

Hot Rolling

Rolling



By rolling, cast ingots, strands and slabs are reduced in size and converted into basic forms such as sheets, rods and plates.

Rolling operations reduce the thickness or change the cross-section of a material through compressive forces exerted by rolls.

These forms can then undergo further deformation to produce a large variety of finished products formed by processes such as forging, extrusion, sheet metal forming etc.

From a tonnage viewpoint, rolling is clearly predominant among all manufacturing processes, with approximately 90% of all metal products experiencing at least one rolling operation.

The Rolling Process

In the basic rolling process metal is passed between two rolls that rotate in opposite directions, the gap between the rolls being somewhat less than the thickness of the material.

Because the rolls rotate faster than the speed of the incoming metal, friction along the contact interface acts to propel the metal forward.

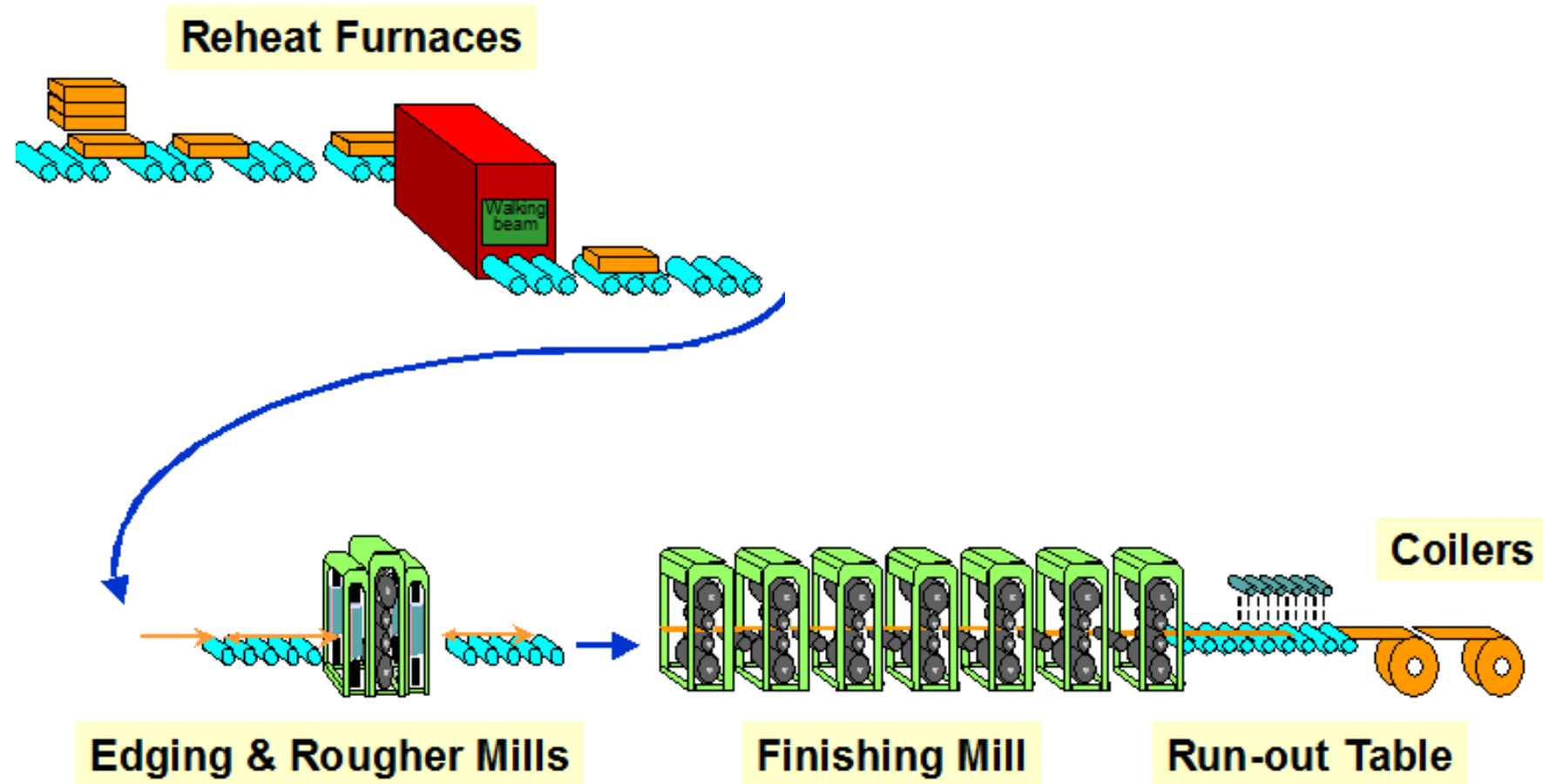
The metal is then squeezed and elongates to compensate for the decrease in thickness.

The amount of deformation that can be achieved in a single pass between one pair of rolls depends on the friction conditions.

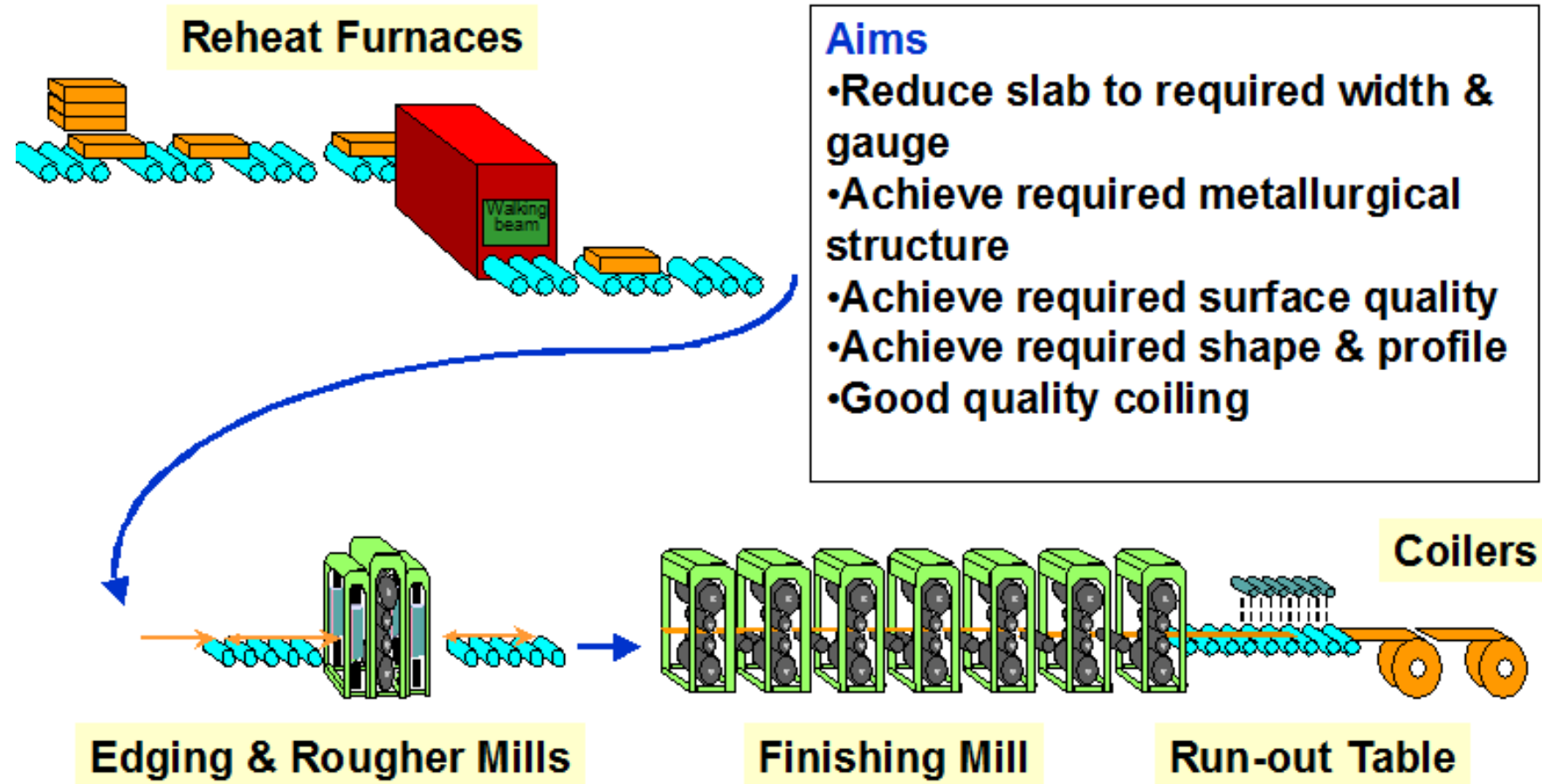
- If too much thickness reduction is demanded the rolls cannot advance the material, and simply skid over its surface.

