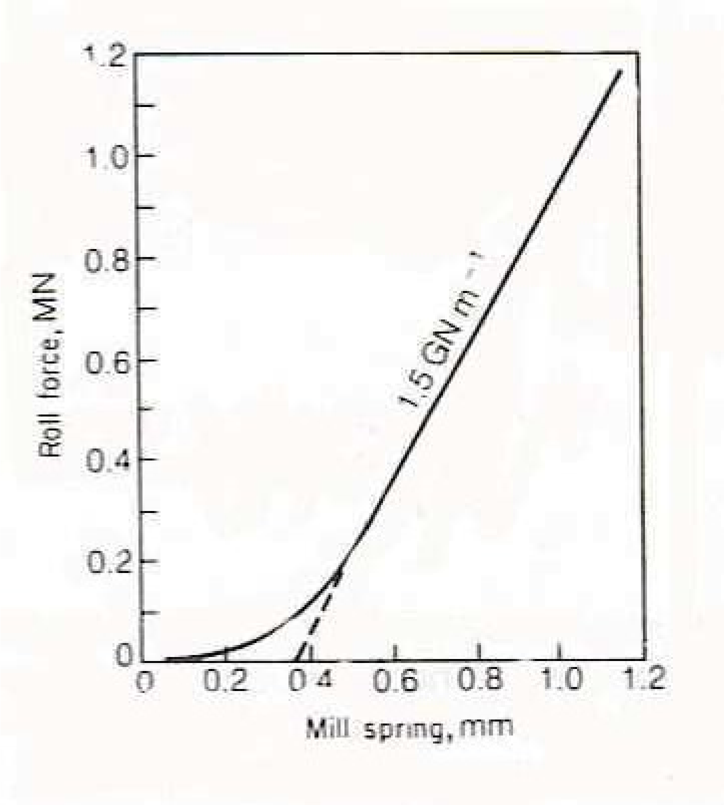
### Defects from cast ingot:

- 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 in Rolled Products

- Defects based on the interaction of the plastically deforming workpiece with the elastically deforming rolls and rolling mill.
- Mill Spring causes the thickness of the sheet exiting from the rolling mill to be greater than the roll gap set under no-load conditions.
  - Precise thickness rolling requires the elastic constant of the mill. Calibration curves are needed.

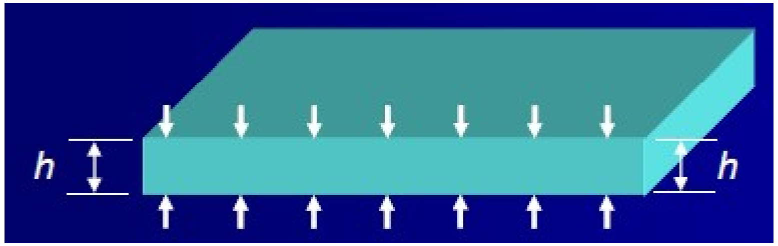
  (Elastic constant: Screw loaded rolling mills – 1 to 3 $GNm^{-1}$, Hydraulically loaded mills – 4 $GNm^{-1}$)



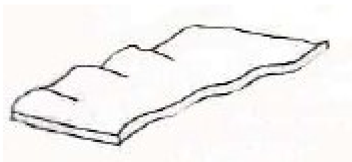
# Defects during rolling

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.

