

Rolling of metals

Subjects of interest



- *Introduction/objectives*
- *Rolling mills*
- *Classification of rolling processes*
- *Hot rolling*
- *Cold rolling*
- *Forces and geometry relationships in rolling*
- *Simplified analysis of rolling load: Rolling variables*
- *Problems and defects in rolled products*
- *Rolling-mill control*
- *Theories of cold rolling*
- *Theories of hot rolling*
- *Torque and power*

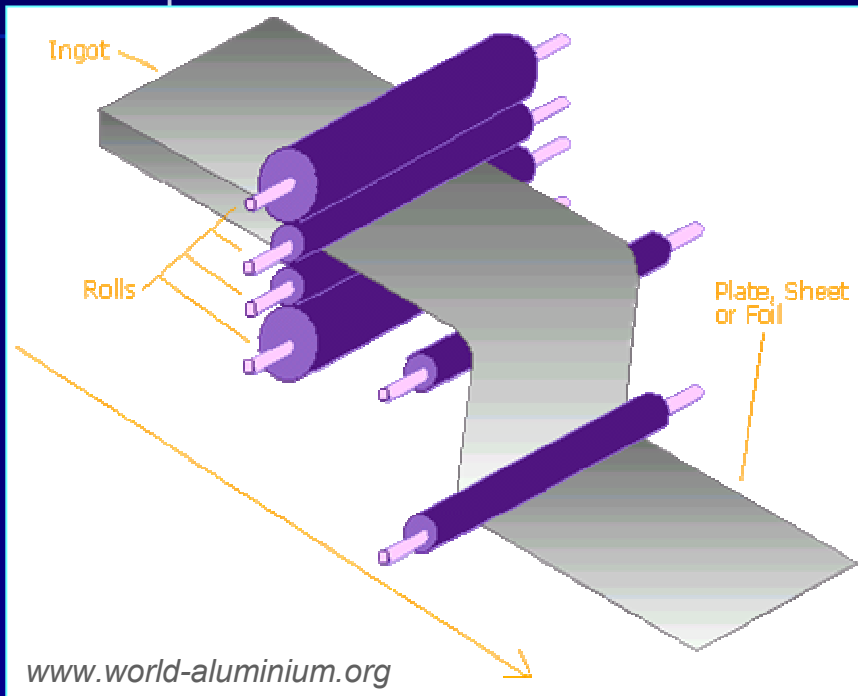


Objectives

- This chapter provides information on different types of metal rolling processes which can also be divided in to hot and cold rolling process.
- Mathematical approaches are introduced for the understanding of load calculation in rolling processes.
- Finally identification of defects occurring during and its solutions are included.



Introduction- Definition of rolling process



Rolling process

- **Definition of Rolling** : The process of plastically deforming metal by passing it between rolls.
- Rolling is the **most widely used** forming process, which provides high production and close control of final product.
- The metal is subjected to high **compressive stresses** as a result of the friction between the rolls and the metal surface.

Note: rolling processes can be mainly divided into 1) hot rolling and 2) cold rolling.



Introduction- Hot and cold rolling processes

Hot rolling

- The initial **breakdown of ingots** into **blooms** and **billets** is generally done by **hot-rolling**. This is followed by further hot-rolling into plate, sheet, rod, bar, pipe, rail.



Cold rolling

- The **cold-rolling** of metals has played a major role in industry by providing sheet, strip, foil with **good surface finishes** and **increased mechanical strength** with close control of product **dimensions**.



Sheet rolling machines



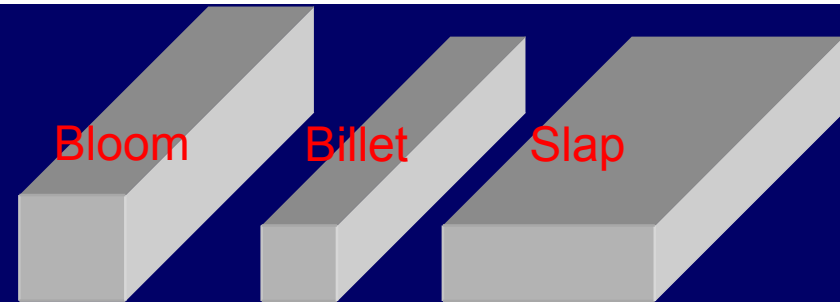
Rolled strips



Rollforming machine



Terminology



Semi-finished products

- **Bloom** is the product of first breakdown of ingot (cross sectional area $> 230 \text{ cm}^2$).
- **Billet** is the product obtained from a further reduction by hot rolling (cross sectional area $> 40 \times 40 \text{ mm}^2$).
- **Slab** is the hot rolled ingot (cross sectional area $> 100 \text{ cm}^2$ and with a width $\geq 2 \times$ thickness).

Further rolling steps

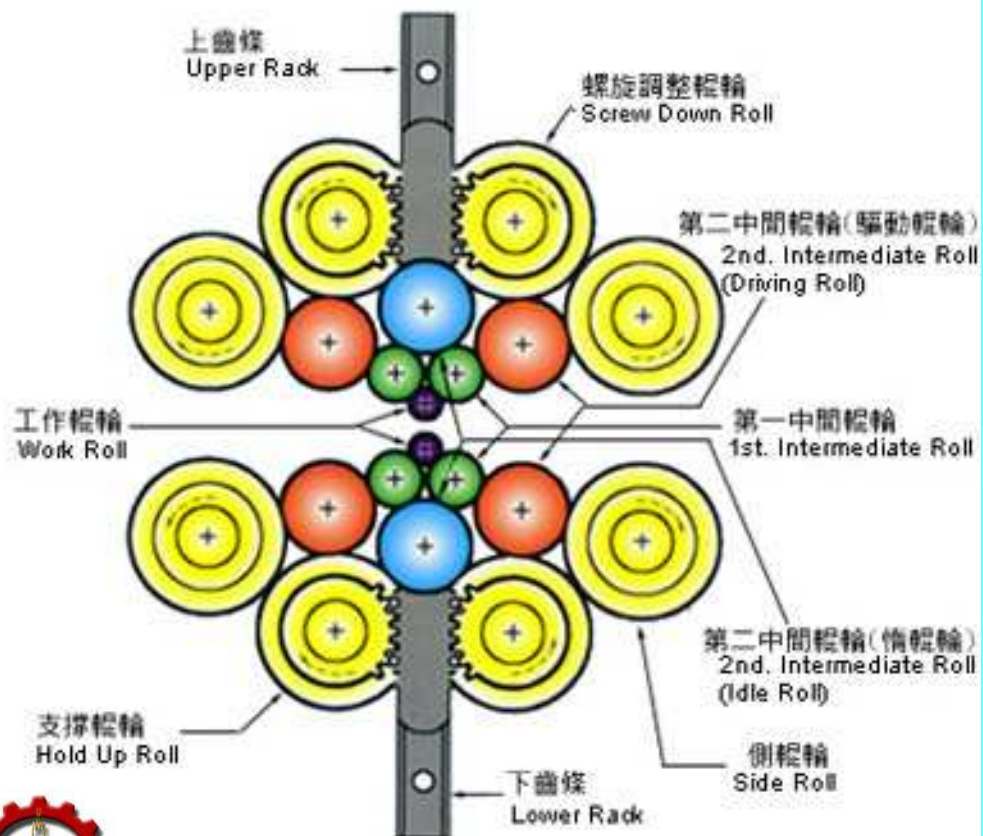
Mill products

- **Plate** is the product with a thickness $> 6 \text{ mm}$.
- **Sheet** is the product with a thickness $< 6 \text{ mm}$ and width $> 600 \text{ mm}$.
- **Strip** is the product with a thickness $< 6 \text{ mm}$ and width $< 600 \text{ mm}$.

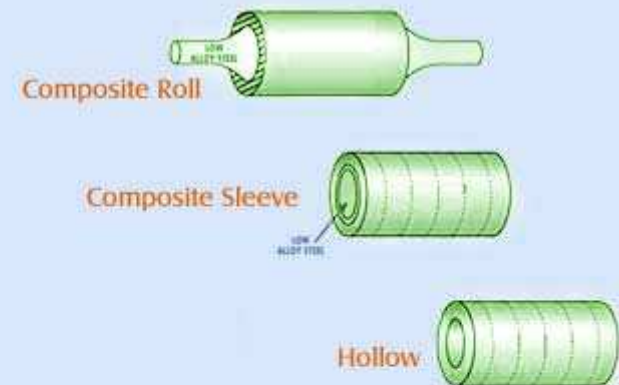


Rolls

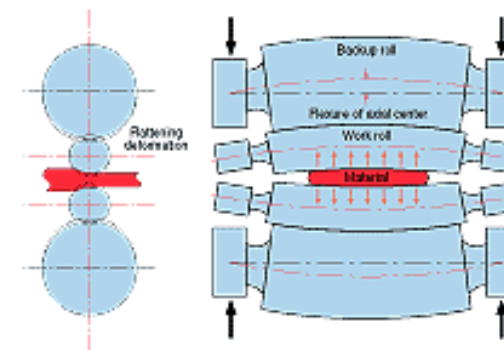
Mill rolls



Mill rolls



3B(2) Elastic Deformation of Rolls in 4-High Rolling Mill



Ring rolls

- Ring rolls are used for tube rolling, ring rolling.
- Ring rolls are made of spheroidized graphite bainitic and pearlitic matrix or alloy cast steel base.



Cantilever mill roll



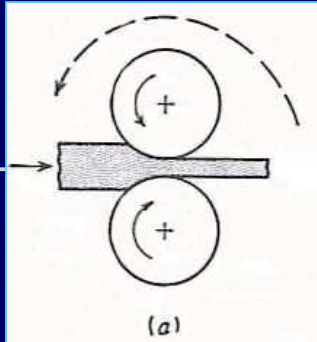
Tube mill roll



Universal roll

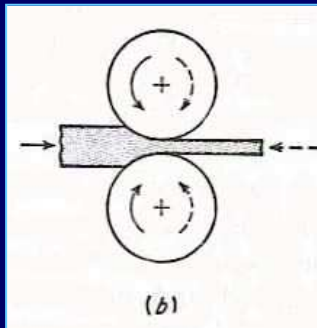


Typical arrangement of rollers for rolling mills



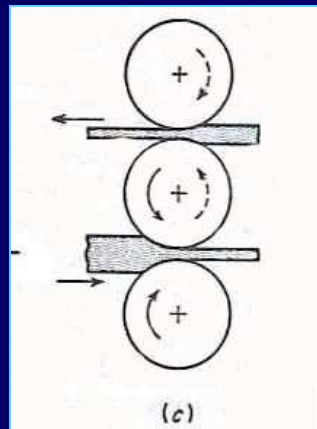
Two-high mill, pullover

The stock is returned to the entrance for further reduction.



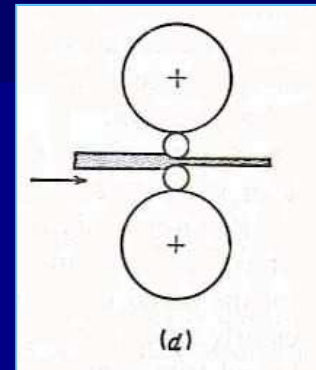
Two-high mill, reversing

The work can be passed back and forth through the rolls by reversing their direction of rotation.



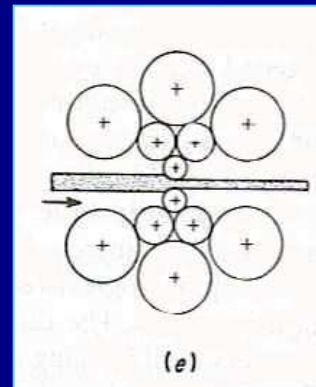
Three-high mill

Consist of upper and lower driven rolls and a middle roll, which rotates by friction.



Four-high mill

Small-diameter rolls (less strength & rigidity) are supported by larger-diameter backup rolls



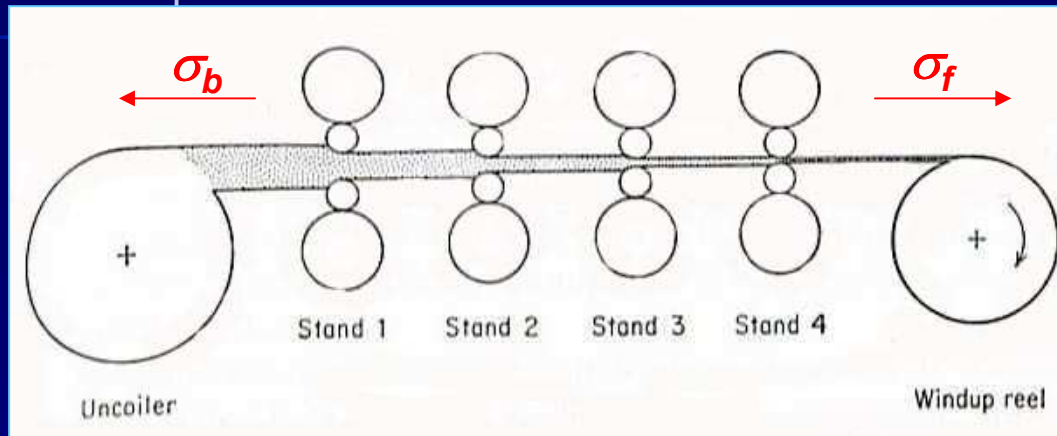
Cluster mill or Sendzimir mill

Each of the work rolls is supported by two backing rolls.



Typical arrangement of rollers for rolling mills

Continuous rolling



- Use a series of rolling mill and each set is called a stand.

- The strip will be moving at **different velocities** at each stage in the mill.

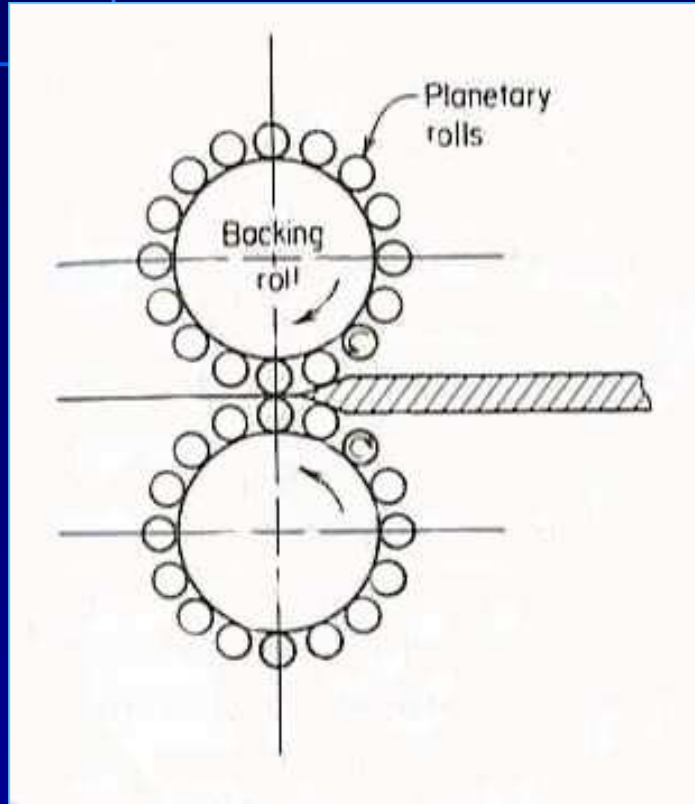
A four stand continuous mill or tandem mil.

- The speed of each set of rolls is **synchronised** so that the input speed of each stand is equal to the output speed of preceding stand.
- The uncoiler and windup reel not only feed the stock into the rolls and coiling up the final product but also provide back tension and front tension to the strip.



Typical arrangement of rollers for rolling mills

Planetary mill



- Consist of a pair of **heavy backing rolls** surrounded by a large number of planetary rolls.
- Each planetary roll gives an **almost constant reduction** to the slab as it sweeps out a circular path between the backing rolls and the slab.
- As each pair of **planetary rolls** ceases to have contact with the work piece, another pair of rolls makes contact and repeat that reduction.
- The overall reduction is the summation of a series of small reductions by each pair of rolls. Therefore, the **planetary mill** can hot reduces a slab directly to strip in one pass through the mill.
- The operation requires **feed rolls** to introduce the slab into the mill, and a pair of **planishing rolls** on the exit to improve the surface finish.