- If too little deformation is given, the operation will be successful, but more passes will be needed to produce a given part which will increase the cost of production.

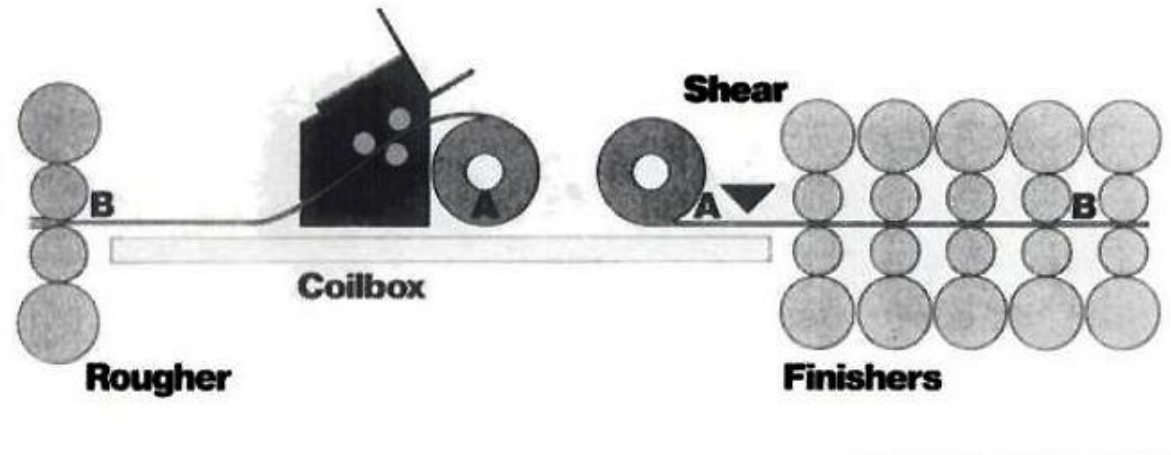
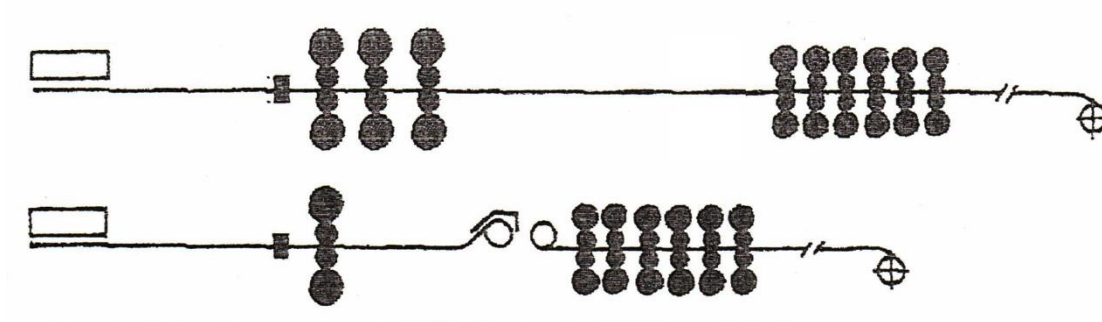
Hot Rolling