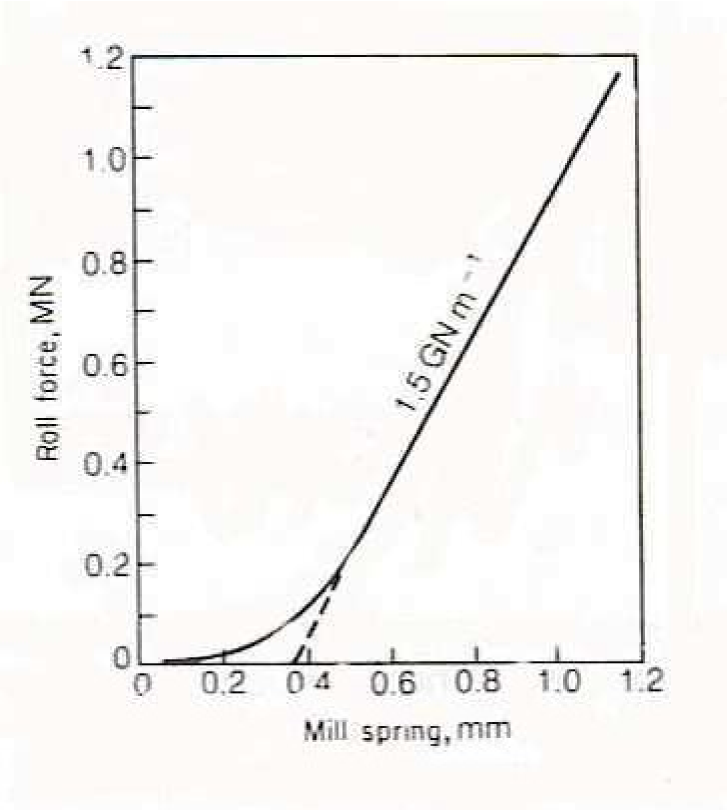


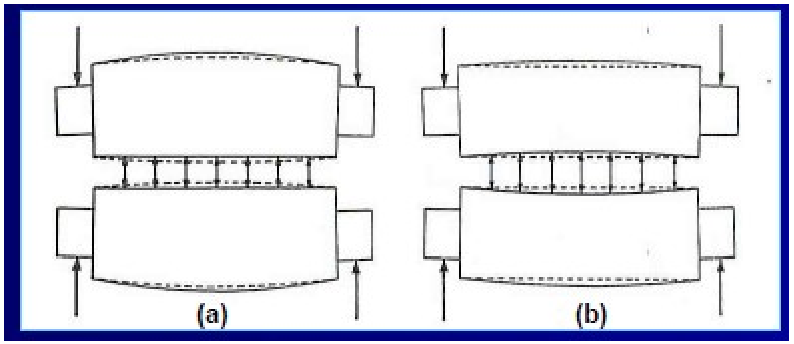

2) Flatness – difficult to measure accurately.



## 1. Uniform thickness

- Under high rolling forces, the rolls flatten and bend, and the entire mill is elastically distorted.
- Mill spring causes the thickness of the sheet exiting from the rolling mill to be greater than the roll gap set under no-load conditions.
- Precise thickness rolling requires the elastic constant of the mill. Calibration curves are needed, see Fig. (1–3 $GNm^{-1}$ for screw-loaded rolling mills, 4 $GNm^{-1}$ for hydraulically loaded mills).



- Roll Flattening: increases the roll pressure and eventually causes the rolls to deform more easily than the metal.
- The limiting thickness is proportional to μ, R, $\sigma_o'$ inversely proportional to E.

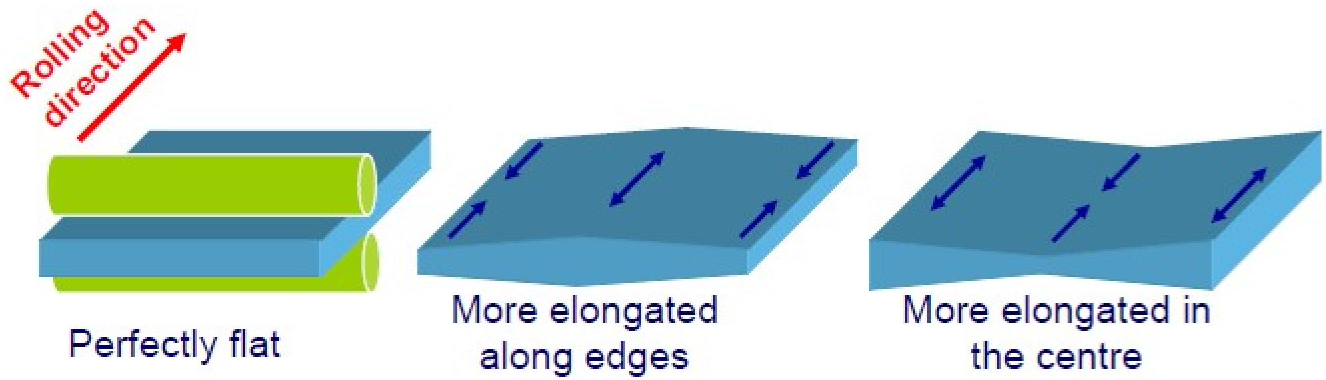
For example in steel rolls the limiting thickness is given by

$$h_{\min} = \frac{\mu R \overline{\sigma}_o}{12.8}$$

In general, problems with limiting gauge can be expected when the sheet thickness is below 1/400 to 1/600 of the roll diameter.