Rolling mills

Rolling mill is a machine or a factory for shaping metal by passing it through rollers



A rolling mill basically consists of

- rolls
- bearings
- a housing for containing these parts
- a drive (motor) for applying power to the rolls and controlling the speed

Modern rolling mill



• Requires very rigid construction, large motors to supply enough power (MN).

Successive stands of a large continuous mill



+ Huge capital investment

- skills
- engineering design
- construction



Different types of rolling processes

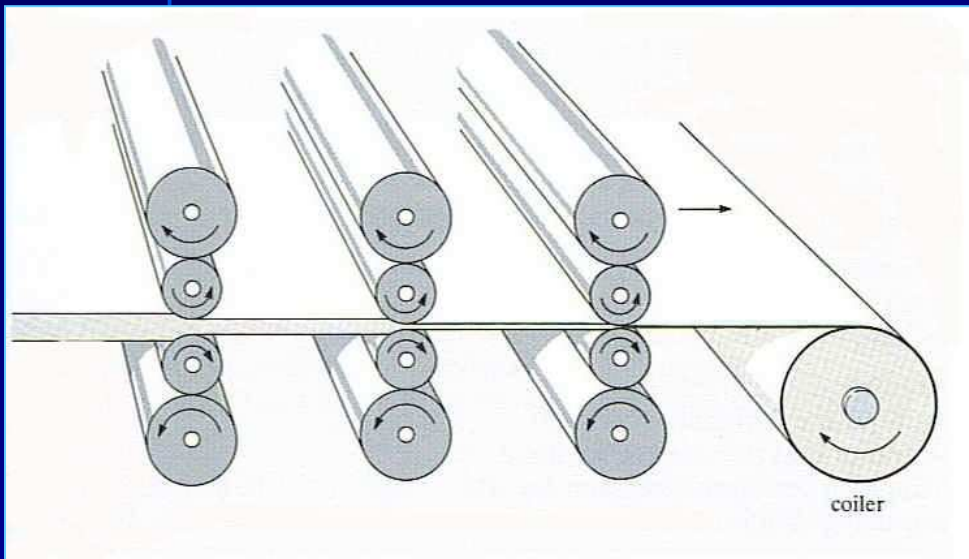
There are different types of rolling processes as listed below;

- ***Continuous rolling***
- ***Transverse rolling***
- ***Shaped rolling or section rolling***
- ***Ring rolling***
- ***Powder rolling***
- ***Continuous casting and hot rolling***
- ***Thread rolling***

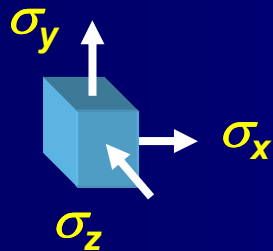


Conventional hot or cold-rolling

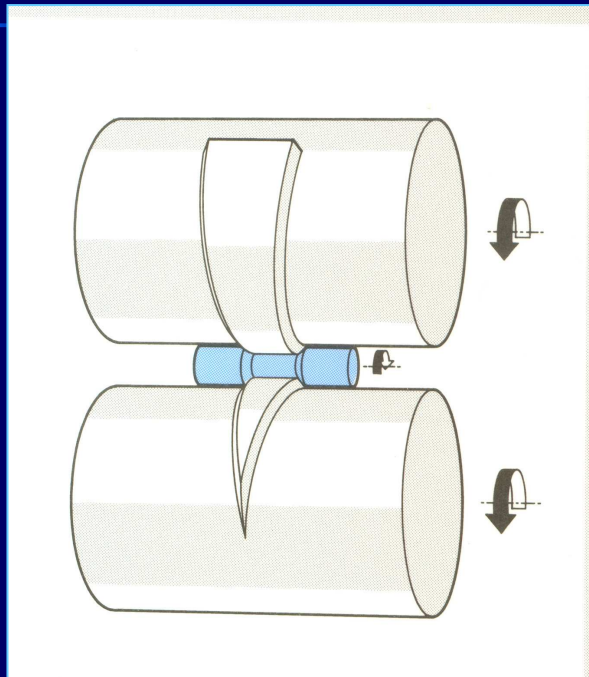
The objective is to **decrease the thickness** of the metal with an **increase in length** and with little increase in width.



- The material in the centre of the sheet is constrained in the **z** direction (across the width of the sheet) and the **constraints of undeformed shoulders of material** on each side of the rolls prevent extension of the sheet in the width direction.
- This condition is known as **plane strain**. The material therefore gets longer and not wider.
- Otherwise we would need the width of a **football pitch** to roll down a steel ingot to make tin plate!



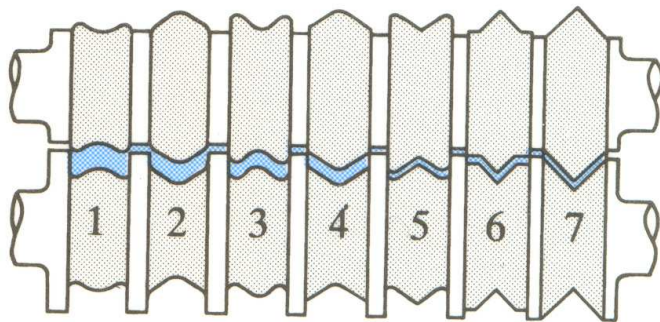
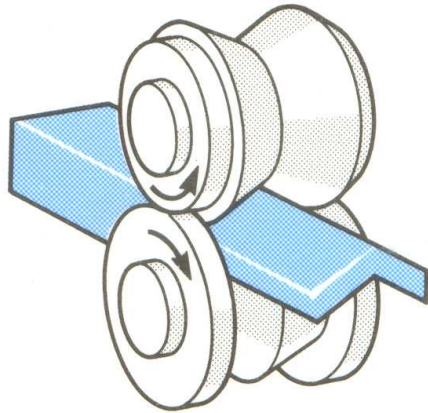
Transverse rolling



- Using circular wedge rolls.
- Heated bar is cropped to length and fed in transversely between rolls.
- Rolls are revolved in one direction.



Shaped rolling or section rolling

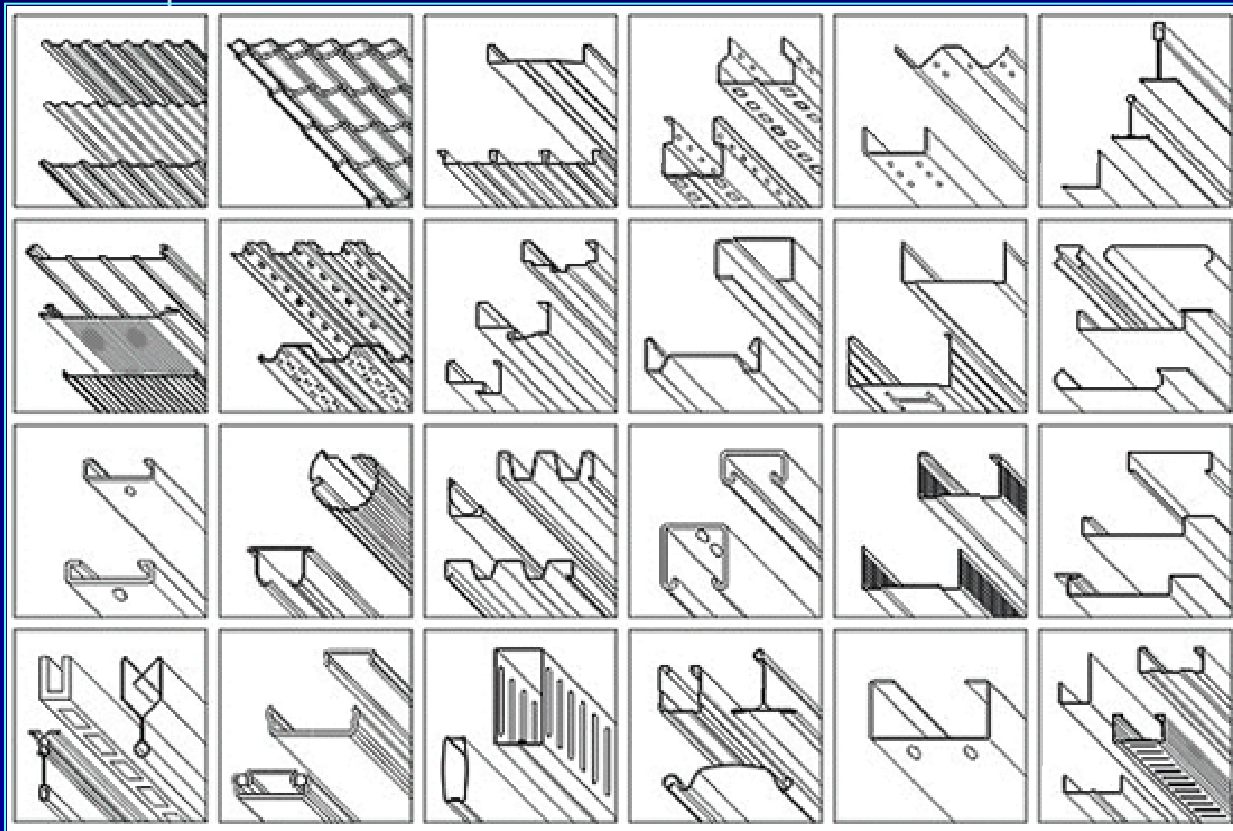


- A special type of cold rolling in which flat slab is progressively bent into **complex shapes** by passing it through a series of **driven rolls**.
- No appreciable change in the thickness of the metal during this process.
- Suitable for producing moulded sections such as irregular shaped channels and trim.



Shaped rolling or section rolling

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 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.

www.formtak.com



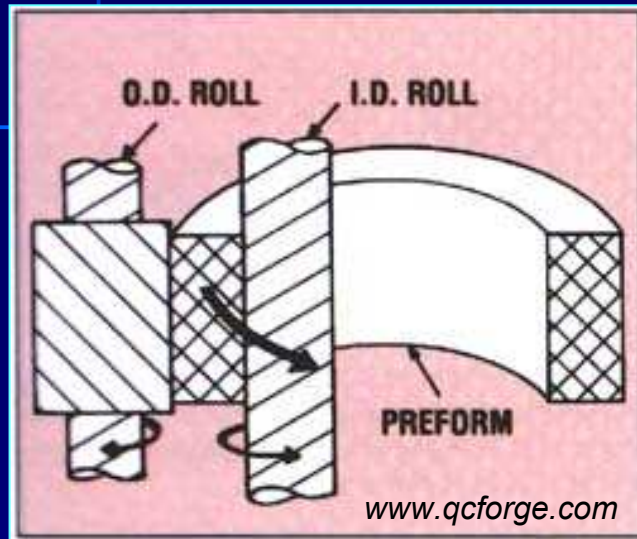
A variety of rolled sections

Ring rolling

Seamless rings



Simulation of ring rolling



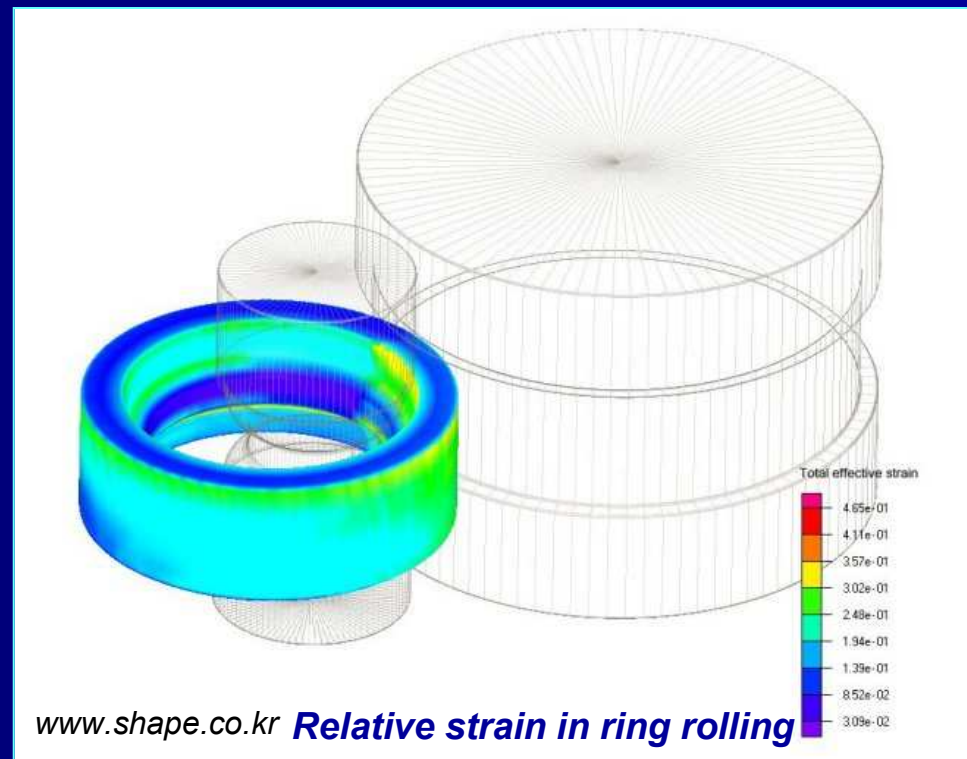
- The **donut shape preform** is placed between a free **turning inside roll** and a **driven outside roll**.
- The ring mills make the section thinner while increasing the ring diameter.