Hot Rolling



Use of coil box



Coilbox

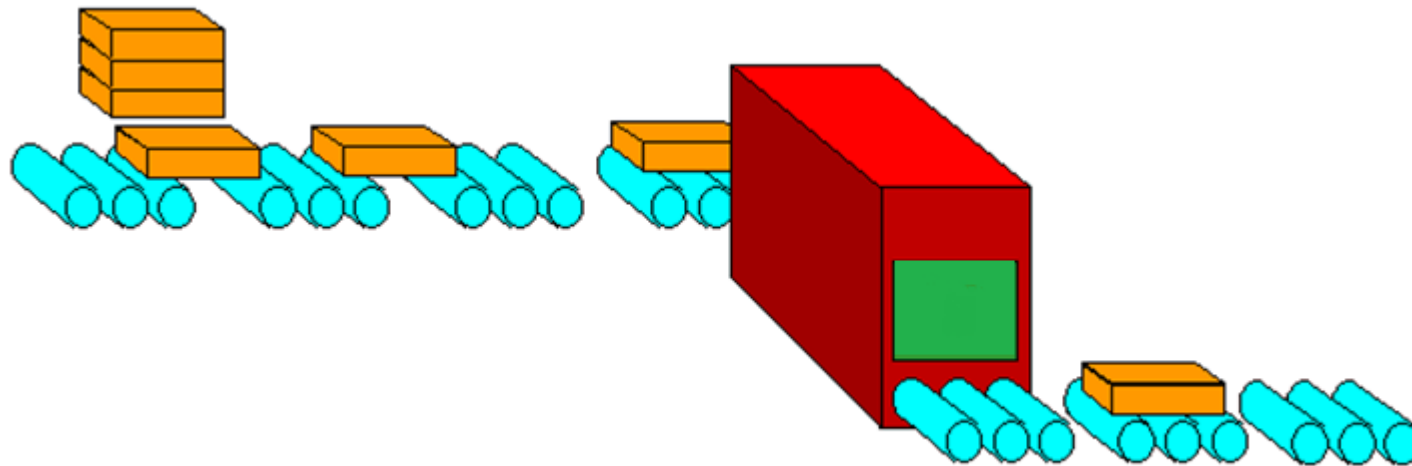
Reduced length of delay table

Peak power requirement reduced by 13%

Energy saving by 6%

Drive power in finishing train reduced as much as 40%

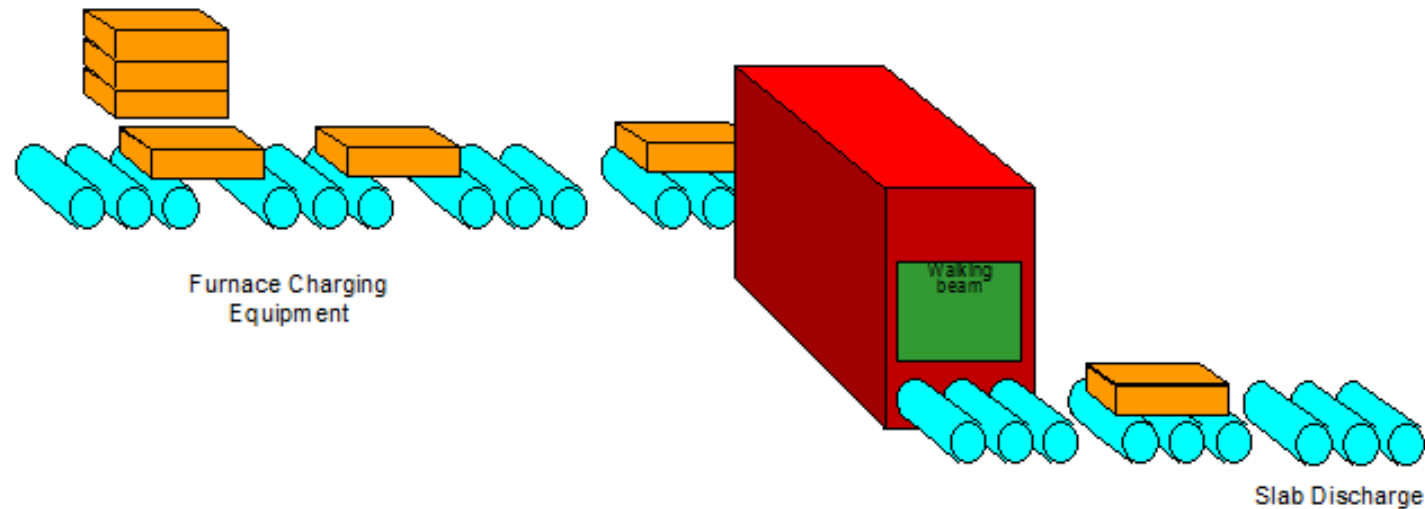
Reheat Furnace



Reheat Furnace

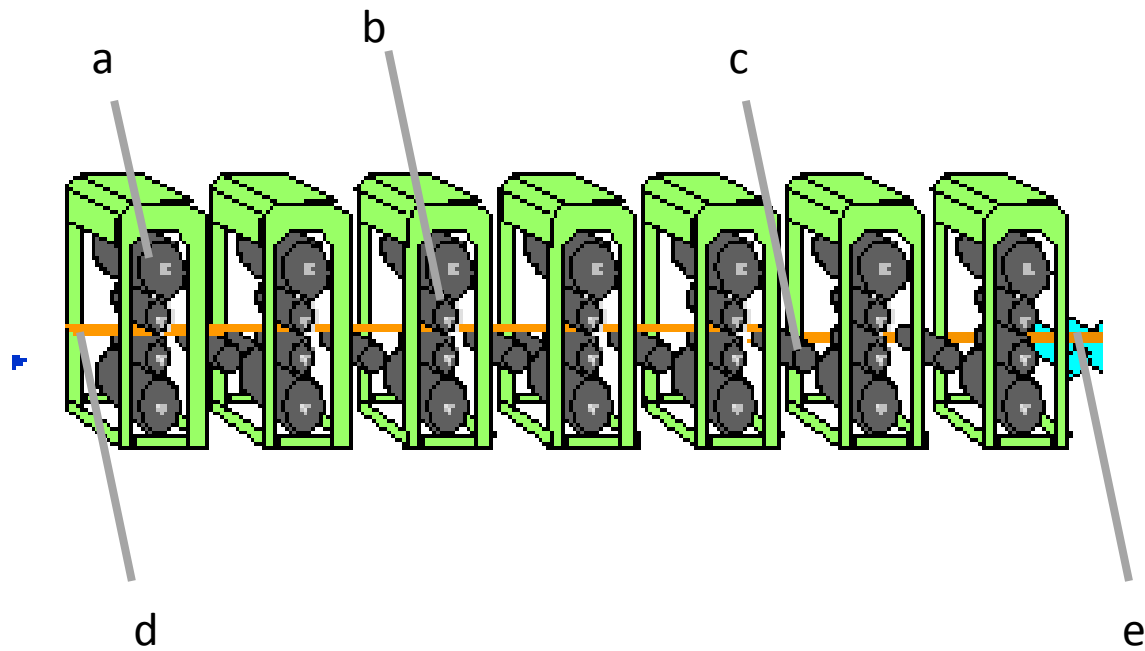
Aims

- Heat slab uniformly to required temperature (approx 1250degC)
- Minimise energy consumption
- Control oxidation/scale formation (gas + controlled O₂ level)



Furnace can be walking beam (PT) or pusher design (LL)

Finishing Mill

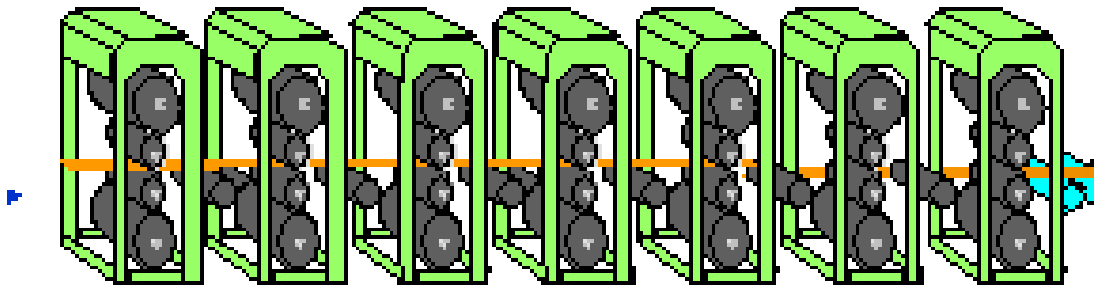


Finishing Mill

Aims

- Reduce strip to final thickness~3mm
- control width

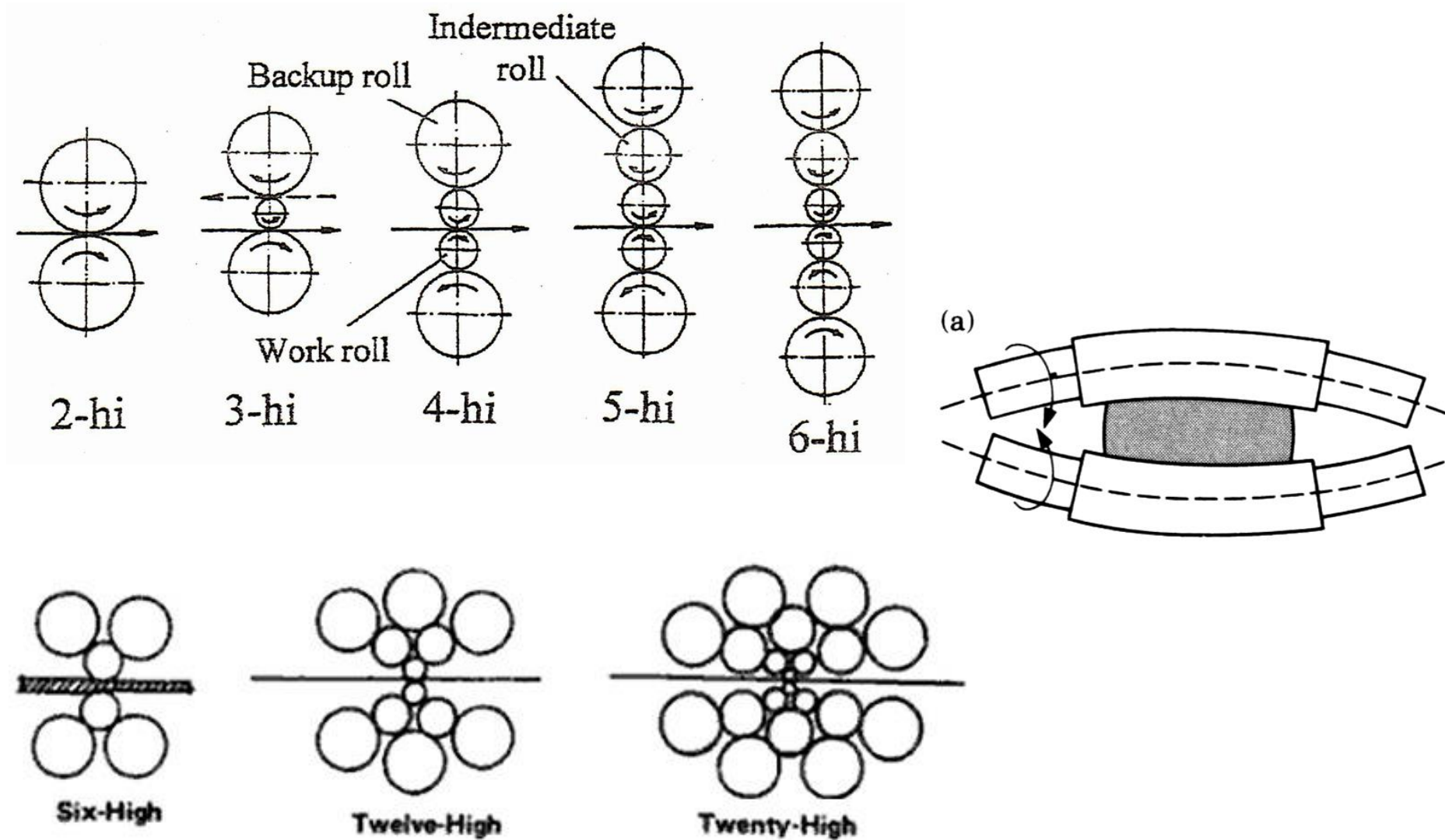
Temperature reduces to ~900°C



From five to seven stands containing work rolls and back up rolls.

Rolling Mills for Flat Products

Types of mill stand by roll arrangement



Types of mill stand by rolling direction

Non reversing

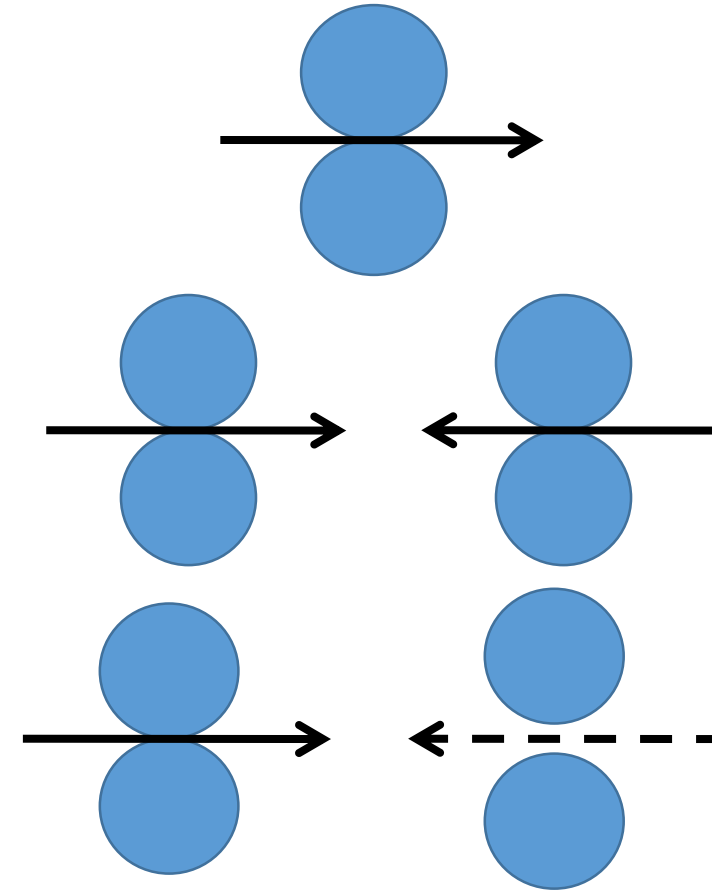
Rolling in forward direction only

Reversing

Rolling in forward & backward direction

Back-pass

Rolling in forward direction
Re-transfer in backward direction



Drive train arrangement

Direct drive (same angular speed as motor)