## 2. Flatness:

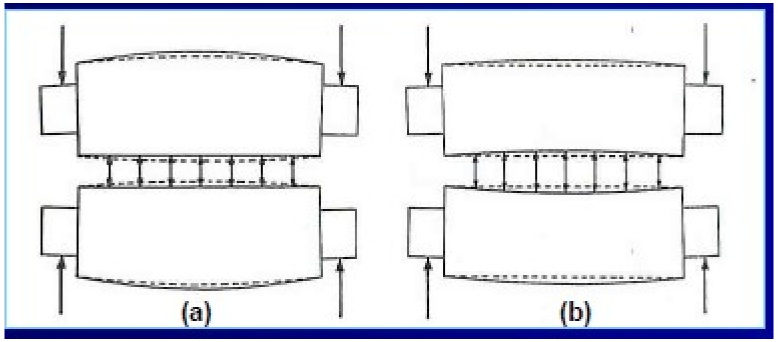
- The roll gap must be perfectly parallel to produce sheets/plates with equal thickness at both ends.
- The rolling speed is very sensitive to flatness. A difference in elongation of one part in 10,000 between different locations in the sheet can cause waviness.




# Solutions to flatness problems

• Camber and crown can be used to correct the roll deflection (at only one value of the roll force). Or

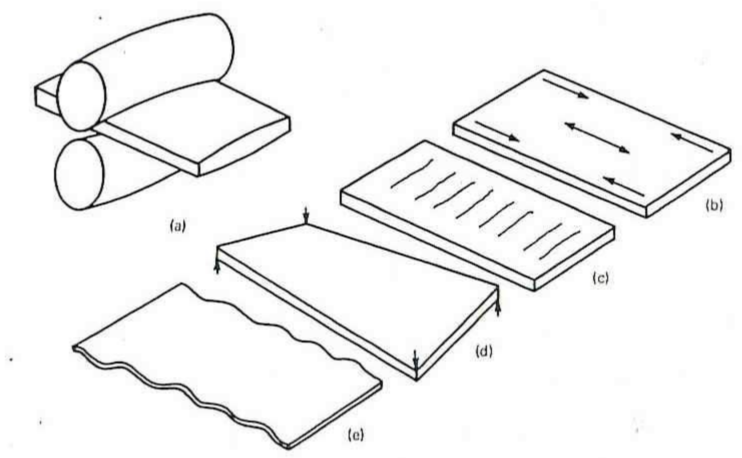
• Use rolling mill equipped with hydraulic jacks to permit the elastic distortion of the rolls to correct deflection.




*(a) The use of cambered rolls to compensate for roll bending.*

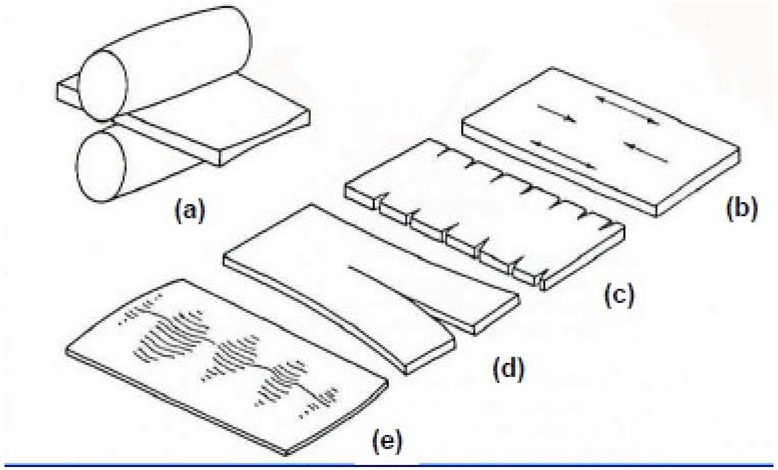
*(b) Uncambered rolls give variation of thickness.*