www.rz.rwth-aachen.de

Simulation
of ring
rolling



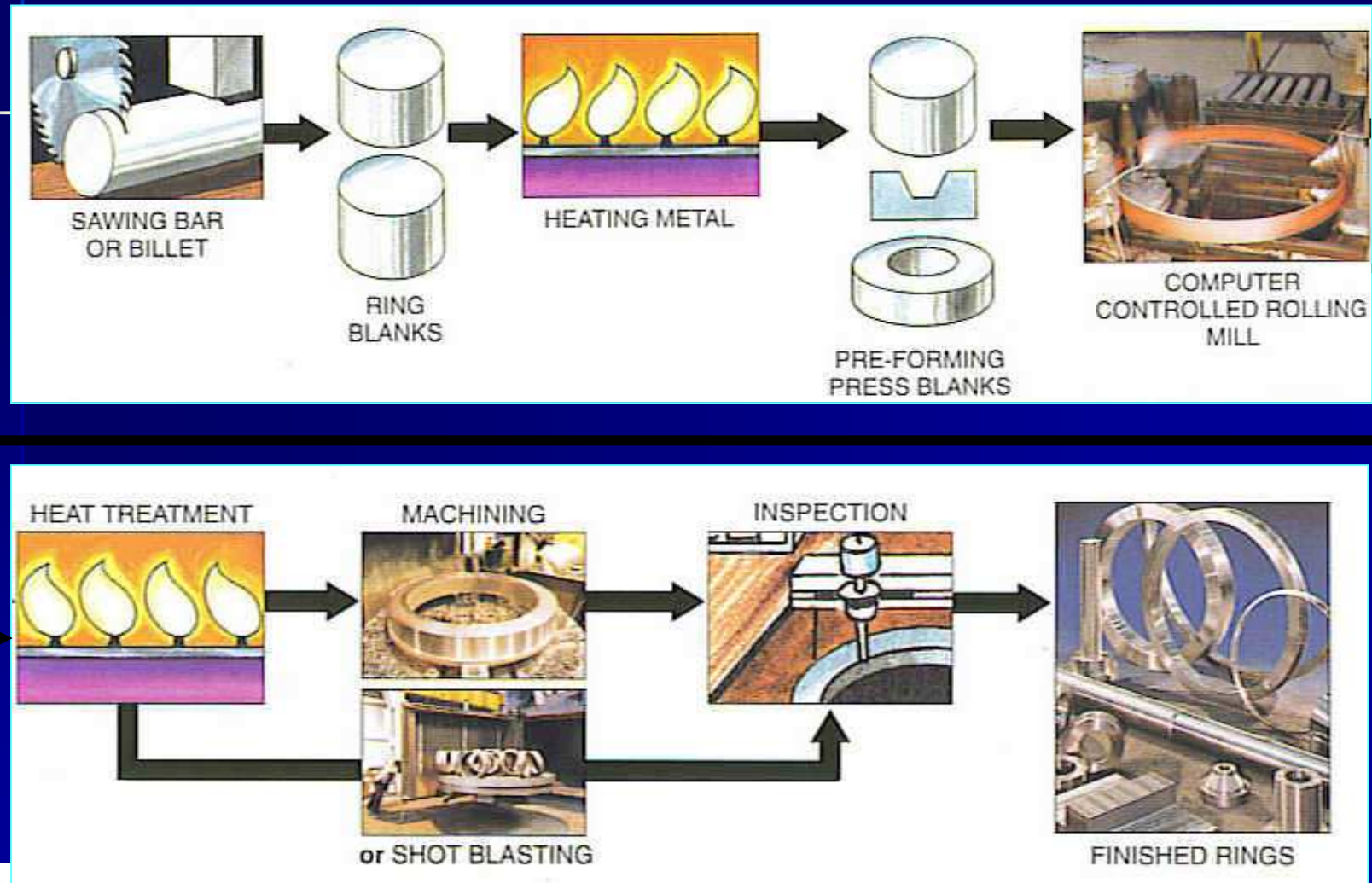
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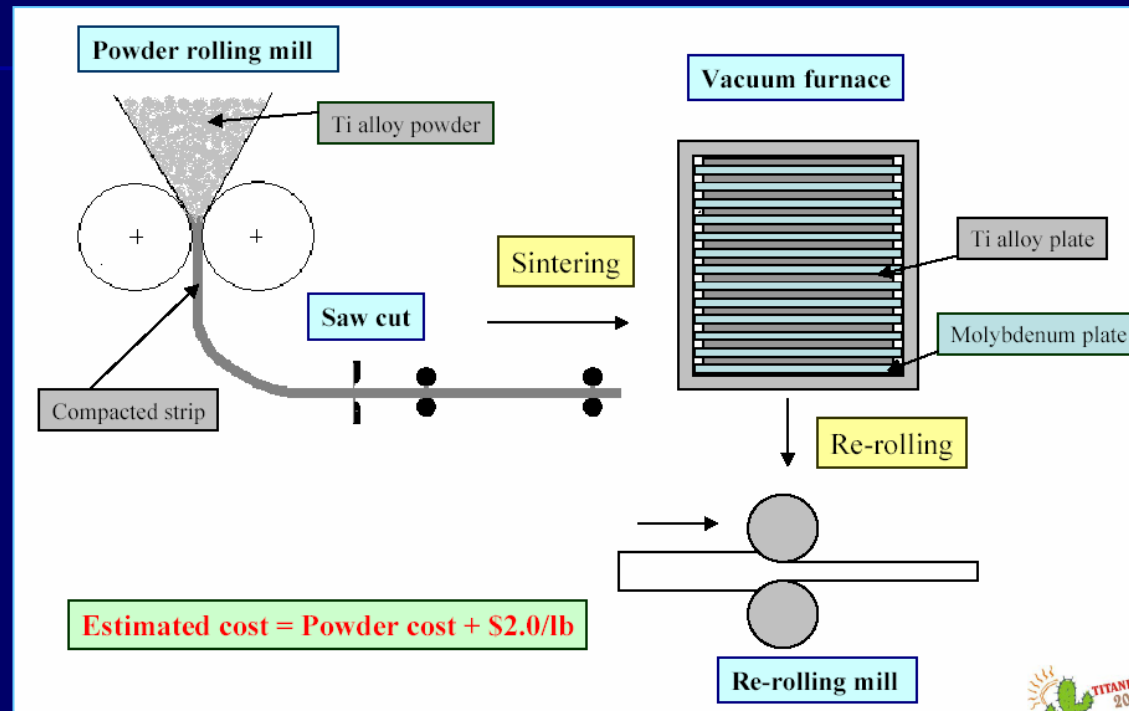
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Seamless ring rolling



Powder rolling

Metal powder is introduced between the rolls and compacted into a 'green strip', which is subsequently sintered and subjected to further hot-working and/or cold working and annealing cycles.

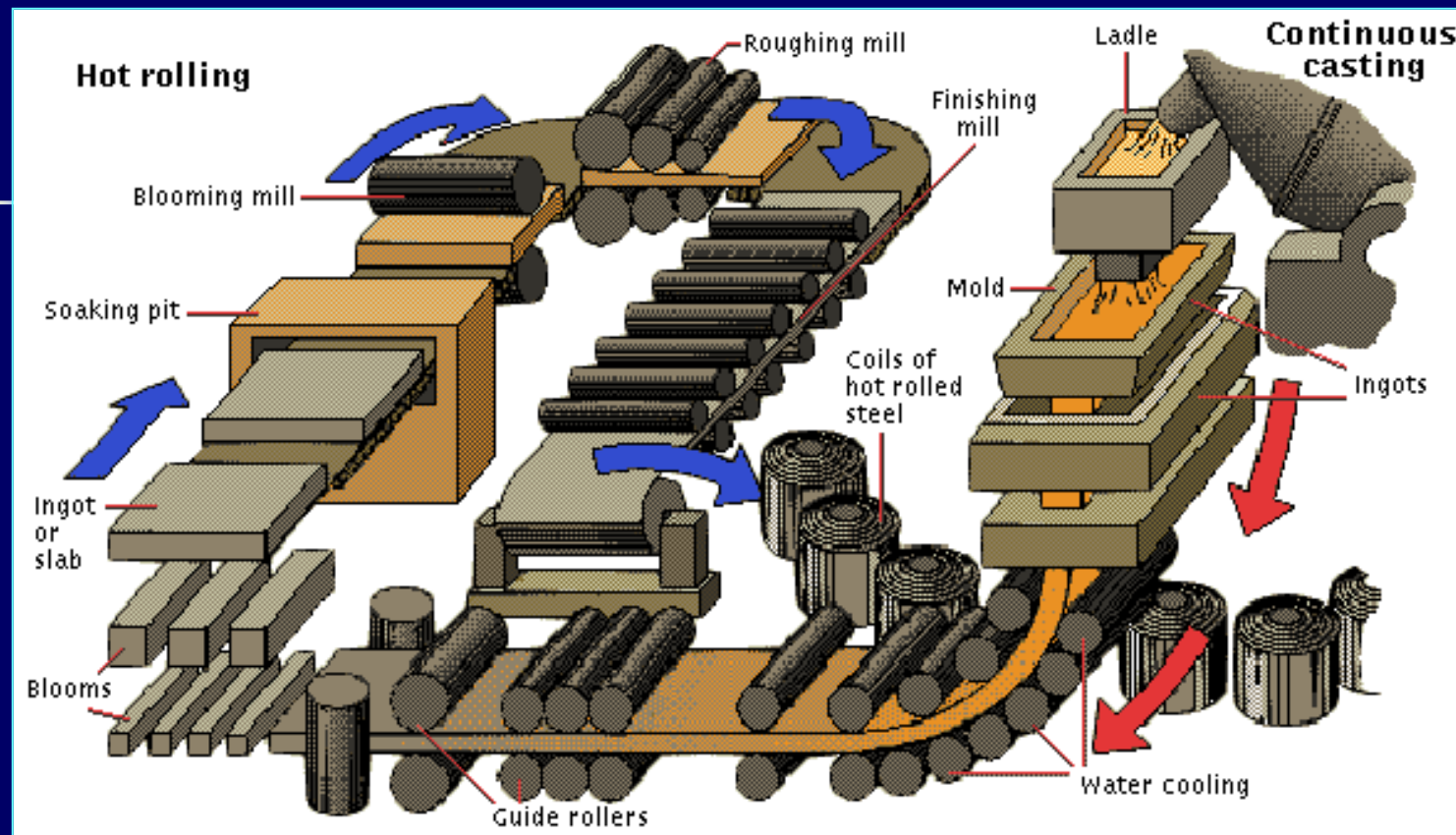


Advantage :

- Cut down the initial hot-ingot breakdown step (reduced capital investment).
- **Economical** - metal powder is cheaply produced during the extraction process.
- Minimise contamination in hot-rolling.
- Provide **fine grain size** with a minimum of preferred orientation.



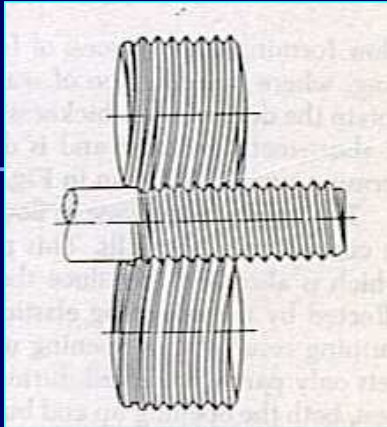
Continuous casting and hot rolling



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



Thread rolling



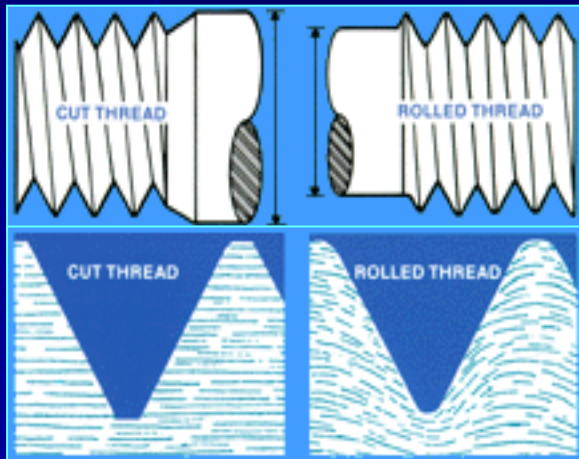
- **Dies** are pressed against the surface of cylindrical blank. As the blank rolls against the in-feeding die faces, the material is displaced to form the **roots** of the thread, and the displaced material flows **radially outward** to form the **thread's crest**.

- A blank is fed between **two grooved die plates** to form the threads.

- The thread is formed by the **axial flow** of material in the work piece. The grain structure of the material is not cut, but is **distorted** to follow the thread form.

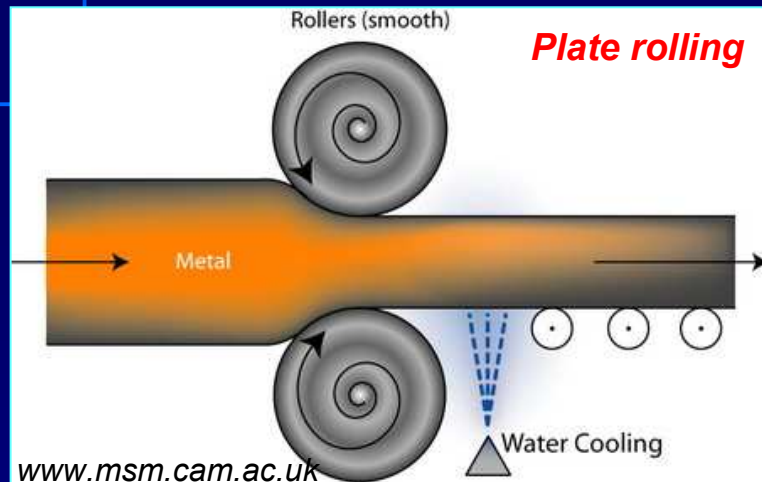
- Rolled threads are produced in a **single pass** at speeds far in excess of those used to cut threads.

- The resultant thread is very much **stronger** than a cut thread. It has a greater resistance to mechanical stress and an increase in fatigue strength. Also the surface is burnished and **work hardened**.



Cut thread and rolled thread

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).

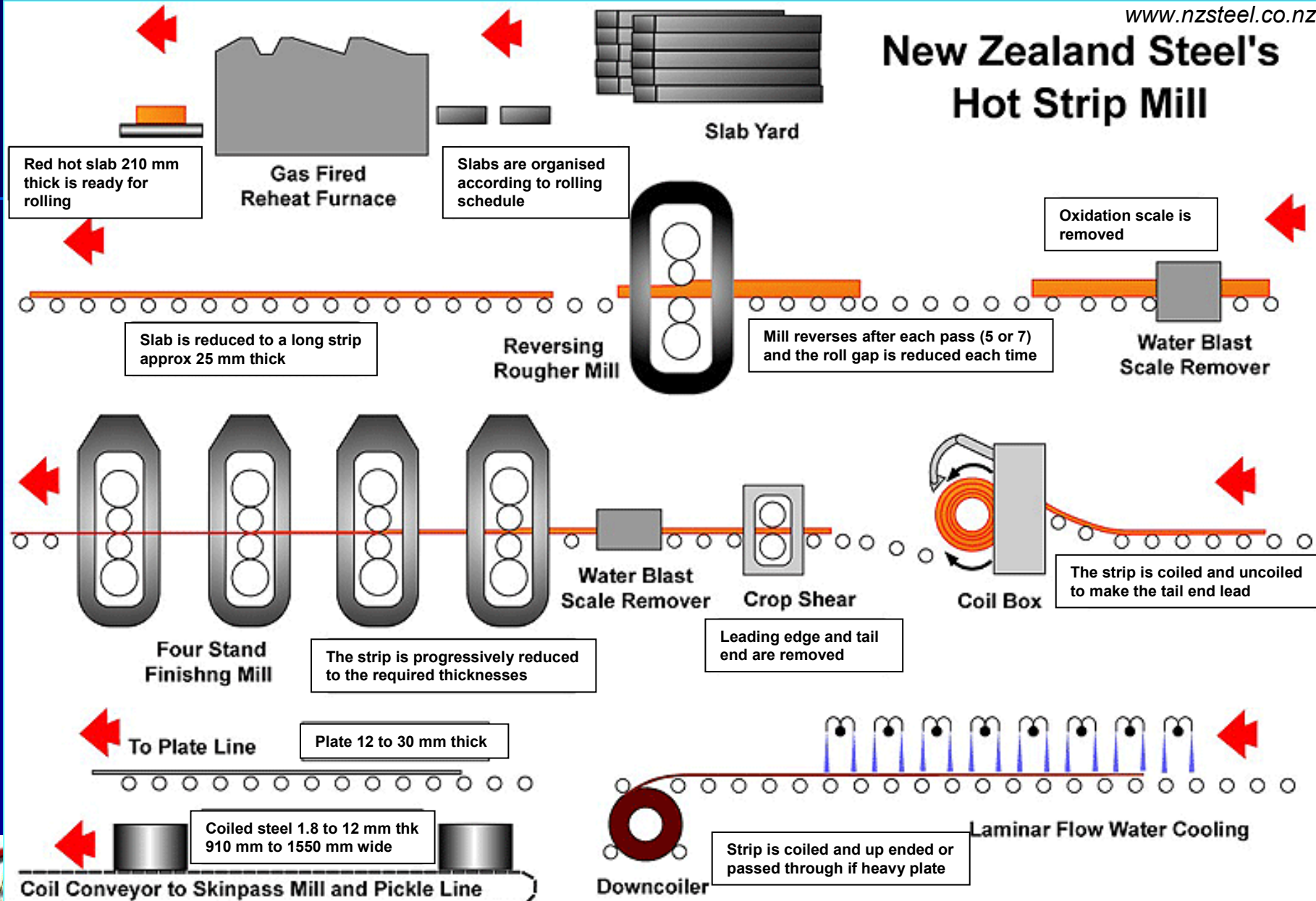
- The objective is to breakdown the cast ingot into blooms or slabs for subsequent finishing into bars, plate or sheet.
- In **hot-rolling steel**, the slabs are heated initially at 1100 -1300 °C. The temperature in the last finishing stand varies from 700 - 900 °C, but should be above the upper **critical temperature** to produce uniform equiaxed ferrite grains.