Gear drive (angular speed adjustable)

Pinion drive (single motor drive of both rolls)

Independent drive (separate motors)

Mill stand arrangement

Open stand

Stand separation greater than rolled product length

Close coupled stand

Stand separation much less than rolled product length

Rolling temperature

Hot rolling

Above 900 (in the γ -region)

Warm rolling

Above 720 (in the $\alpha + \gamma$ region)

Cold rolling

Room temperature

- From 912 to 1,394 °C (1,674 to 2,541 °F) alpha iron undergoes a phase transition from body-centred cubic (BCC) to the face-centred cubic (FCC) configuration of gamma iron, also called austenite.
- This is similarly soft and ductile but can dissolve considerably more carbon (as much as 2.03% by mass at 1,146 °C (2,095 °F)).
- This gamma form of iron is the most commonly used type of stainless steel for making hospital and food-service equipment.

Classification of hot rolling

Conventional

Deformation in γ -region (above Ar_3)

Controlled

Initial deformation in γ -region

Final deformation in $\alpha + \gamma$ region

Low finishing temperature

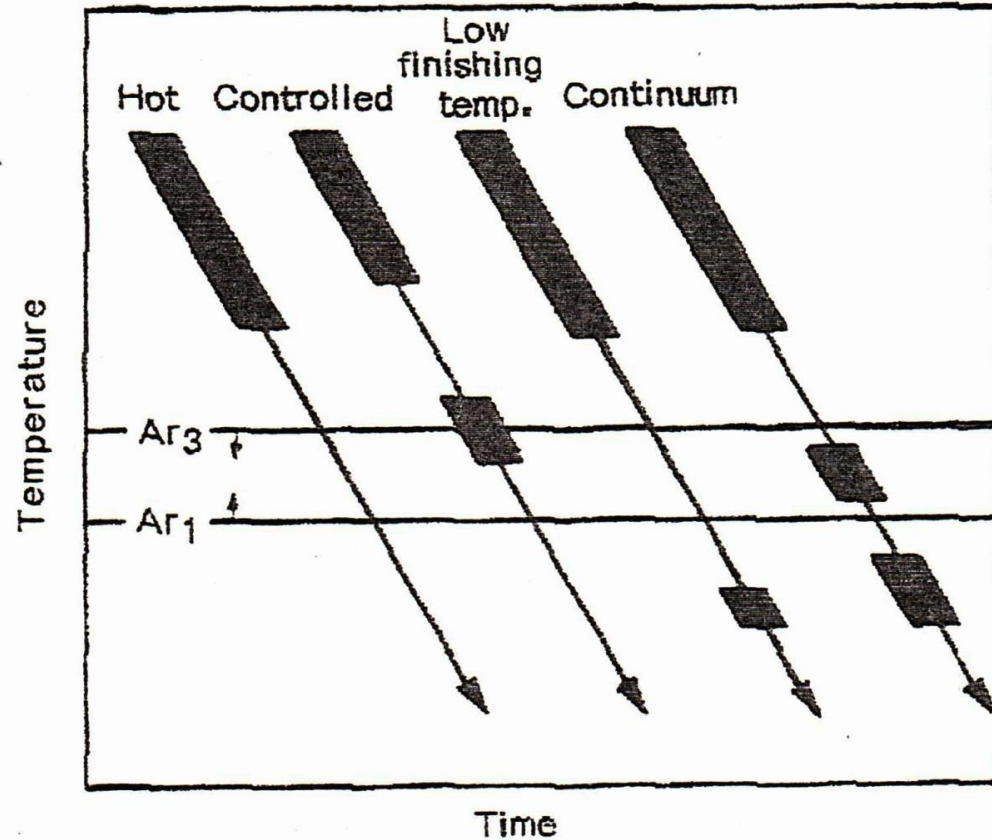
Initial deformation in γ -region

Final deformation in α region

Continuum

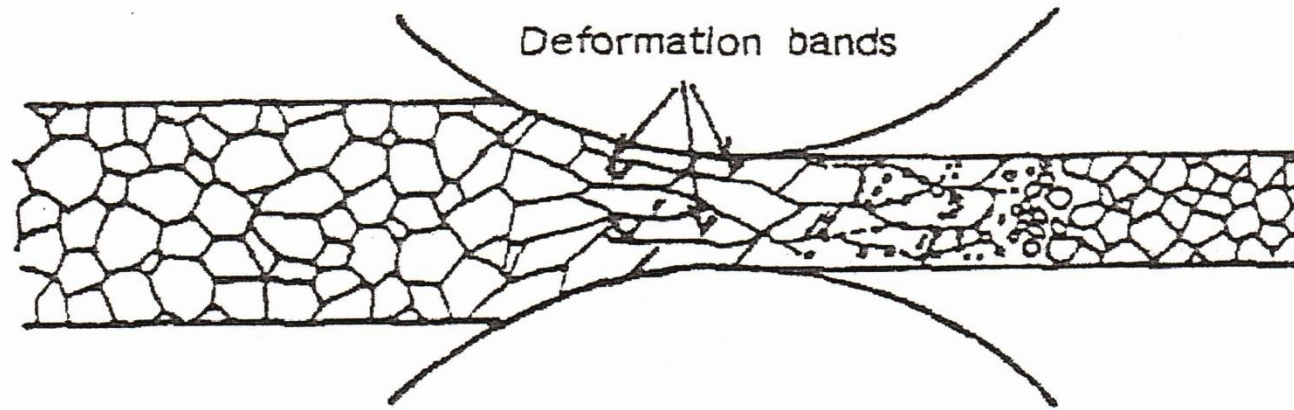
Roughing in γ -region,

Finishing in $\alpha + \gamma$ region and α region



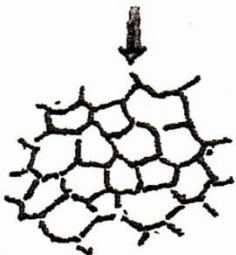
Conventional hot rolling of plain carbon steel

Finishing mill



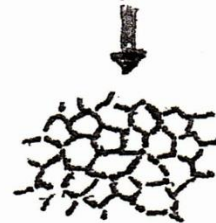
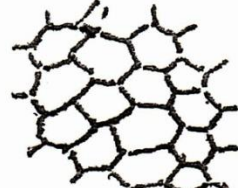
ROT and coiling

FT well above A_3
Coarse γ



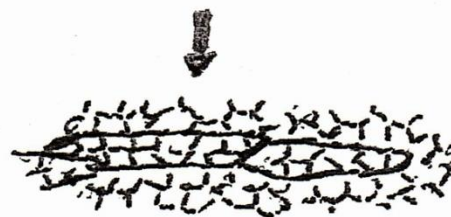
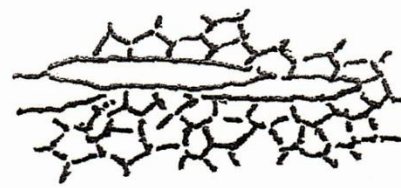
Coarse α