# Possible effects when rolling without and 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).

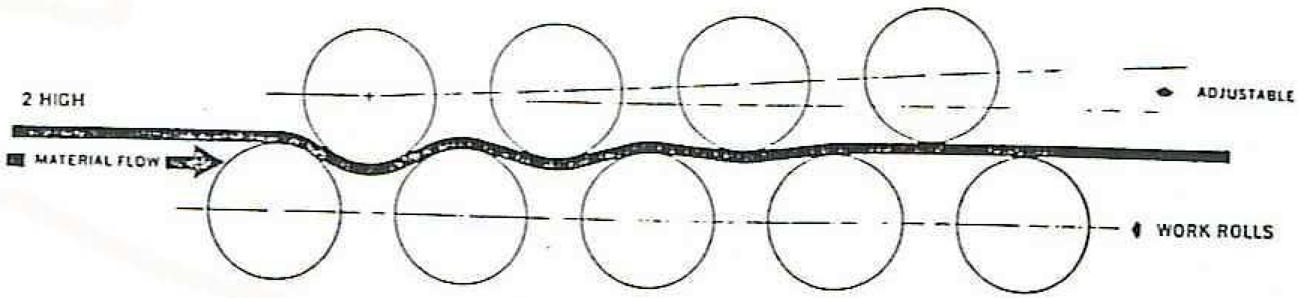
# Possible effects when rolls are without or over cambered




- 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).

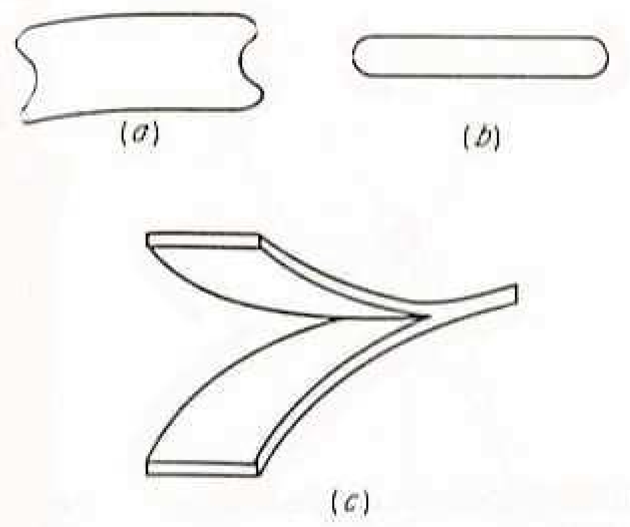
# Problem in rolling of thin strip

- Shape problems are greatest when rolling in thin strip (<0.01 in) because fractional errors in the roll gap profile increase with decrease in thickness, producing larger internal stress.
- Thin sheet is also less resistant to buckling.
- Mild shape problems may be corrected by stretch levelling the sheet in tension or by bend flexing the sheet in a roller-leveller, see Fig.

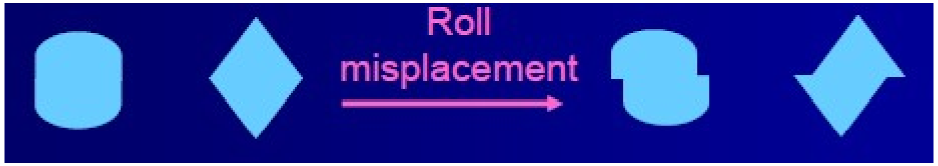


- Edging can also be caused by inhomogeneous deformation in the thickness direction.
- If only the surface of the workpiece is deformed (as in a light reduction on a thick slab), the edges are concaved (a). The overhanging material is not compressed in the subsequent step of rolling, causing this area under tensile stress and leading to edge cracking. This has been observed in initial breakdown of hot-rolling when $h/L_p > 2$

- With heavy reduction, the centre tends to expand more laterally than the surface to produced barrelled edges (b). This causes secondary tensile stresses by barrelling, which are susceptible to edge cracking.
- Alligatoring (c) will occur when lateral spread is greater in the centre than the surface (surface in tension, centre in compression) and with the presence of metallurgical weakness along the centerline



- Surface defects are more easily occur 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.