Example for hot strip mill process

www.nzsteel.co.nz

New Zealand Steel's Hot Strip Mill



- **Flat plate** of large thickness (10-50 mm) is passed through different set of **working rolls**, while each set consecutively reduces thickness.



www.reverecopper.com

Plate rolling



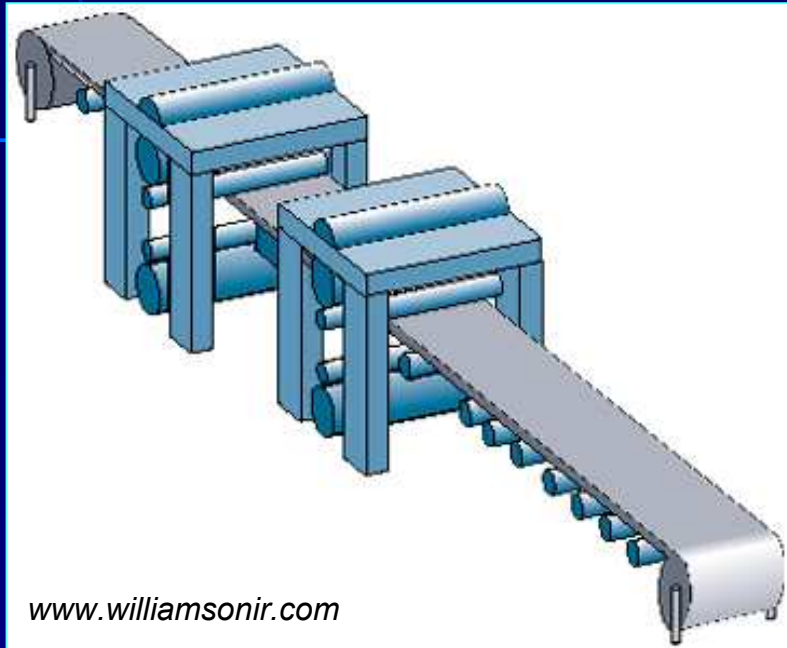
www.uksteel.org.uk

- **Hot strip** is coiled to reduce its increasing length due to a reduction of thickness.
- Reducing the complication of controlling strips of **different speeds** due to different thicknesses. (**thinner section moves faster**)

Hot rolled coil produced on strip mill



Cold-rolling



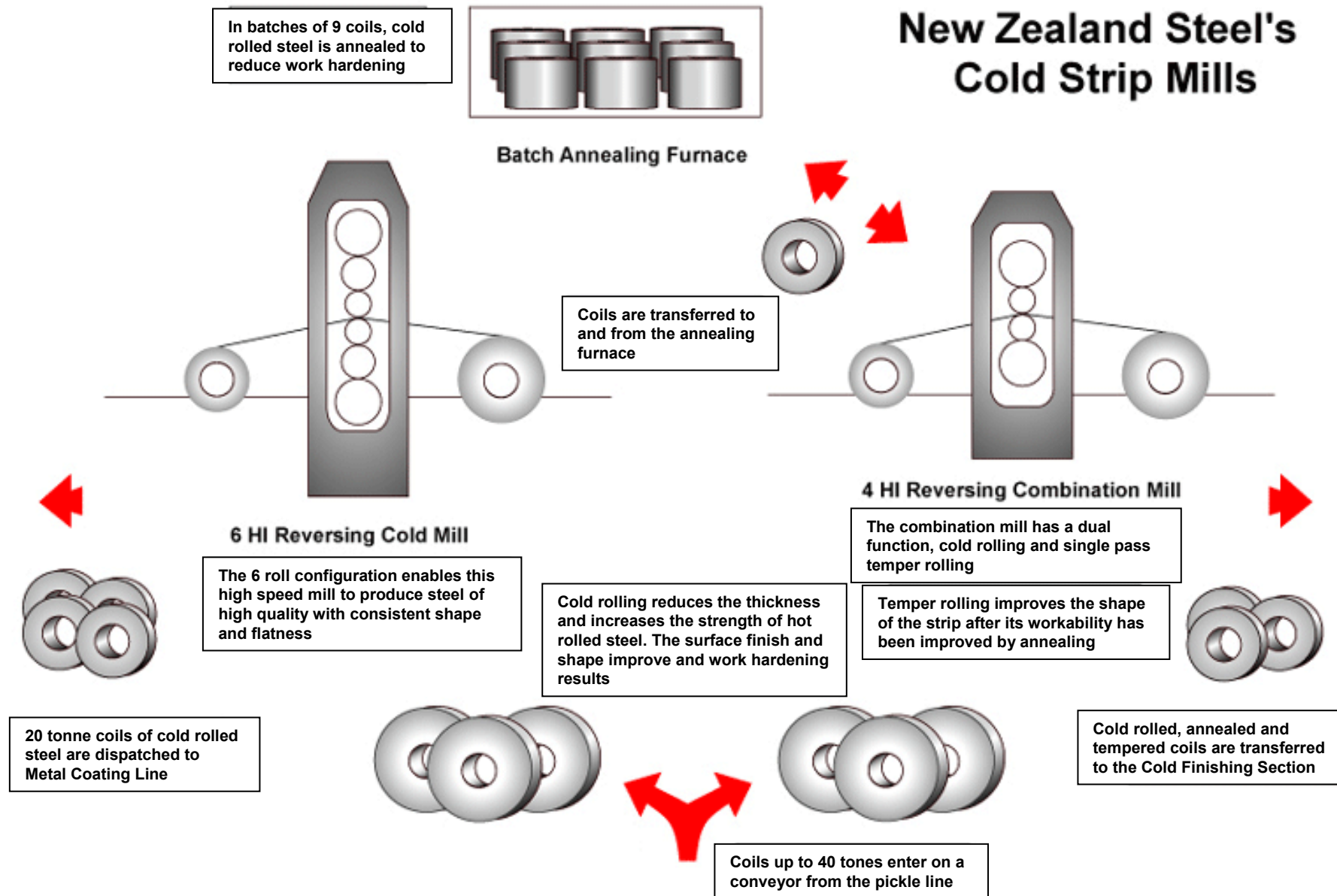
- Cold rolling is carried out under recrystallisation temperature and introduces work hardening.
- The starting material for cold-rolled steel sheet is pickled hot-rolled breakdown coil from the continuous hot-strip mill.

- 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, gage, and surface finish.



Example for cold strip mill process.

www.nzsteel.co.nz

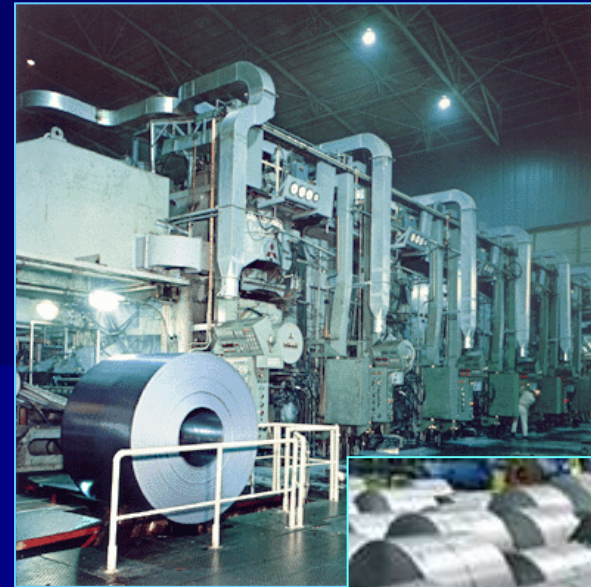


Cold-rolling

- 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 strips

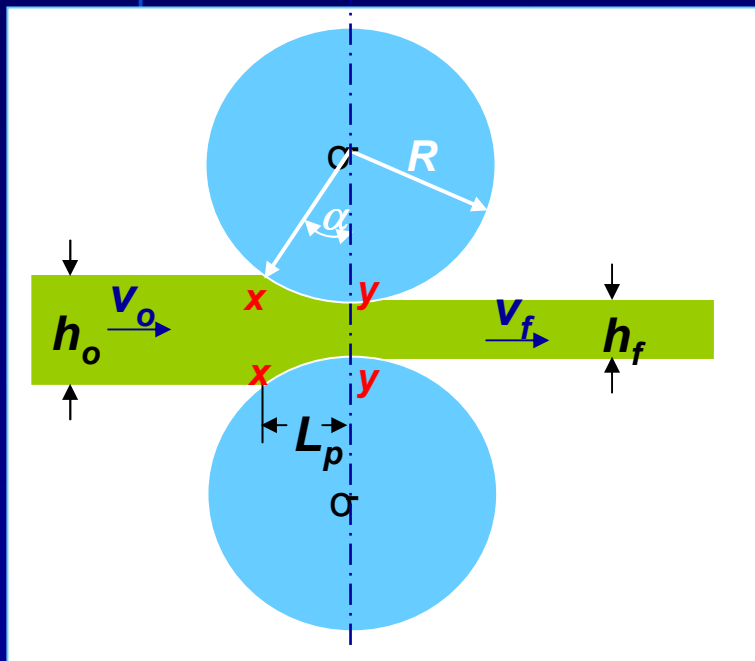
Cold rolled metals are rated as 'temper'

- **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°.
- **Full hard** : Metal is compressed by 50% with no cracking. Can be bent up to 45°.



Fundamental concept of metal rolling

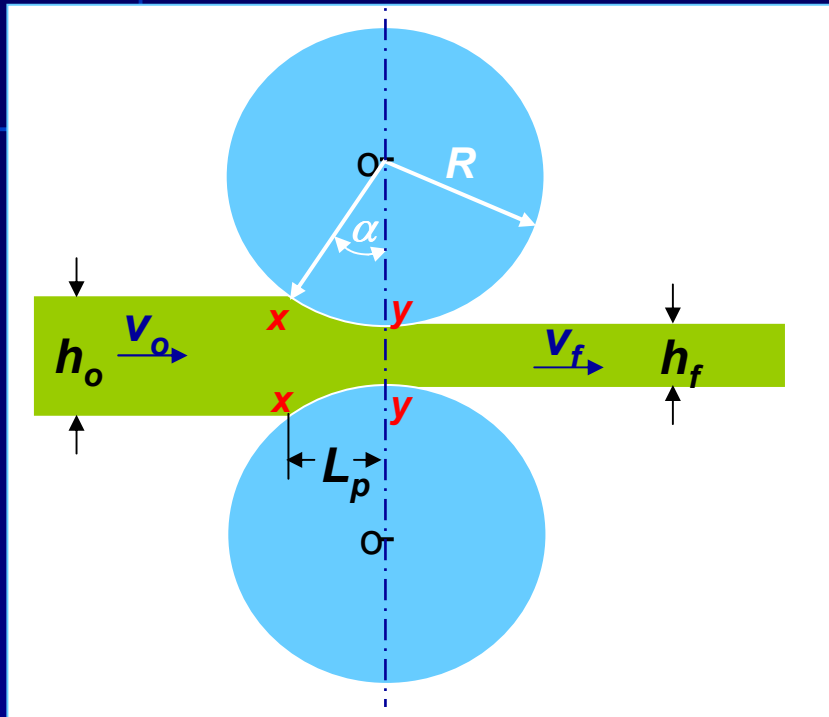
Assumptions



- 1) The arc of contact between the rolls and the metal is a part of a circle.
- 2) The coefficient of friction, μ , is constant in theory, but in reality μ 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



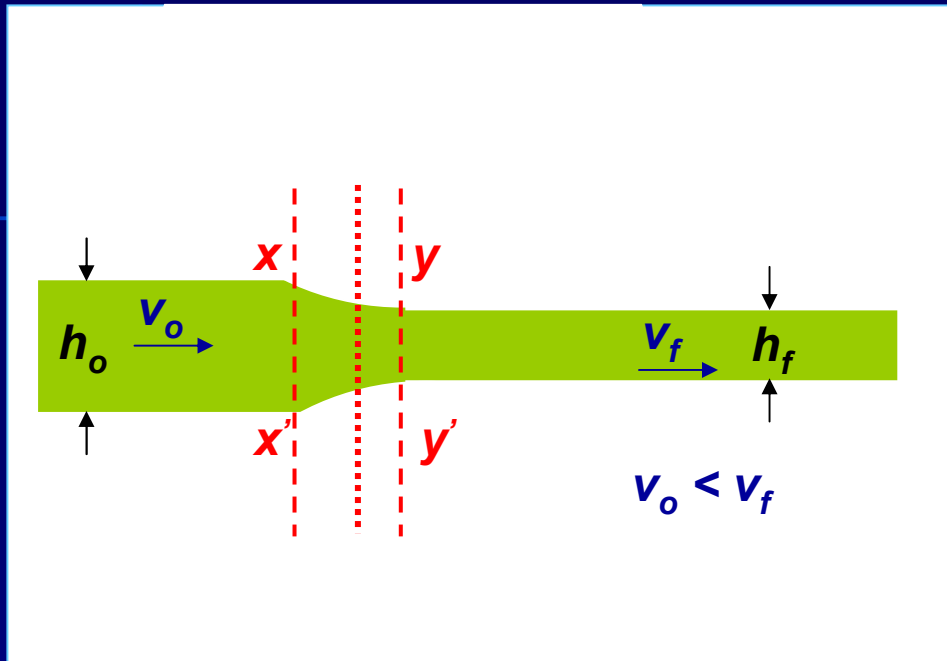
$$bh_o v_o = bhv = bh_f v_f \quad \dots \text{Eq.1}$$

- 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 throughout the process, therefore

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 $b_o = b_f$

$$h_o \frac{L_o}{t} = h_f \frac{L_f}{t}$$

Then we have

$$v_o h_o = v_f h_f$$

$$\frac{v_o}{v_f} = \frac{h_f}{h_o} \quad \dots \text{Eq.2}$$

When $h_o > h_f$, we then have $v_o < v_f$

The **velocity** of the sheet must steadily increase from entrance to exit such that a vertical element in the sheet remain **undistorted**.

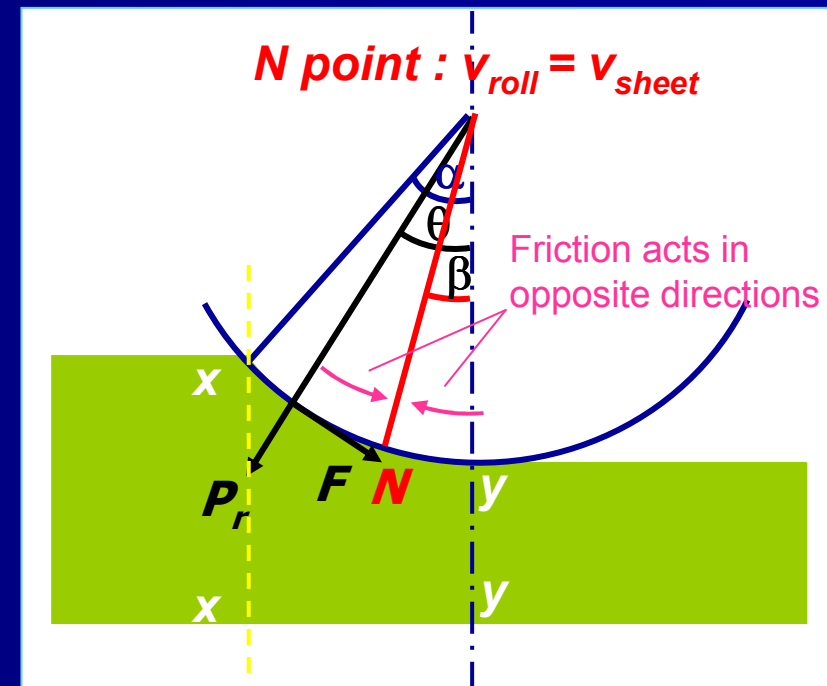


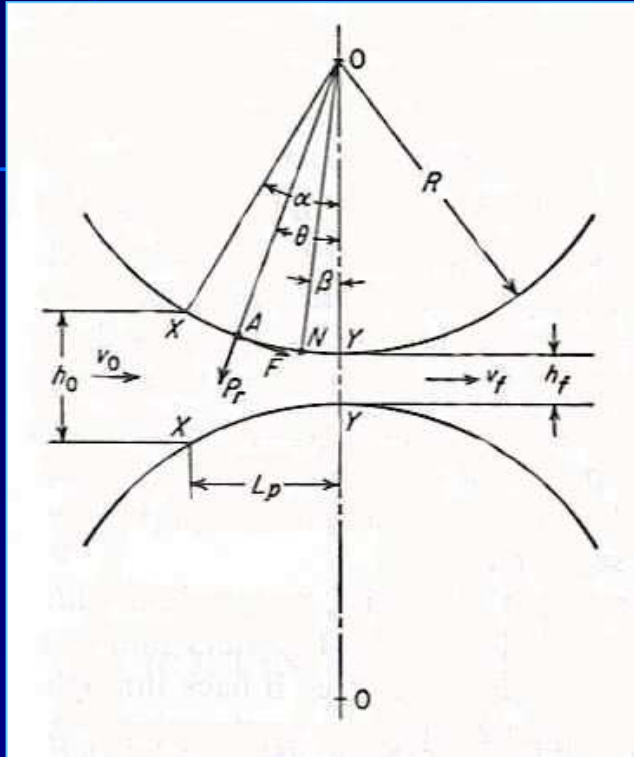
- At only one point along the surface of contact between the roll and the sheet, two forces act on the metal: 1) a radial force P_r and 2) a tangential frictional force F .

- 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 .

- 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) of 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.