FT just above A_3
Fine γ



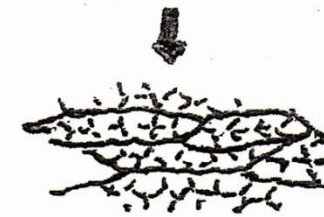
Fine α

Partly recrystallized
partly deformed γ



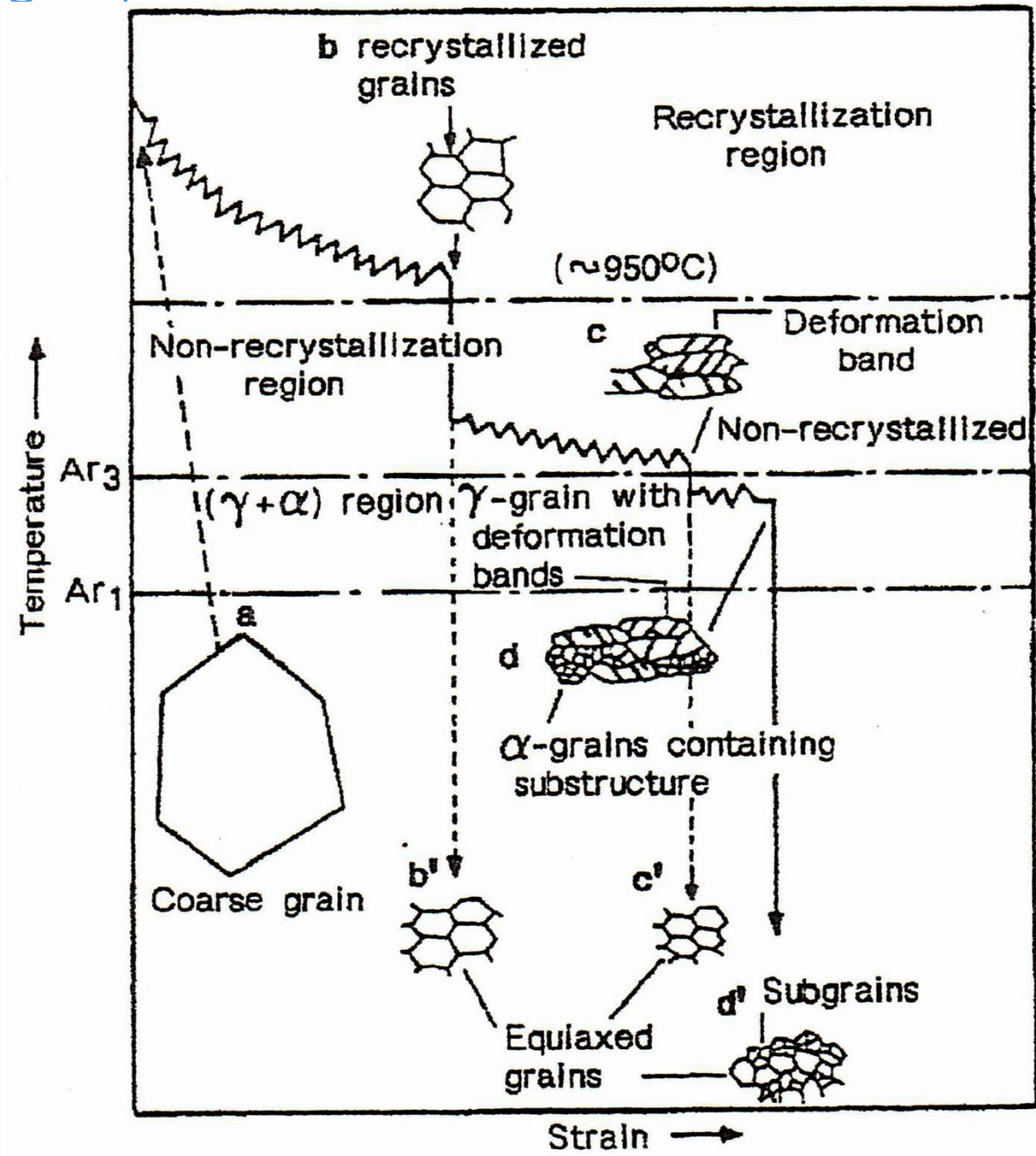
Mixed α grain size

Deformed γ



α grains in bands

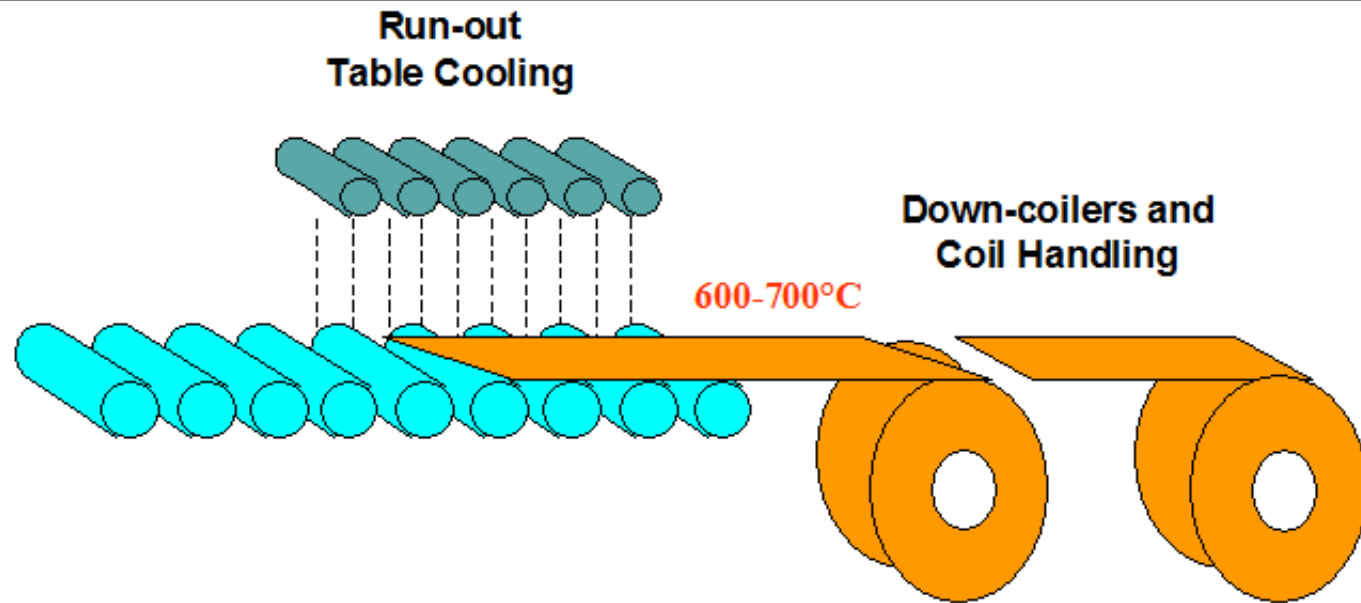
Controlled hot rolling of plain carbon steel



Run Out Table and Coiler

Aims

- Achieve required cooling regime/metallurgical structure
- Achieve required coiling temperature
- Produce high standard of coiling
- Uniquely identify coils



Hot Rolling

In hot rolling temperature control is required for success.

The starting material should be heated to a uniform elevated temperature, which is usually carried out in gas or oil-fired soaking pits or reheat furnaces. For plain carbon and low alloy steels, the soaking temperature is about 1200C.

Because of the oxidising atmosphere in the reheat furnaces, the slab surface becomes oxidised.

This surface scale must be removed before rolling.

This is achieved with high pressure water jets.

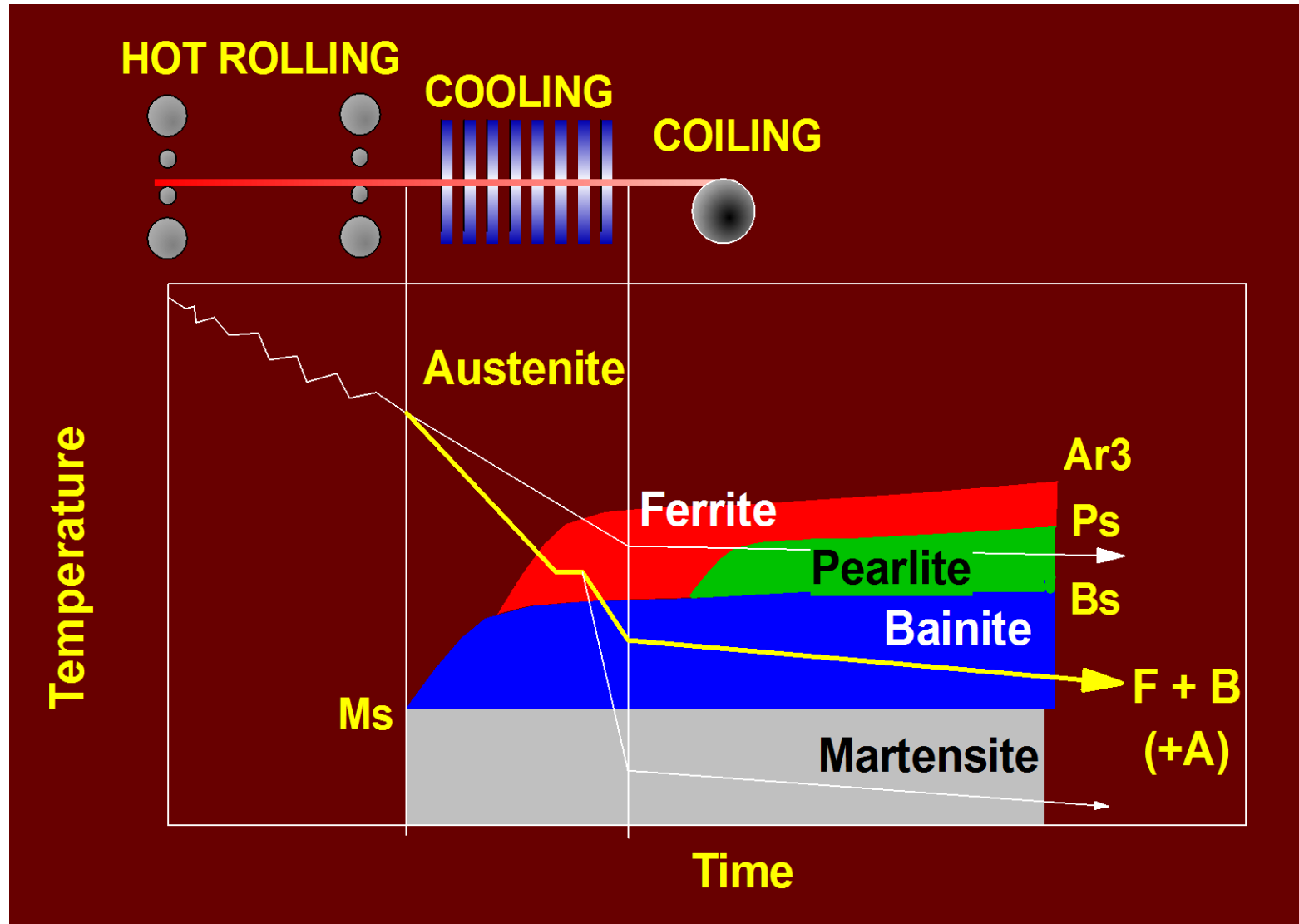
In most plants, the hot slab is then rolled through horizontal and vertical mill stands, known as 'scale breakers' which fracture and detach most of the oxide layer.