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.

$$p = \frac{P}{bL_p} \quad \dots \text{Eq.3}$$

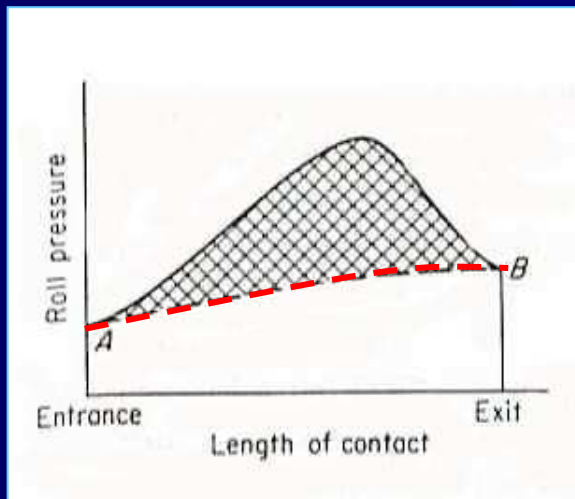
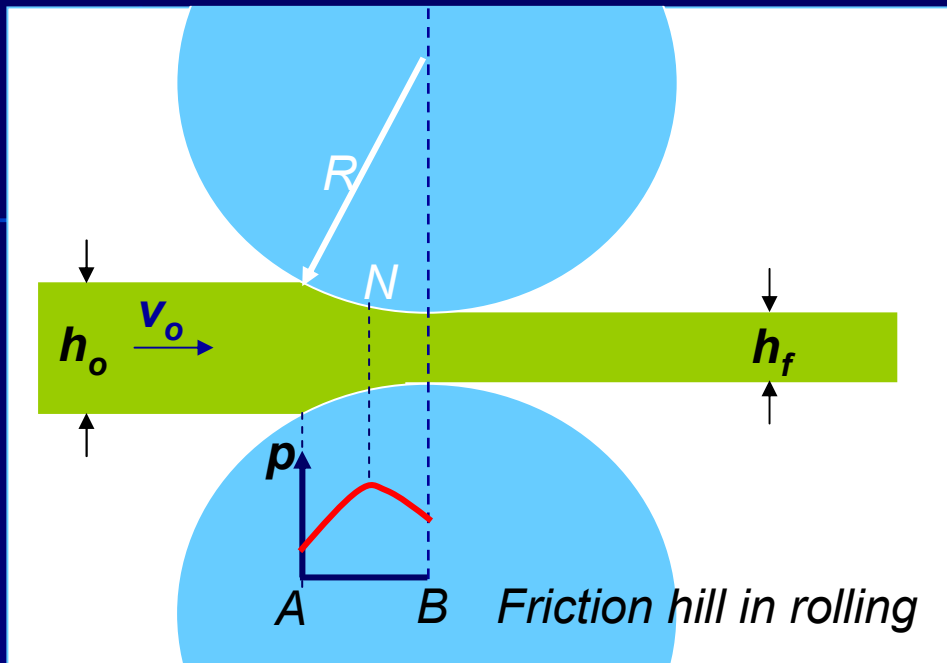
Where b is the width of the sheet.

L_p is the projected length of the arc of contact.

$$L_p = \left[R(h_o - h_f) - \frac{(h_o - h_f)^2}{4} \right]^{1/2} \approx [R(h_o - h_f)]^{1/2} \quad \dots \text{Eq.4}$$

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

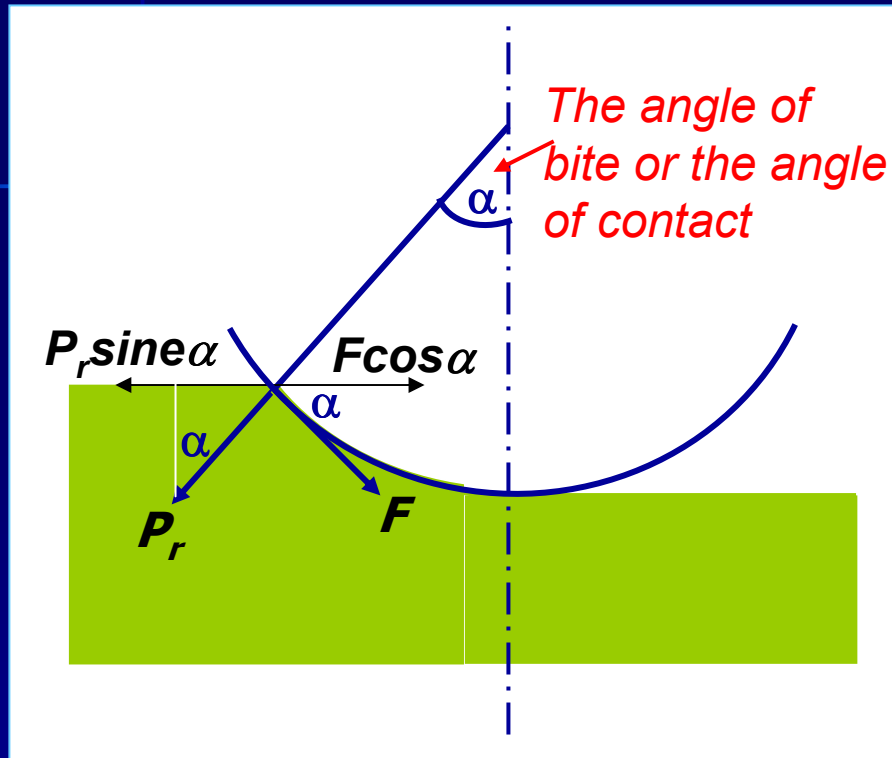




- The **distribution of roll pressure** along the arc of contact shows that the pressure rises to a maximum at the neutral point and then falls off.
- The pressure distribution does not come to a sharp peak at the neutral point, which indicates that the **neutral point is not really a line** on the roll 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



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**.

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

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

But we know

$$F = \mu P_r$$

Therefore

$$\mu = \tan \alpha$$

...Eq.5

F
P_r

is a tangential friction force
is radial force

- If **$\tan \alpha > \mu$** , the workpiece cannot be drawn.
- If **$\mu = 0$** , rolling cannot occur.



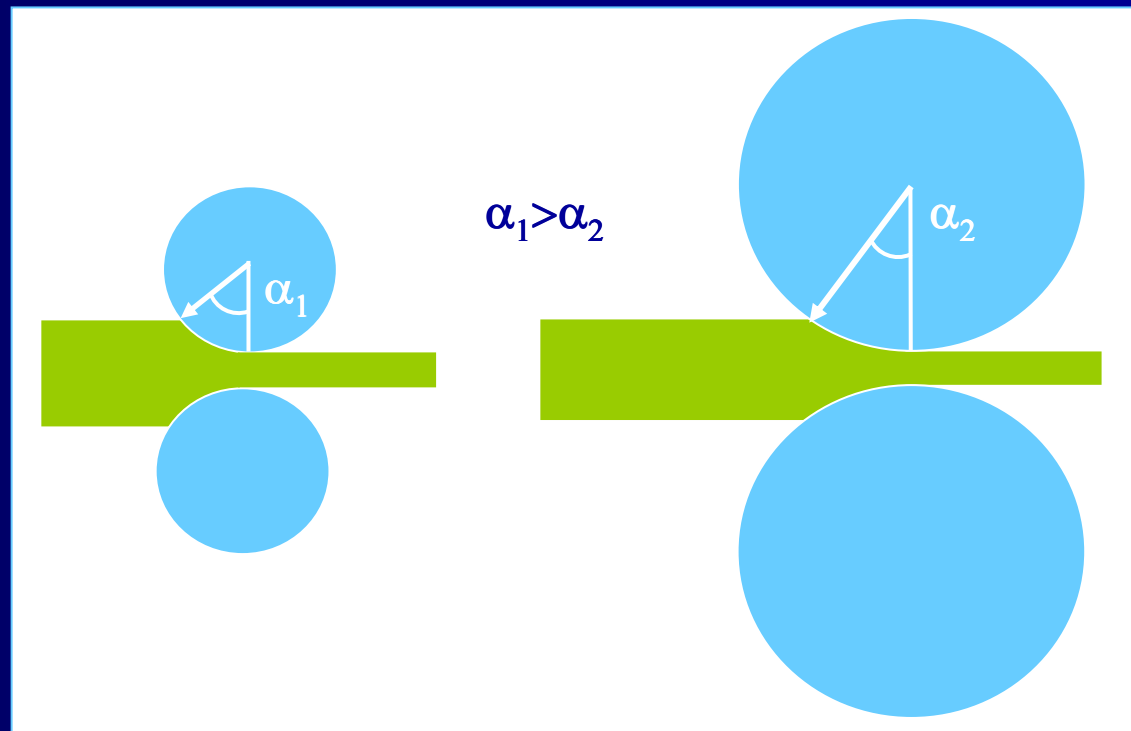
Therefore Free engagement will occur when $\mu > \tan \alpha$



Increase the effective values of μ , for example grooving the rolls parallel to the roll axis.

+

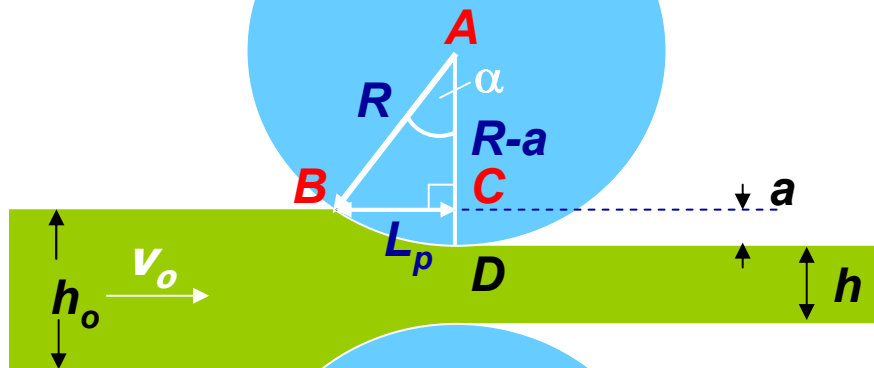
Using big rolls to reduce $\tan \alpha$ or if the roll diameter is fixed, reduce the h_o



The maximum reduction

The critical variables are

L_p and h



A large diameter roll will permit a thicker slab to enter the rolls than will a small-diameter roll.

From triangle **ABC**, we have

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

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

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

As a is much smaller than R , we can then ignore a^2 .

$$L_p \approx \sqrt{2Ra} \approx \sqrt{R\Delta h} \quad \dots \text{Eq.6}$$

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

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

$$\Rightarrow (\Delta h)_{\max} = \mu^2 R \quad \dots \text{Eq.7}$$



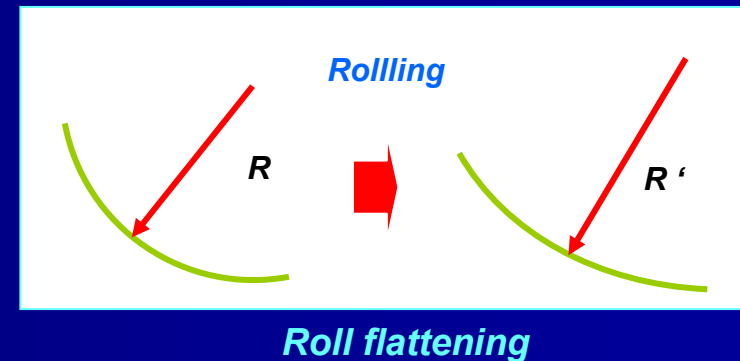
Problem with roll flattening

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 $R \rightarrow R'$. (**roll flattening**)

According to analysis by Hitchcock,

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



Where $C = 16(1-\nu^2)/\pi E = 2.16 \times 10^{-11} \text{ Pa}^{-1}$ for steel rolls.
 P' = rolling load based on the deformed roll radius.



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,

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

For cold-rolling

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

For hot-rolling

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

Alternatively, we can use the relationship below

$$\sin \alpha = \frac{L_p}{R} = \frac{\sqrt{R\Delta h}}{R}, \alpha = \tan^{-1}(\mu)$$
$$\Delta h = 1.92 \text{ mm}$$



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



1) No friction situation

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**).



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

...Eq.8

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



2) Normal friction situation



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

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

...Eq.9

Where $\frac{Q}{h}$

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

= the mean thickness between entry and exit from the rolls.

From Eq.8,

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

We have

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

...Eq.10

Roll diameter ↑

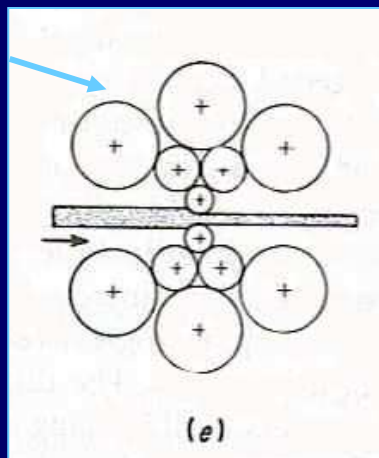
Rolling load ↑



- 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.

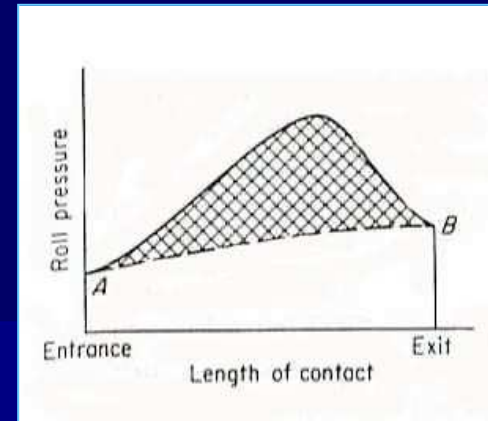
Backup rolls



Example: the rolling of aluminium cooking foil. Roll diameter < 10 mm with as many as 18 backing rolls.



- **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, $\mu \sim 0.05 - 0.10$.
- For hot-rolling , $\mu \sim 0.2$ 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 $\mu = 0.30$. 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.

$$\frac{h_o - h_f}{h_o} \times 100 = 30\%$$

$$\frac{(40) - (h_f)}{(40)} \times 100 = 30$$

$$h_f = 28\text{mm}$$

$$\Delta h = h_o - h_f = (40) - (28) = 12\text{mm}$$



$$\bar{h} = \frac{h_o + h_f}{2} = \frac{(40) + (28)}{2} = 34\text{mm}$$

$$Q = \frac{\mu L_p}{\bar{h}} = \frac{\mu \sqrt{R \Delta h}}{\bar{h}} = \frac{(0.30) \sqrt{450 \times 12}}{(34)} = 0.65$$

$$\bar{\sigma}_o' = \frac{\sigma'_{\text{entrance}} + \sigma'_{\text{exit}}}{2} = \frac{140 + 200}{2} = 170\text{MPa}$$

From *Eq.10*

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

$$P = 170 \left[\frac{1}{(0.65)} (e^{0.65} - 1) (0.76) \sqrt{0.45 \times 0.012} \right] = 13.4\text{MN}$$



3) Sticky friction situation

What would be the rolling load if sticky friction occurs?

Continuing the analogy with compression in plane strain

$$\bar{p} = \sigma'_o \left(\frac{a}{2h} + 1 \right) = \sigma'_o \left(\frac{L_p}{4\bar{h}} + 1 \right)$$

From Eq.8,

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

From example:

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

$$P = 170 \left(\frac{\sqrt{0.45 \times 0.012}}{4 \times 0.034} + 1 \right) (0.76) \sqrt{0.45 \times 0.012}$$

$$P = 14.6 \text{ MN}$$



Example: The previous example neglected the influence of roll flattening under very high rolling loads. If the deformed radius R' of a roll under load is given in Eq.11, using $C = 2.16 \times 10^{-11} \text{ Pa}^{-1}$, $P' = 13.4 \text{ MPa}$ from previous example.

$$R' = R \left[1 + \frac{CP'}{b(h_o - h_f)} \right] \quad \dots \text{Eq.11}$$

Where $C = 16(1-\nu^2)/\pi E$, P' = Rolling load based on the deformed roll radius.

$$R' = 0.45 \left[1 + \frac{2.16 \times 10^{-11} (13.4 \times 10^6)}{0.76 \times 0.012} \right] = 0.464 \text{ m}$$



We now use R' to calculate a new value of P' and in turn another value of R'

$$Q = \frac{\mu \sqrt{R \Delta h}}{\bar{h}} = \frac{0.30 \sqrt{464 \times 12}}{34} = 0.66$$

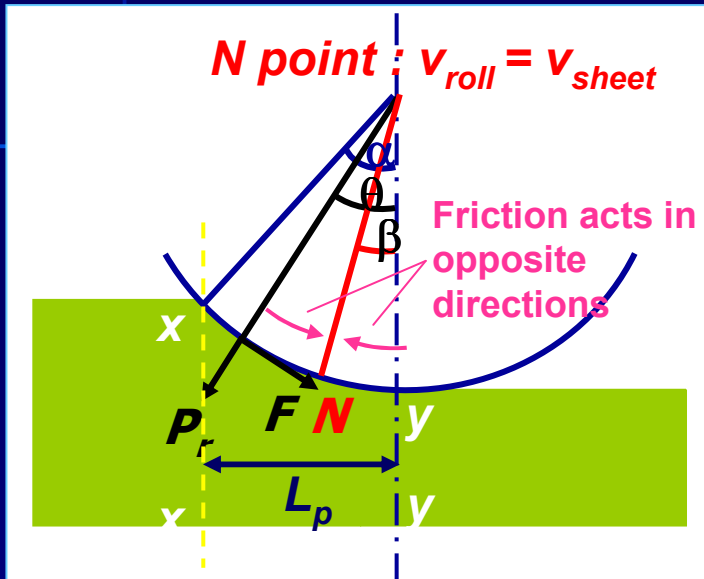
$$P'' = 170 \left[\frac{1}{0.66} (e^{0.66} - 1) 0.76 \sqrt{0.464 \times 0.012} \right] = 13.7 \text{ MN}$$

$$R'' = 0.45 \left[1 + \frac{2.16 \times 10^{-11} (13.7 \times 10^6)}{0.76 \times 0.012} \right] = 0.465 \text{ m}$$

The difference between the two estimations of R' is not large, so we stop the calculation at this point.



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 M_T (per unit of width b) is given by

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

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

$$\frac{M_T}{b} = \int_0^{L_p} (\mu p dx) R = \mu R \int_0^{L_p} p dx = \mu R \frac{P}{b}$$

thus

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

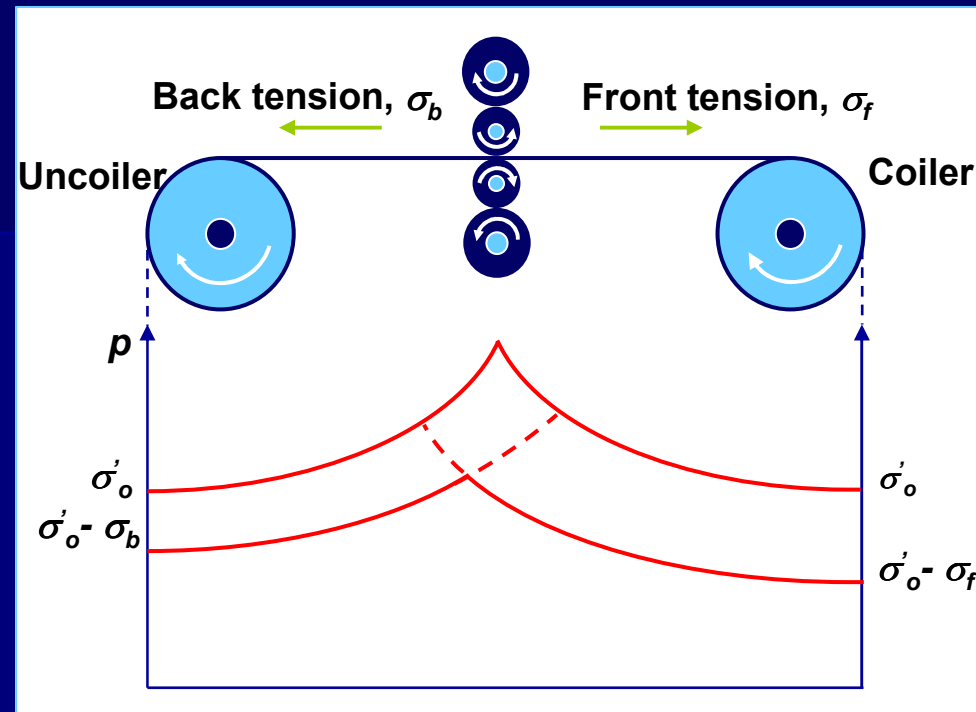


Back and front tensions in sheet

- 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 ~ twice as effective in reducing the rolling load **P** as front tension.
- The effect of sheet tension on reducing rolling pressure **p** can be shown simply by

$$p = \sigma'_o - \sigma_h = \frac{2}{\sqrt{3}} \bar{\sigma}_o - \sigma_h \quad \dots \text{Eq.11}$$

Where σ_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.



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.

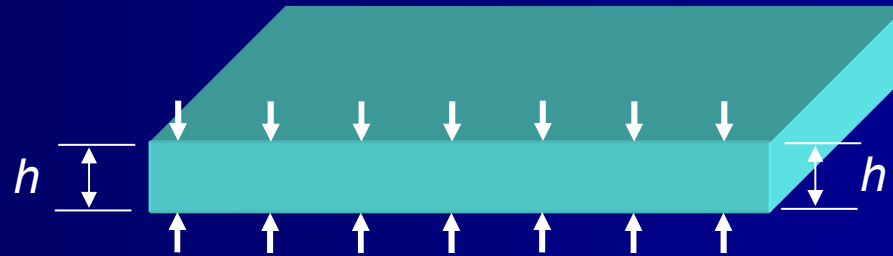
- Porosity, cavity, blow hole occurred in the cast ingot will be closed up during the rolling process.
- Longitudinal stringers of non-metallic inclusions or pearlite banding are related to melting and solidification practices. In severe cases, these defects can lead to laminations which drastically reduce the strength in the thickness direction.



Defects 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.

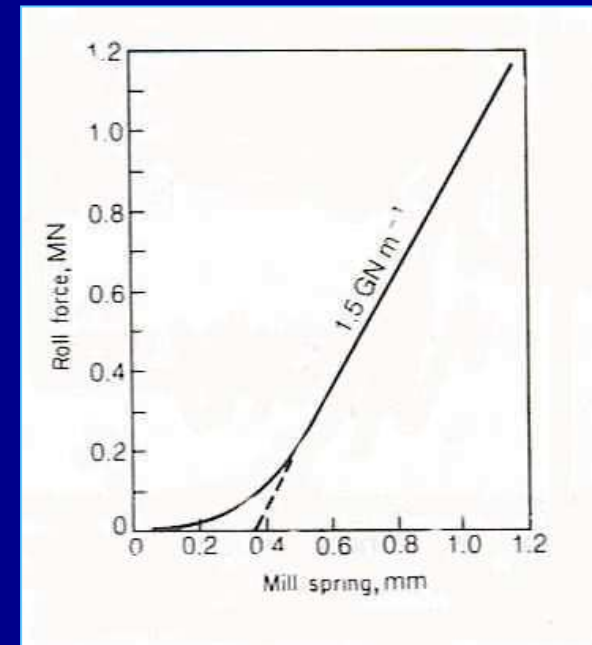


- 2) **Flatness** – difficult to measure accurately.



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 nearly proportional to μ, R, σ'_o but inversely proportional to E .

For example in steel rolls the limiting thickness is given by

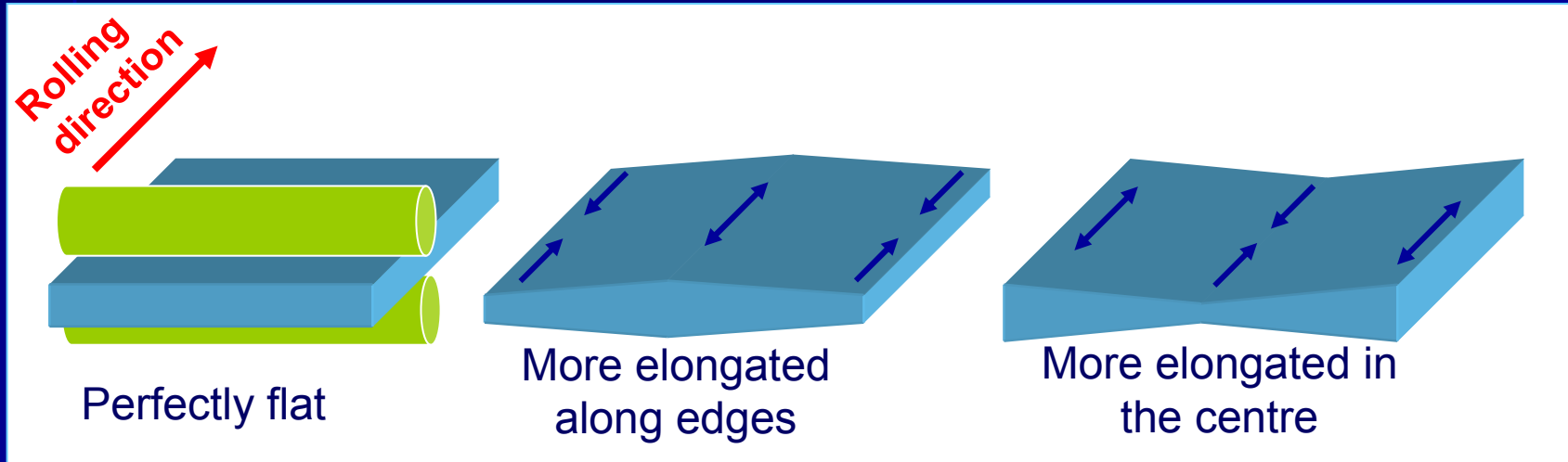
$$h_{\min} = \frac{\mu R \bar{\sigma}_o}{12.8} \quad \dots \text{Eq.12}$$

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



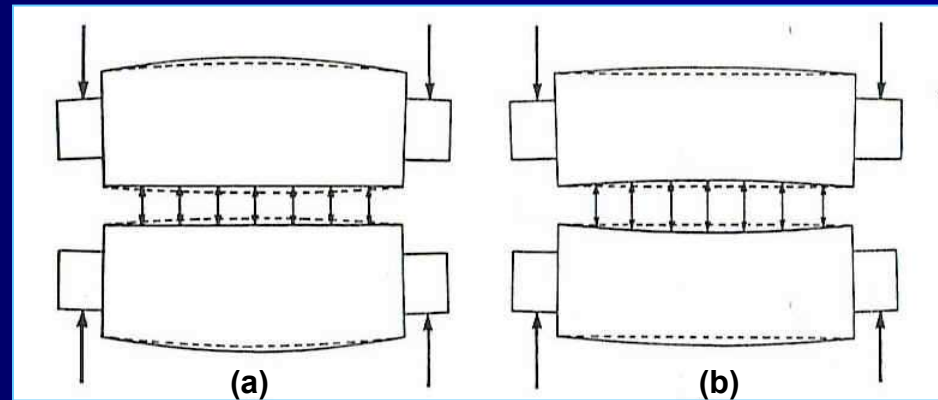
Flatness

- 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.

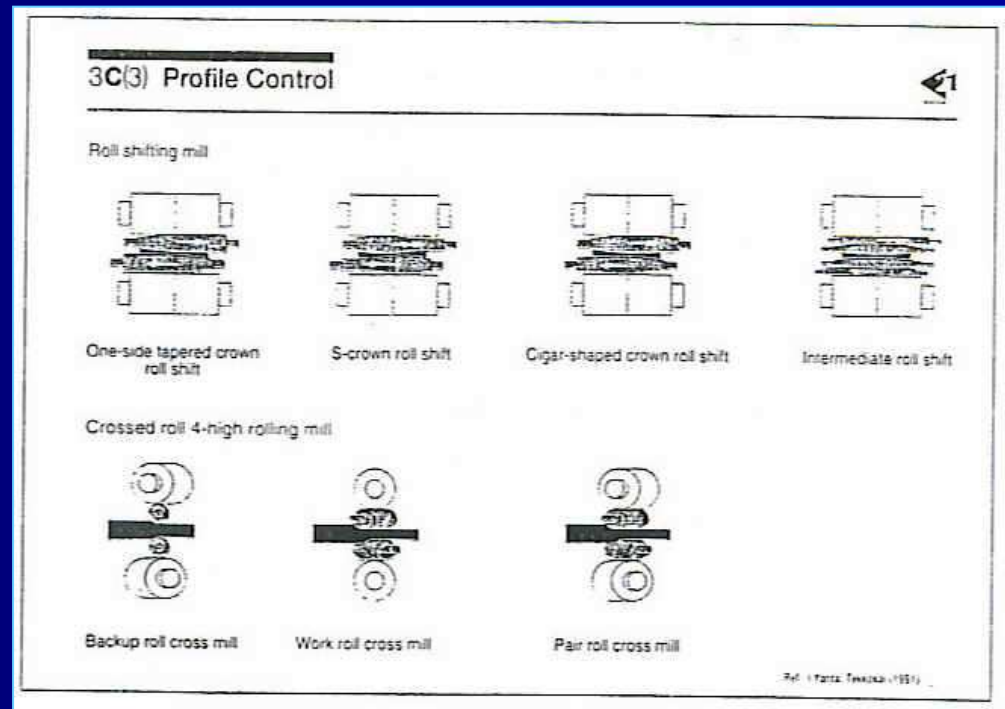
(b) Uncambered rolls give variation of thickness.



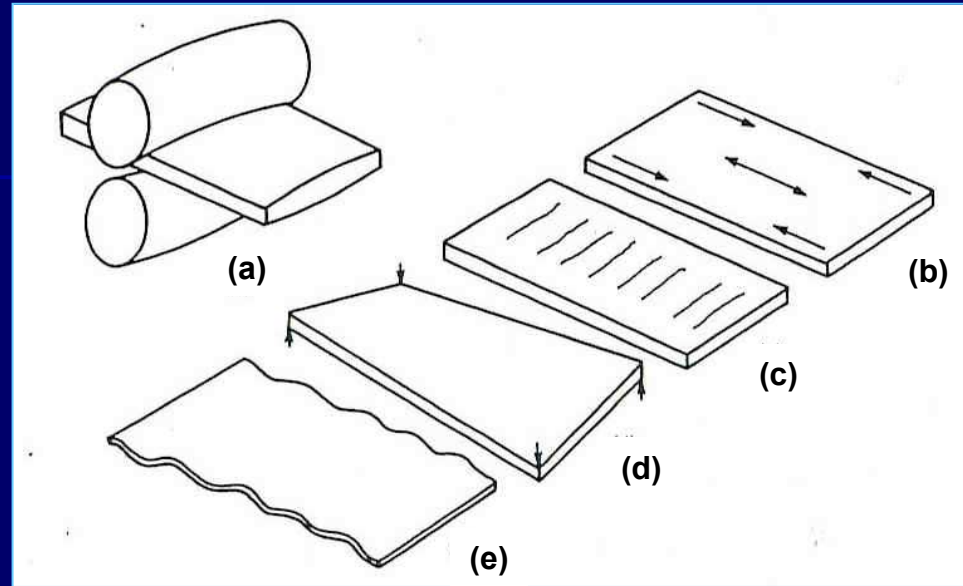


- Hot mill can be provided with facilities for **crown control** to improve the control of the profile of hot strip mill.
- For example work roll bending with continuous variable crown and pair cross mills.

- The roll cross angle of rolls incorporated in a stand of each rolling mill is set at a predetermined value beforehand.
- If there is a roll cross angle that will enable a target sheet crown to be applied to each sheet and the roll bender load of each stand is adjusted on-line, thereby effecting sheet crown control.



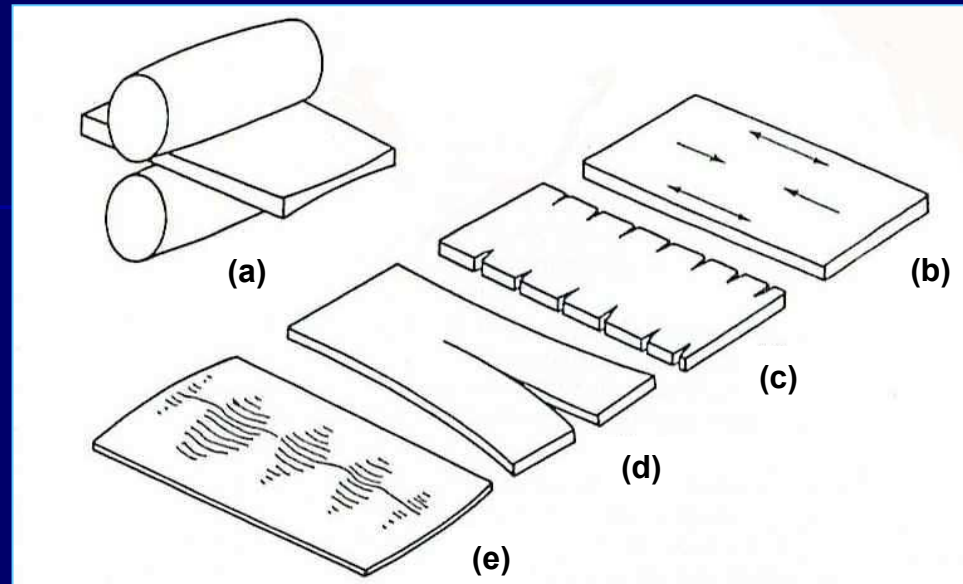
Possible effects when rolling with insufficient camber



- 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).