Hot Rolling

For any steel a wide range of microstructures and properties can be obtained by control of :

- The slab reheating temperature.
- The temperature of the steel during rough rolling.
- The finishing temperature(FT) of the steel exiting the final stand of the finishing mill.
- The coiling temperature(CT).
- The run out table(ROT) cooling schedule defining the patterns of cooling from FT to CT.

Run Out Table



Rolling

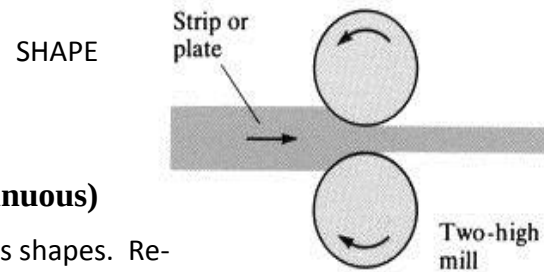
PROCESS

Bulk

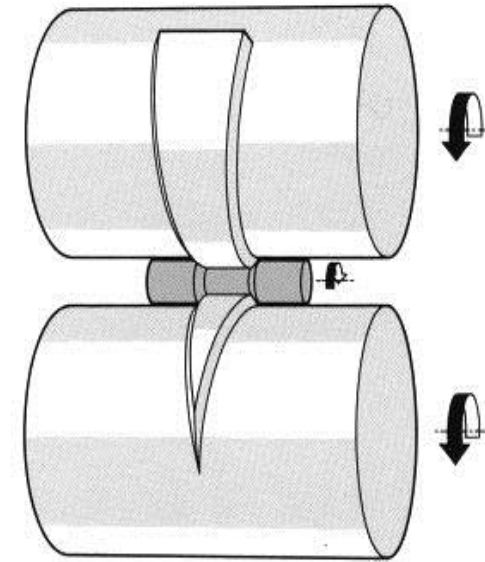
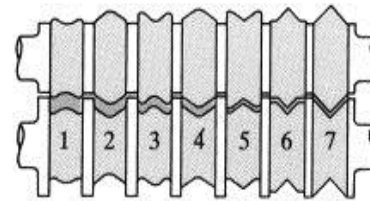
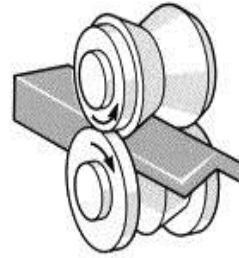
Continuous forming of bulk metal between rotating tooling (rolls).

2D (continuous)

Continuous shapes. Re-entrant angles possible in 2D profile.



Rolling



Transverse rolling

Circular wedge rolls used. Heated bar cropped to length fed in transversely between rolls. One revolution of rolls only.

Flat sheet rolling

Long continuous lengths. Rolls may be reversed. Roll gap altered on each pass.

Shaped rolling

Flat slab passed through a series of rolls with shaped grooves in them (1-7).

MATERIALS

Metals

Any metal that is ductile at temperature of forming.

CYCLE TIME

Dependent on product length but production rate very rapid.

QUALITY

Generally good but depends primarily on rolling temperature. Surface texture deteriorates with increasing temperature.

FLEXIBILITY

Most rolls non-dedicated, shaped rolls dedicated. Setting up time of shaped rolls can be large.

MATERIALS UTILIZATION

Scrap only produced when cutting continuous product to length.

OPERATING COST

Machines and rolls are costly.

Cold Rolling

- **Cold rolled steel is essentially hot rolled steel that has had further processing. The steel is processed further in cold reduction mills, where the material is cooled (at room temperature) followed by annealing and/or tempers rolling. This process will produce steel with closer dimensional tolerances and a wider range of surface finishes**

- **Pickled Hot Rolled Coils**

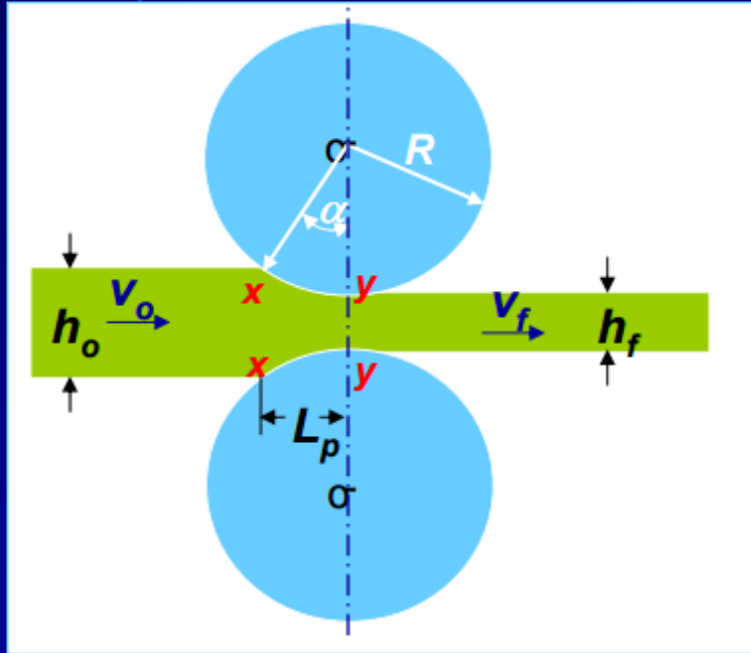


- **Cold Rolling Mill**
 - usually multi-stand close-coupled four-high horizontal mills
 - reductions of ~50-70% for sheet (~0.5-1.5 mm)
 - reductions of ~85-90% for tinplate (0.15 to 0.3 mm)
 - cold rolling deforms the ferrite grains without recrystallization
 - tensile strength increases but ductility falls
 - roll lubrication with oil/water emulsions.