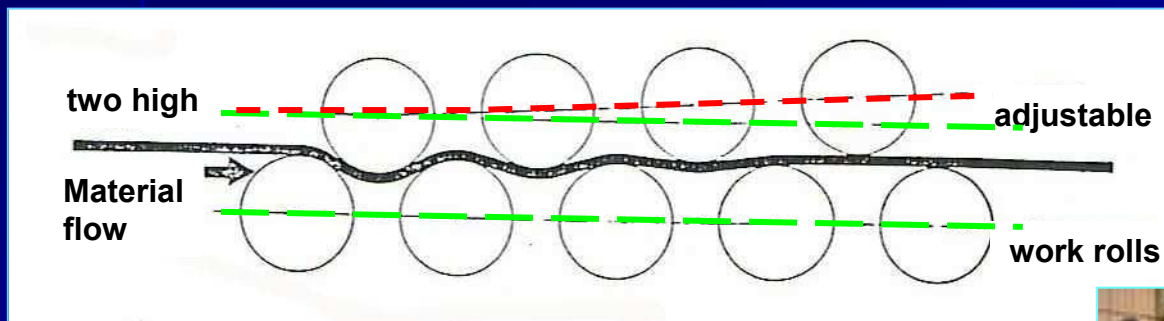
Possible effects when rolls are over-cambered.



- 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).



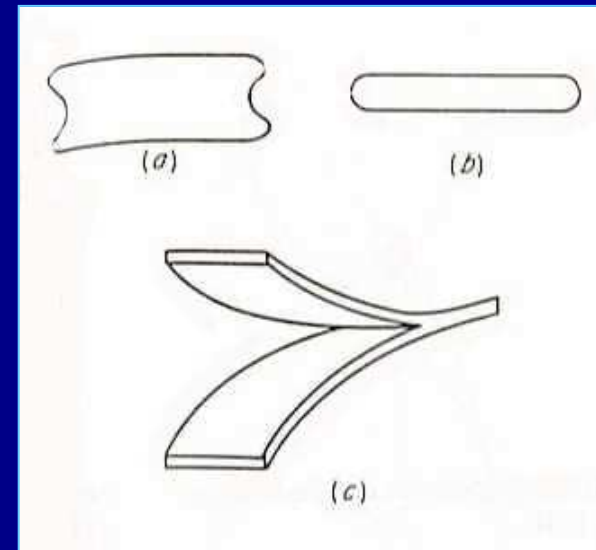
- Shape problems are greatest when rolling in thin strip (<0.01 in) because **fractional errors** in the roll gap profile increase with decrease in thickness, producing larger internal stress.
- Thin sheet is also less resistant to **buckling**.
- Mild shape problems may be corrected by **stretch levelling**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



Roller-leveller

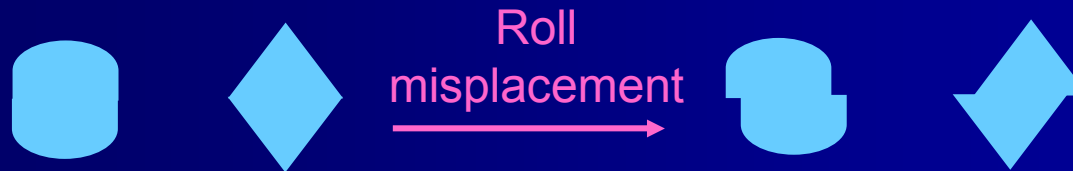


- **Edging** can also be caused by inhomogeneous deformation in the thickness direction.
- If only the surface of the workpiece is deformed (as in a light reduction on a thick slab), the edges are concaved (a). The overhanging material is not compressed in the subsequent step of rolling, causing this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



- 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.



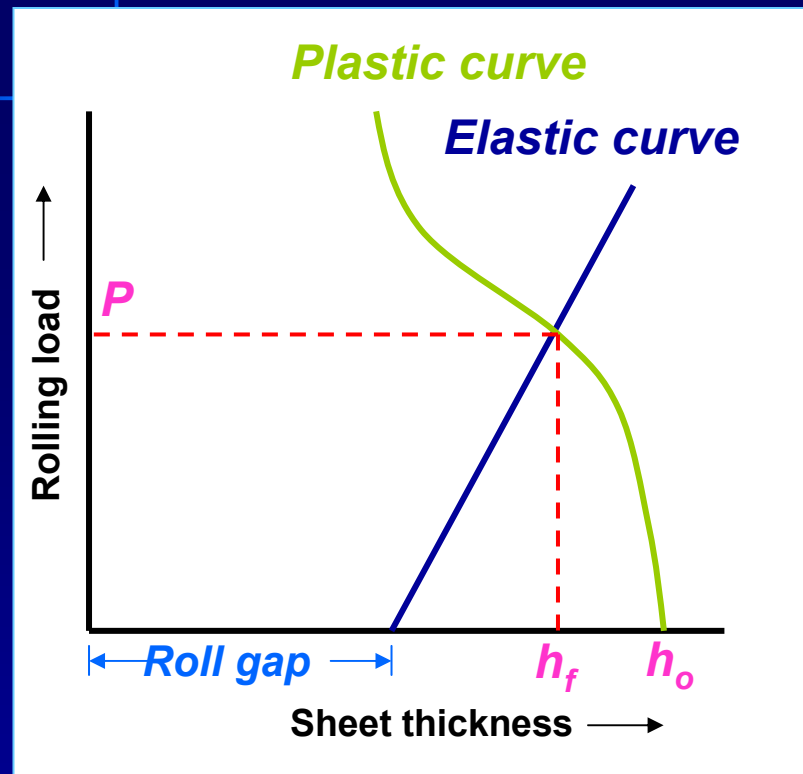
Rolling mill control

- Modern continuous hot-strip and cold rolling mills operated under automatic control provide high throughput and production rate.
- Of all the metal working processes, rolling is the best suited for the adoption of automatic control because it is an essentially steady-state process in which the tooling geometry (roll gap) may be changed readily during the process.
- Automatic control in rolling such as the development of online sensors to continuously measure sheet thickness. The most widely used instruments are
 - 1) flying micrometer
 - 2) x-ray or isotope, gauges which measure thickness by monitoring the amount of radiation transmitted through the sheet.
- More recently control procedures have been aimed at controlling strip shape as well as thickness.



Problem of gauge control

Normal situation



Characteristic elastic and plastic curves for a rolling mill

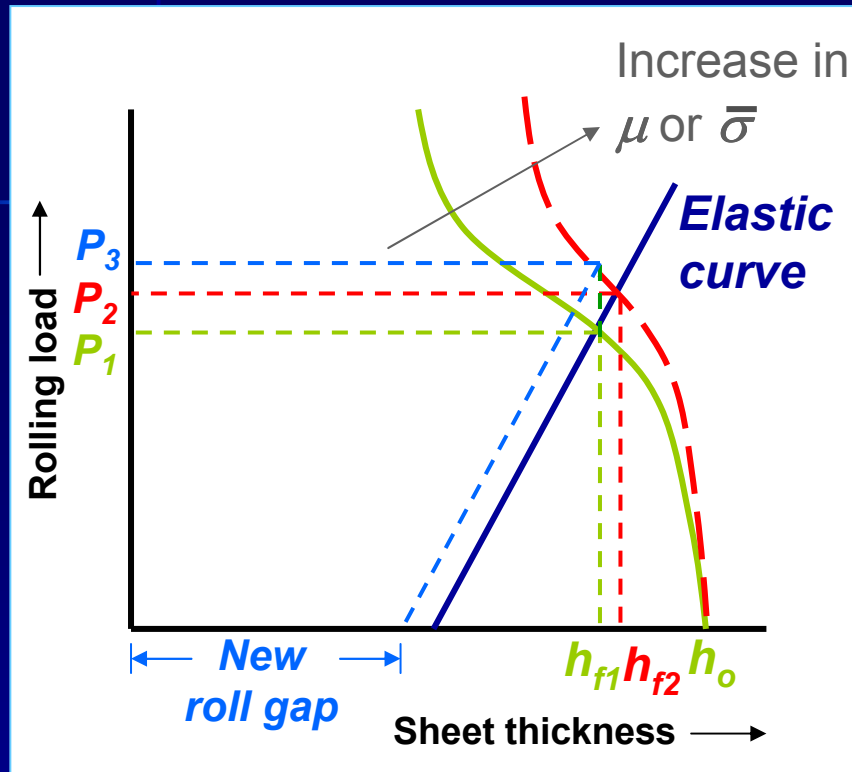
- For a given set of rolling conditions, the rolling load varies with the final sheet thickness, according to the plastic curve, which can be obtained in Eq.10.

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

- The **elastic curve** for mill spring indicates that a sheet of initial thickness **h_o** will have a final thickness **h_f** and the load on the mill would be **P** in normal situation.



Situation where μ or flow stress increase



μ ↑ due to lubricant breakdown
 $\bar{\sigma}$ ↑ due to Temp ↓

The plastic curve will be raised.

Therefore rolling load $P_1 \rightarrow P_2$
 final thickness $h_{f1} \rightarrow h_{f2}$

In order to maintain a constant thickness h_{f1} , under these new condition, the roll gap would have to be decreased. This moves the elastic curve to the left and further increases the rolling load to P_3 .

Use of characteristic curves to show changes in rolling condition.

- Example:**
- If the sheet thickness increases, the plastic curve will move to the right relative to the elastic curve.
 - If there is an increase in strip tension, the plastic curve will move to the left.



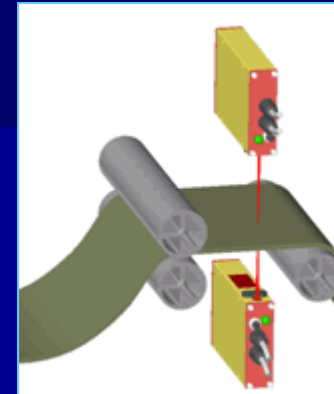
Thickness measurement in continuous hot mill

- In a continuous hot mill, the strip thickness is measured indirectly by measuring the rolling load and using the characteristic curve of the mill to establish the thickness.
- The error signal is feedback to the rolling mill screws to reposition them so as to minimise the error.
- An x-ray gauge is used after the last stand to provide an absolute measurement of sheet gauge.



Thickness measurement in continuous cold strip mills

- Thickness is measured by x-ray gauges while the error in the thickness following the first stand is usually feedback to adjust the gap sitting on the first stand.
- Gauge control in subsequent stands usually is achieved by controlling the strip tension through controlling the relative roll speed in successive stands or the coiler speed.
- Gauge control through control of strip tension has faster response time than control through change in roll setting.



sensors

Thickness gauging is achieved by using two opposing sensors with laser spots aimed at opposite sides of a target. The sensor readings are subtracted from the sensor separation distance to yield a real-time thickness measurement.



Theory of cold rolling

A theory of rolling is aimed at expressing the external forces, such as the rolling load and the rolling torque, in terms of the geometry of the deformation and the strength properties of the material being rolled.

Assumptions

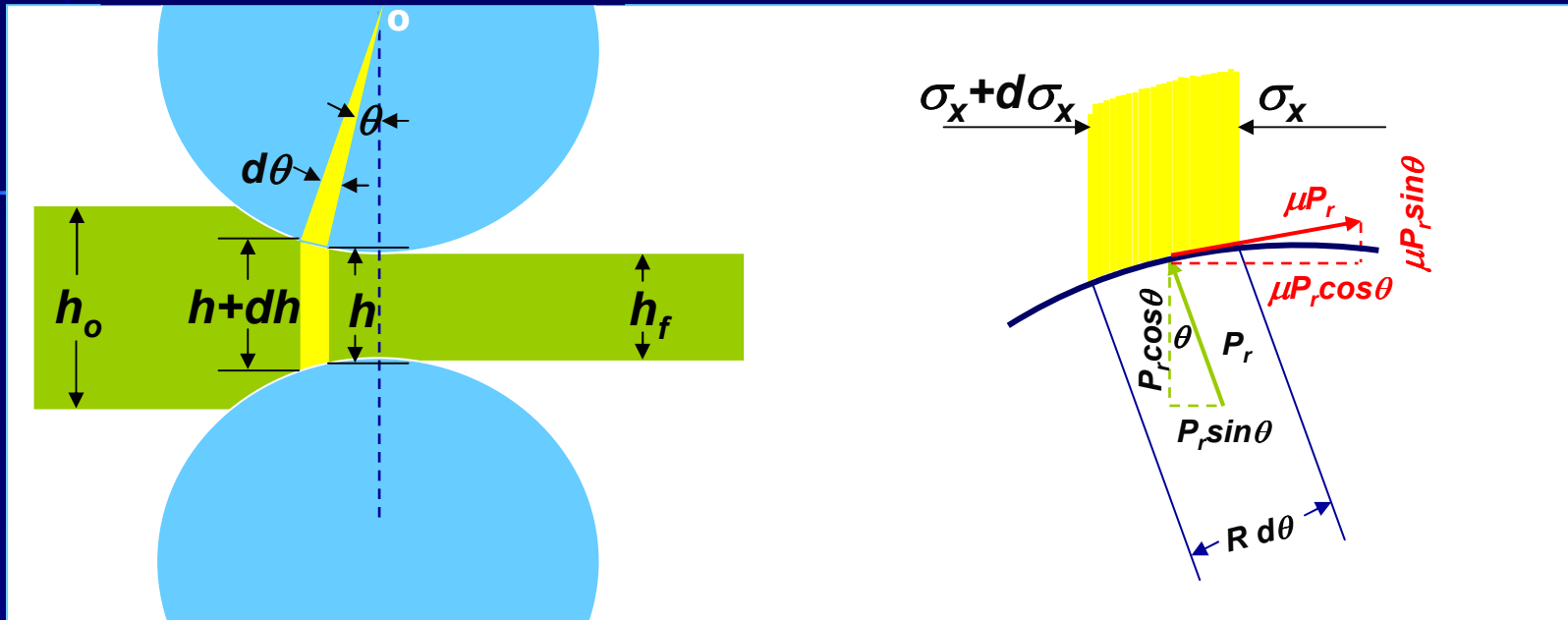
- 1) The arc of the contact is circular – no elastic deformation of the roll.
- 2) The coefficient of friction is constant at all points on the arc of contact.
- 3) There is no lateral spread, so that rolling can be considered a problem in plain strain.
- 4) Plane vertical section remain plane: i.e., the deformation is homogeneous.
- 5) The peripheral velocity of the rolls is constant
- 6) The elastic deformation of the sheet is negligible in comparison with the plastic deformation.
- 7) The distortion-energy criterion of yielding, for plane strain, holds.

$$\sigma_1 - \sigma_3 = \frac{2}{\sqrt{3}} \sigma_o = \sigma_o'$$

← Yield stress in plane strain condition

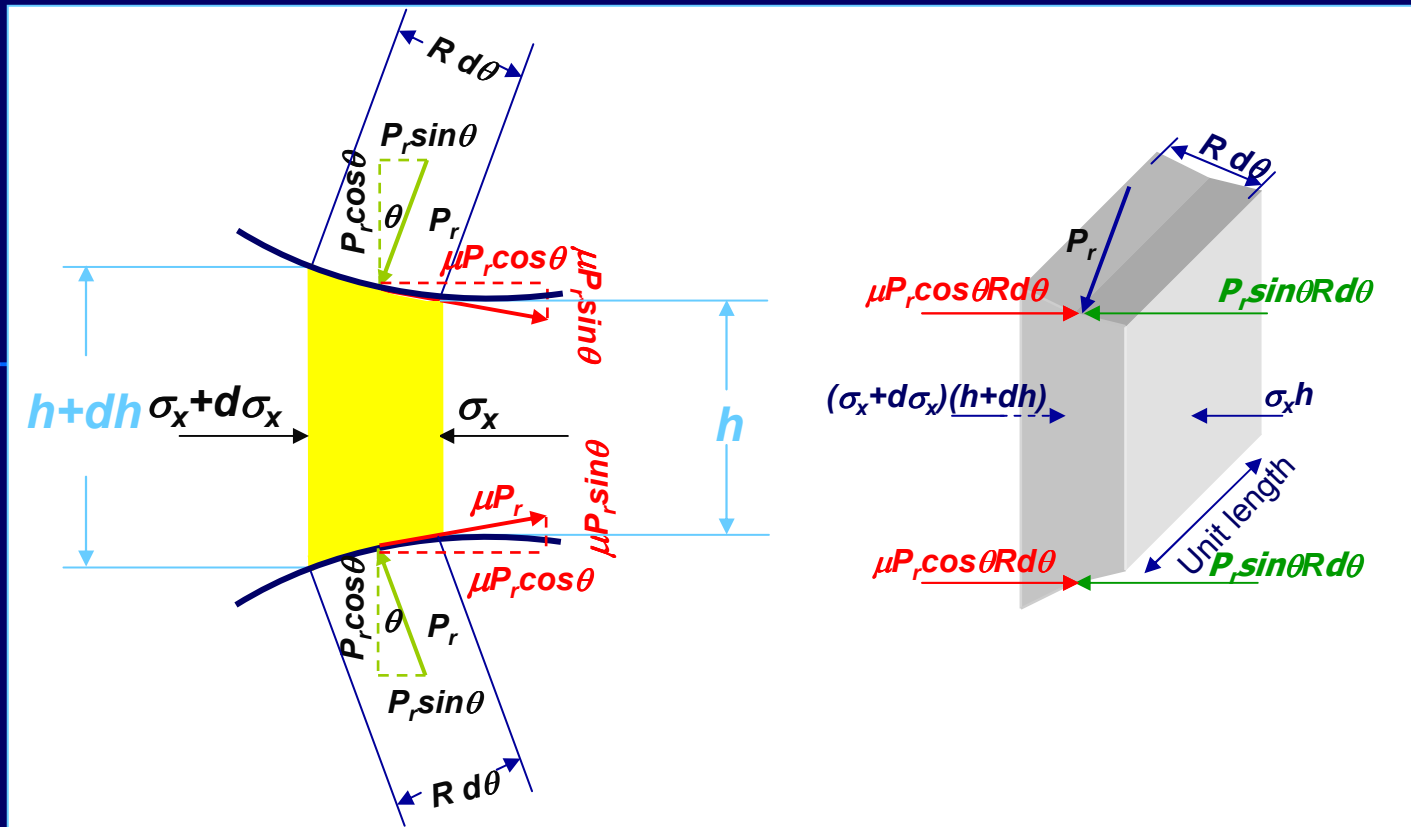


The stresses acting on an element of strip in the roll gap



- At any point of contact between the strip and the roll surface, designated by the angle θ , the **stresses** are the **radial pressure** p_r and the **tangential shearing stress** $\tau = \mu p_r$. These stresses are resolved into their horizontal and vertical components (b).
- The stress σ_x is assumed to be uniformly distributed over the vertical faces of the element.





Taking summation of the horizontal forces on the element results in

$$(\sigma_x + d\sigma_x)(h + dh) + 2\mu p_r \cos \theta R d\theta = \sigma_x h + 2p_r \sin \theta R d\theta$$

Which simplifies to

$$\frac{d(\sigma_x h)}{d\theta} = 2p_r R (\sin \theta \pm \mu \cos \theta)$$

...Eq.14



The forces acting in the vertical direction are balanced by the specific roll pressure p . Taking the equilibrium of forces in the vertical direction results in a relationship between the normal pressure and the radial pressure.

$$p = p_r (1 \mp \mu \tan \theta) \quad \dots \text{Eq.14}$$

The relationship between the normal pressure and the horizontal compressive stress σ_x is given by the distortion energy criterion of yielding for plane strain.

$$\sigma_1 - \sigma_3 = \frac{2}{\sqrt{3}} \sigma_o = \sigma_o'$$

$$p - \sigma_x = \sigma_o'$$

...Eq.15

Where p is the greater of the two compressive principal stresses.



The solution of problems in cold rolling are complicated. Some simplification to this problem has been provided by **Bland** and **Ford**.

By restricting the analysis to cold rolling under conditions of **low friction** and for **angles of contact** $< 6^\circ$, then we can put **$\sin \theta \sim \theta$** and **$\cos \theta \sim 1$** . Thus **Eq.14** can be written

$$\frac{d(\sigma_x h)}{d\theta} = 2p_r R' (\theta \pm \mu) \quad \dots \text{Eq.16}$$

It is also assumed that **$p_r \sim p$** , so that **Eq.15** can be written **$\sigma_x = p_r - \sigma'_o$** . By substituting into **Eq.16** and integrating, relatively simple equations of the radial pressure result.

Roll entrance to neutral point:

$$p_r = \frac{\sigma'_o h}{h_o} \left(1 - \frac{\sigma_{xb}}{\sigma'_{01}} \right) e^{\mu(H_1 - H)} \quad \dots \text{Eq.17}$$

Neutral point to roll exit:

$$p_r = \frac{\sigma'_o h}{h_f} \left(1 - \frac{\sigma_{xf}}{\sigma'_{02}} \right) e^{\mu H} \quad \dots \text{Eq.18}$$

Where

$$H = 2 \left(\frac{R'}{h_f} \right)^{1/2} \tan^{-1} \left[\left(\frac{R'}{h_f} \right)^{1/2} \theta \right]$$

and **σ_{xb}** = back tension
 σ_{xf} = front tension



The rolling load or total force P is the integral of the specific roll pressure over the arc of contact.

$$P = R'b \int_0^{\theta=\alpha} p d\theta$$

...Eq.19

Where b = width of sheet
 α = contact angle

The solution is replaced by the modern digital computer.



Theory of hot-rolling

In hot working processes, the flow stress for hot-rolling is a function of both temperature and strain rate (speed of rolls)

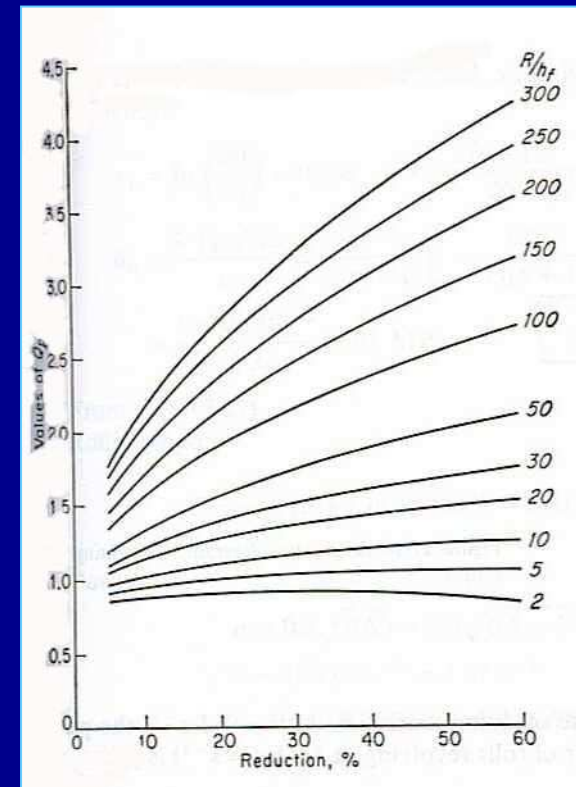
Calculation of rolling load by Sims

$$P = \sigma'_o b [R(h_o - h_f)]^{1/2} Q_p \quad \dots \text{Eq.20}$$

Where Q_p is a complex function of the reduction in thickness and the ratio R/h_f . Values of Q_p may be obtained from

$$Q_p = \sqrt{\frac{h_o}{4\Delta h}} \left[\pi \tan^{-1} \sqrt{\frac{\Delta h}{h_f}} - \sqrt{\frac{R}{h_f}} \ln \frac{h_n^2}{h_o h_f} \right] - \frac{\pi}{4}$$

$\dots \text{Eq.21}$



Torque and power

Torque is the measure of the force applied to a member to produce rotational motion.

Power is applied to a rolling mill by applying a torque to the rolls and by means of strip tension.

The power is spent principally in four ways

- 1) The energy needed to deform the metal.
- 2) The energy needed to overcome the frictional force.
- 3) The power lost in the pinions and power-transmission system.
- 4) Electrical losses in the various motors and generators.

Remarks: *Losses in the windup reel and uncoiler must also be considered.*



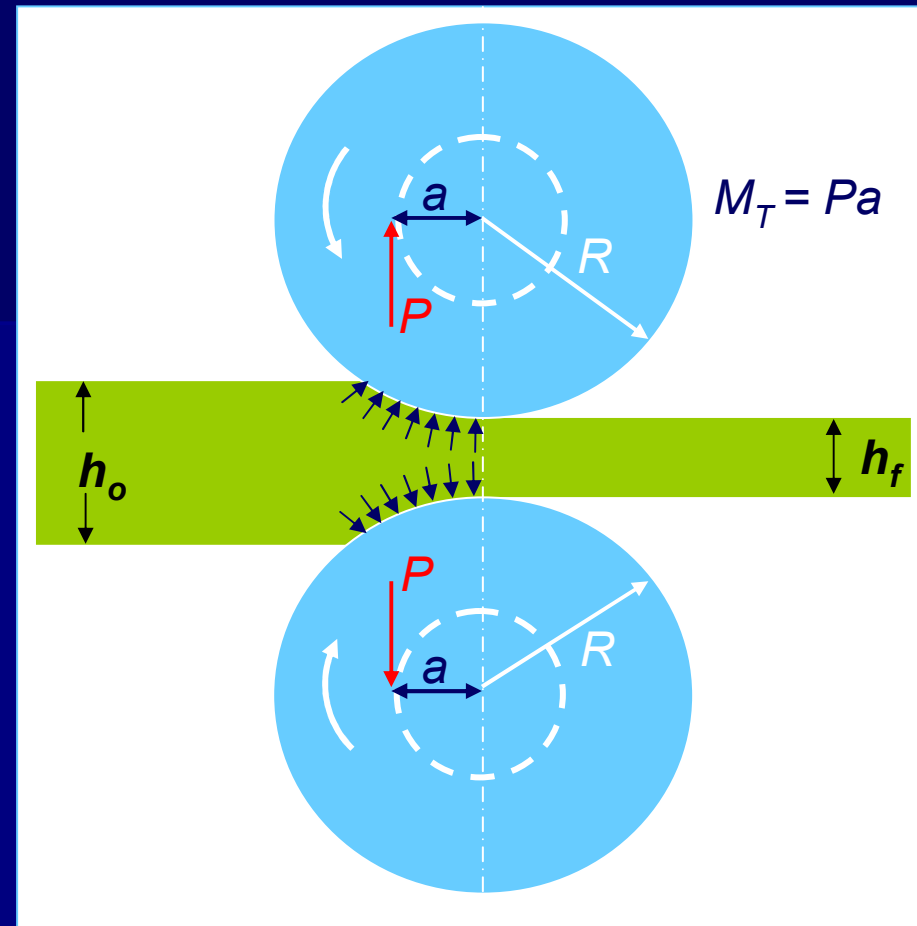
The **total rolling load** is distributed over the **arc of contact** in the typical friction-hill pressure distribution.

However the total rolling load can be assumed to be concentrated at **a point along the act of contact at a distance a** from the line of centres of the rolls.

The ratio of the moment arm a to the projected length of the act of contact L_p can be given as

$$\lambda = \frac{a}{L_p} = \frac{a}{\sqrt{R\Delta h}}$$

...Eq.22



Schematic diagram illustrating roll torque

Where λ is 0.5 for hot-rolling and 0.45 for cold-rolling.



The torque M_T is equal to the total rolling load P multiplied by the effective moment arm a . Since there are two work rolls, the torque is given by

$$M_T = 2Pa \quad \dots \text{Eq.23}$$

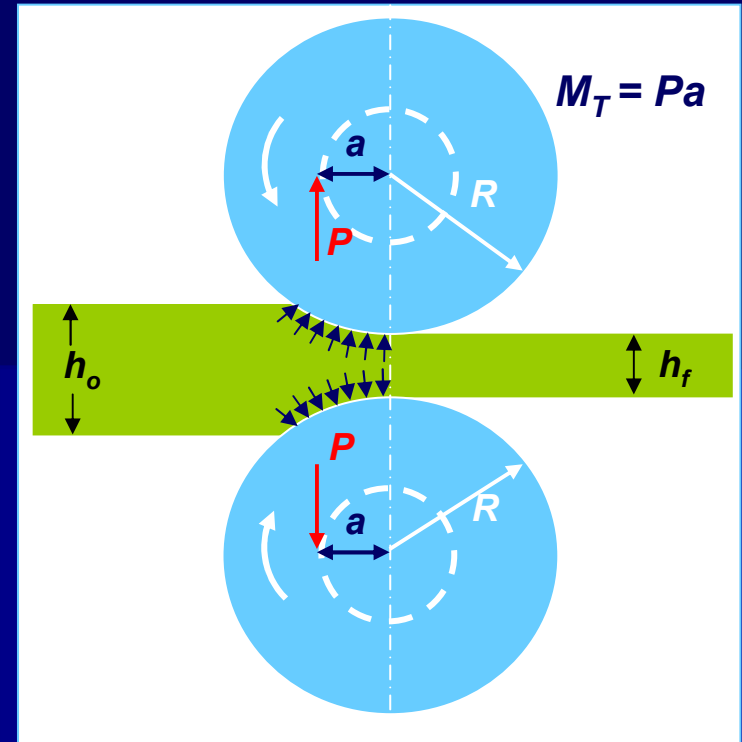
During one revolution of the top roll the resultant rolling load P moves along the circumference of a circle equal to $2\pi a$. Since there are two work rolls, the work done W is equal to

$$Work = 2(2\pi a)P \quad \dots \text{Eq.24}$$

Since power is defined as the rate of doing work, i.e., $1 \text{ W} = 1 \text{ J s}^{-1}$, the power (in watts) needed to operate a pair of rolls revolving at N Hz (s^{-1}) in deforming metal as it flows through the roll gap is given by

$$W = 4\pi aPN \quad \dots \text{Eq.25}$$

Where P is in newtons and a is in metres.



Example: A 300 mm-wide aluminium alloy strip is hot-rolled in thickness from 20 to 15 mm. The rolls are 1 m in diameter and operate at 100 rpm. The uniaxial flow stress for aluminium alloy can be expressed as $\sigma = 140\varepsilon^{0.2}$ (MPa). Determine the rolling load and the power required for this hot reduction.

From Eq.20

$$P = \sigma'_o b [R(h_o - h_f)]^{1/2} Q_p$$

$b = 0.3$ m, $R = 0.5$ m, $h_o = 0.02$ m and $h_f = 0.015$ m, we need to know σ'_o and Q_p .

$$\varepsilon_1 = \ln\left(\frac{20}{15}\right) = 0.288$$

$$r = \frac{20 - 15}{20} = 0.25$$

$$\frac{R}{h_f} = \frac{500}{15} = 33.3$$

$$\sigma'_o = \frac{k \int_0^{\varepsilon_1} \varepsilon^n d\varepsilon}{\varepsilon_1} = \frac{k \varepsilon^{n+1}}{\varepsilon_1 (n+1)} \bigg|_0^{\varepsilon_1} = \frac{k \varepsilon_1^n}{n+1}$$

$$\sigma'_o = \frac{140(0.288)^{0.2}}{1.2} = 91 \text{ MPa}$$

Q_p can be found from graph (~1.5) when reduction r and R/h_f are known.

$$P = \frac{2}{\sqrt{3}} (91)(0.3)[0.5(0.020 - 0.015)]^{1/2} (1.5) = 2.36 \text{ MN}$$

$$a = 0.5\sqrt{R\Delta h} = 0.5\sqrt{0.5 \times 0.005} = 0.025 \text{ m}$$

$$N = 100 / 60 = 1.67 \text{ s}^{-1}$$

$$W = 4\pi(0.025)(2.36 \times 10^{-6})(1.67) \text{ Js}^{-1} = 1.24 \text{ MW}$$



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