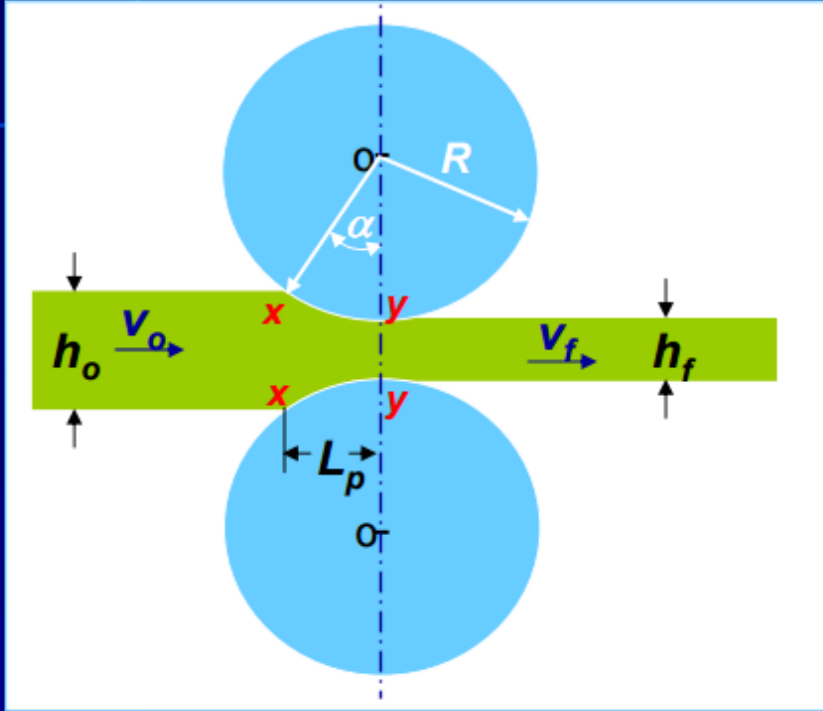
Fundamental concept of metal rolling

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

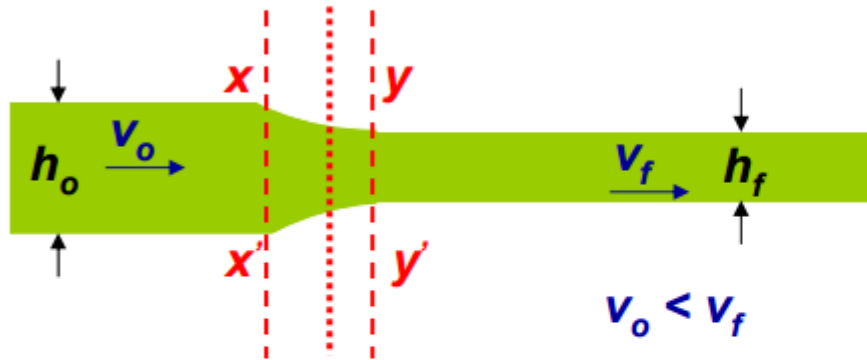


$$bh_o v_o = bh v = bh_f v_f \quad \dots \text{Eq.1}$$

- 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 $v_o < v_f$

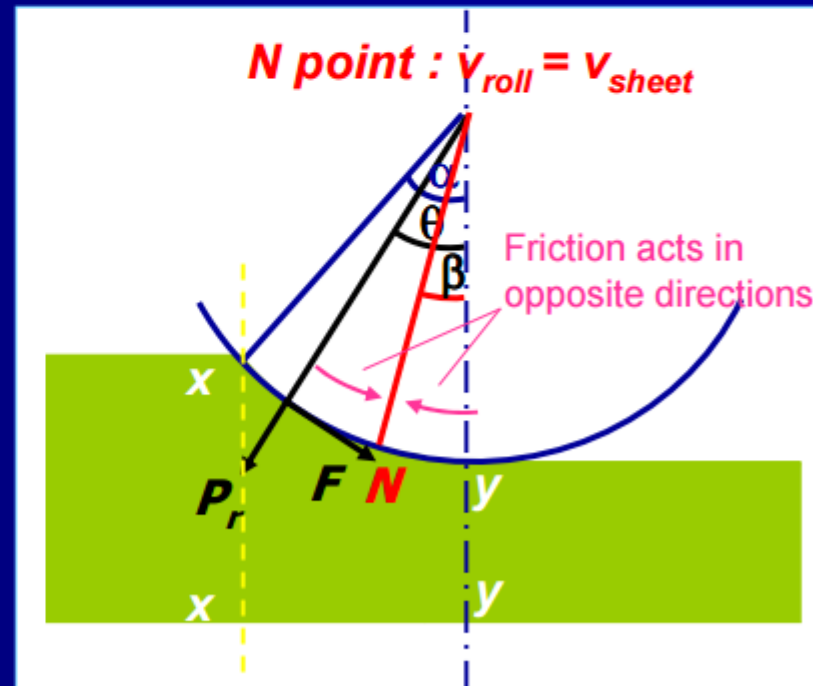
The **velocity** of the sheet must steadily increase from entrance to exit such that a vertical element in the sheet remain **undistorted**.

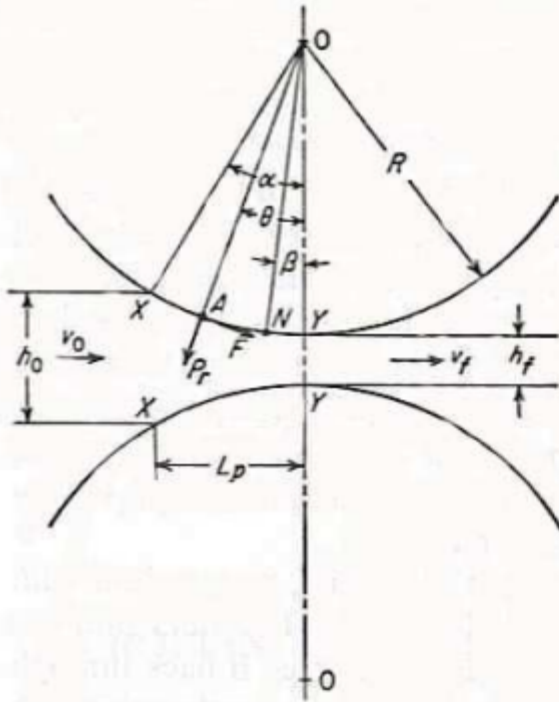
- At only one point along the surface of contact between the roll and the sheet, two forces act on the metal: 1) a radial force P_r and 2) a tangential frictional force F .

- 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.

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

...Eq.3

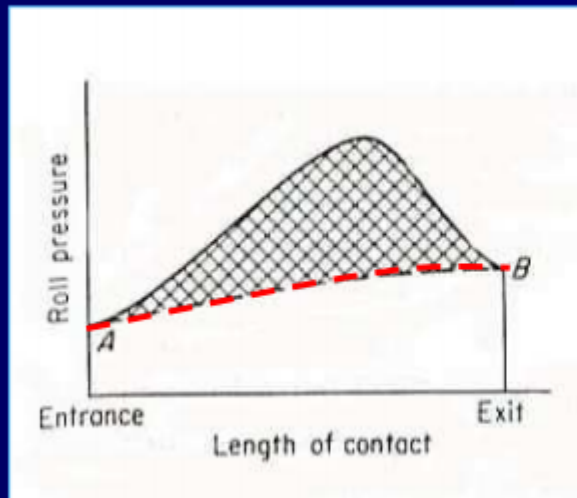
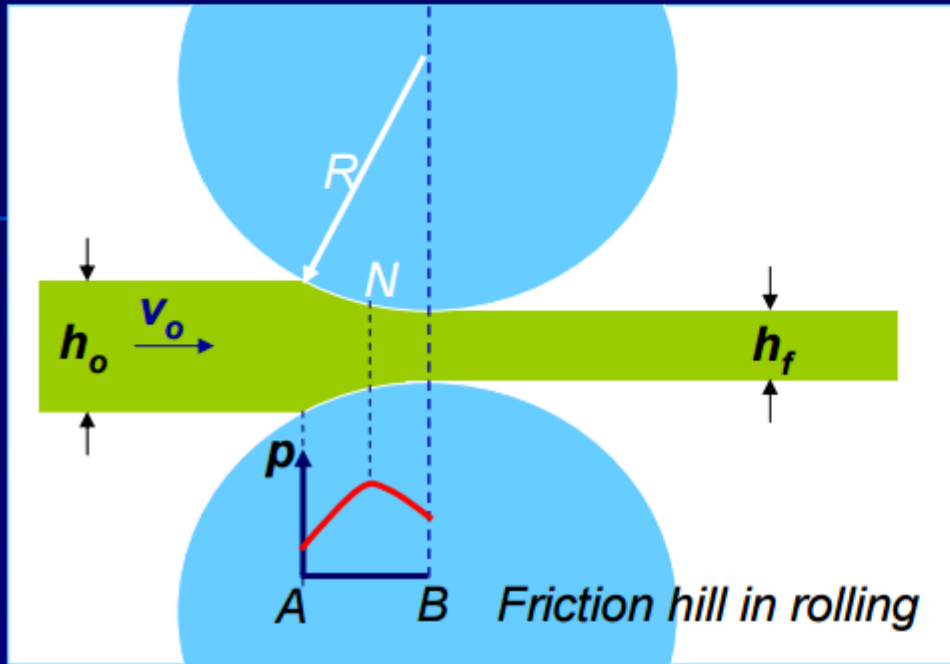
Where b is the width of the sheet.

L_p is the projected length of the arc of contact.

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

...Eq.4

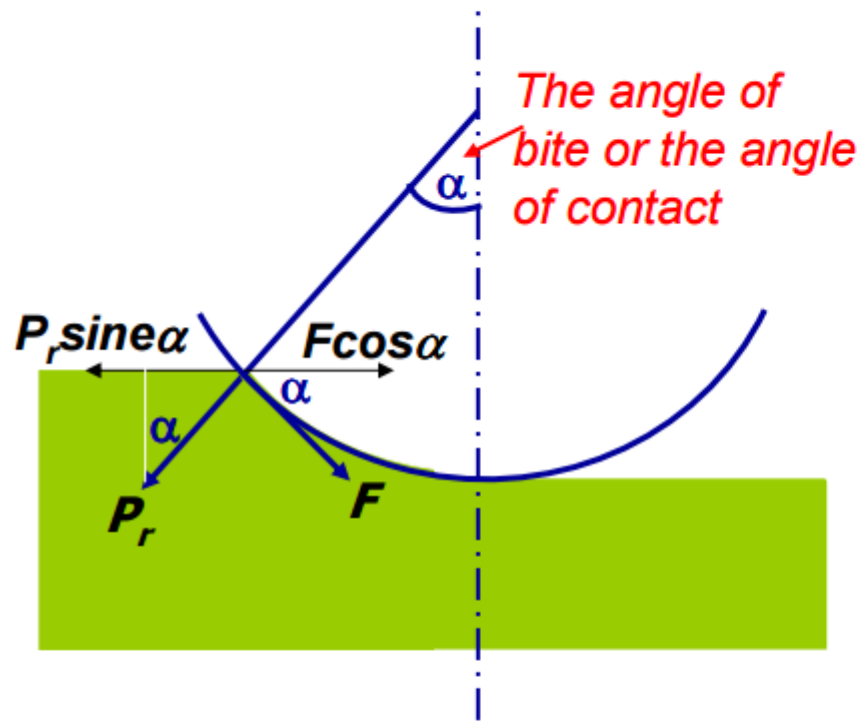
$$L_p \approx \sqrt{R\Delta h}$$



- 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.

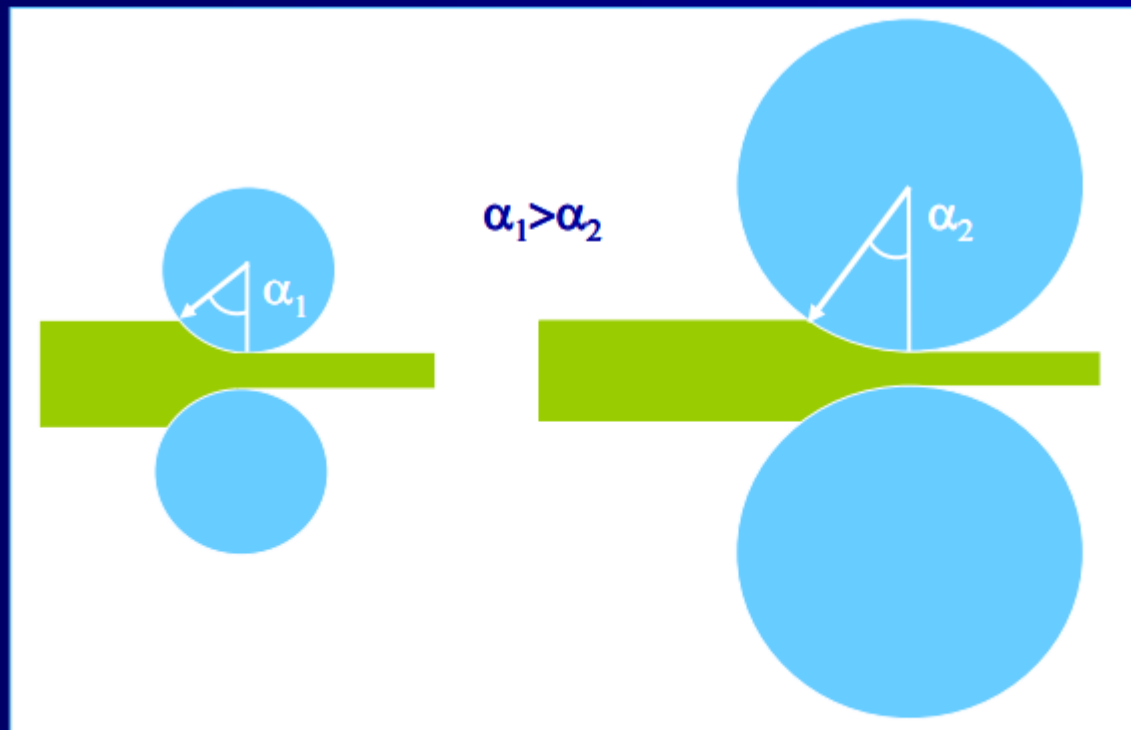
Therefore Free engagement will occur when $\mu > \tan \alpha$



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

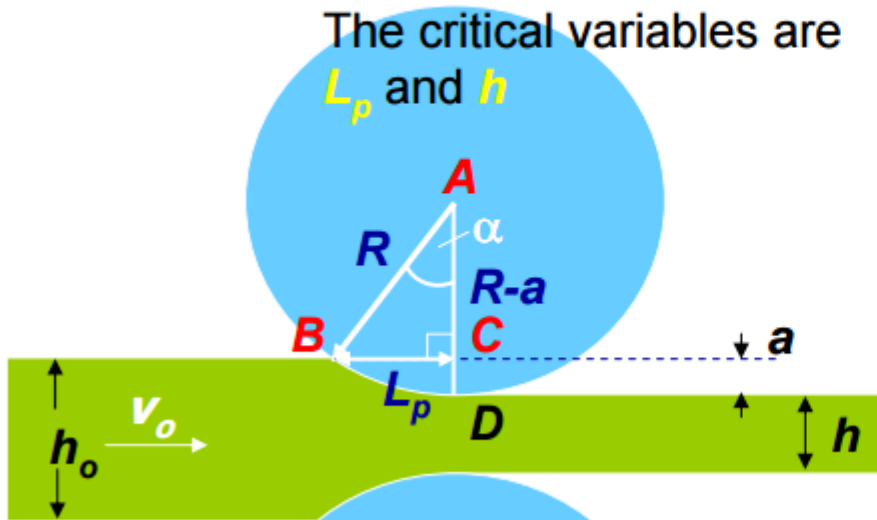
+

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

$$\mu = \tan \alpha = \frac{L_p}{R - \Delta h/2} \approx \frac{\sqrt{R\Delta h}}{R - \Delta h/2} \approx \sqrt{\frac{\Delta h}{R}} \quad \Rightarrow \quad (\Delta h)_{\max} = \mu^2 R \quad \dots \text{Eq.7}$$

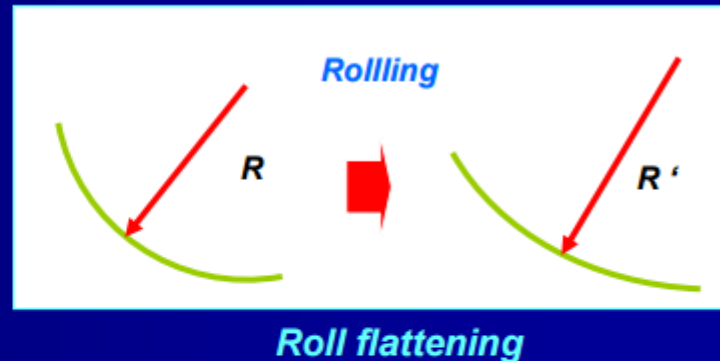
Problem with roll flattening

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

Simplified analysis of rolling load

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1) No friction condition

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3) Sticky friction condition

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 Q
 $\bar{h}$

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

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

From Eq.8,

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

We have

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

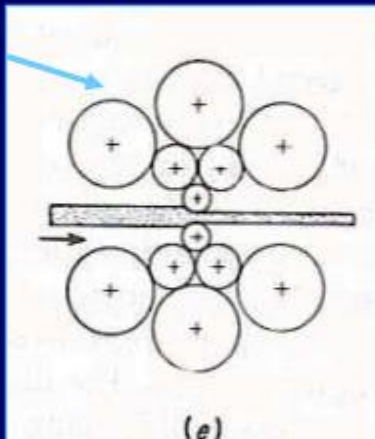
...Eq.10

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).

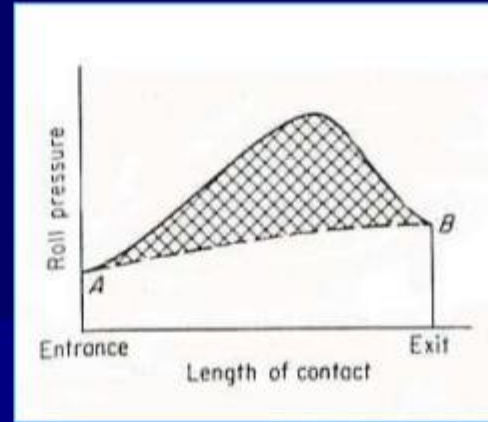
- At one point, **no further reduction in thickness** can be achieved if the deformation resistance of the sheet is greater than the roll pressure. The rolls in contact with the sheet are both severely elastically deformed.
- **Small-diameter rolls** which are properly stiffened against deflection by 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

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

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