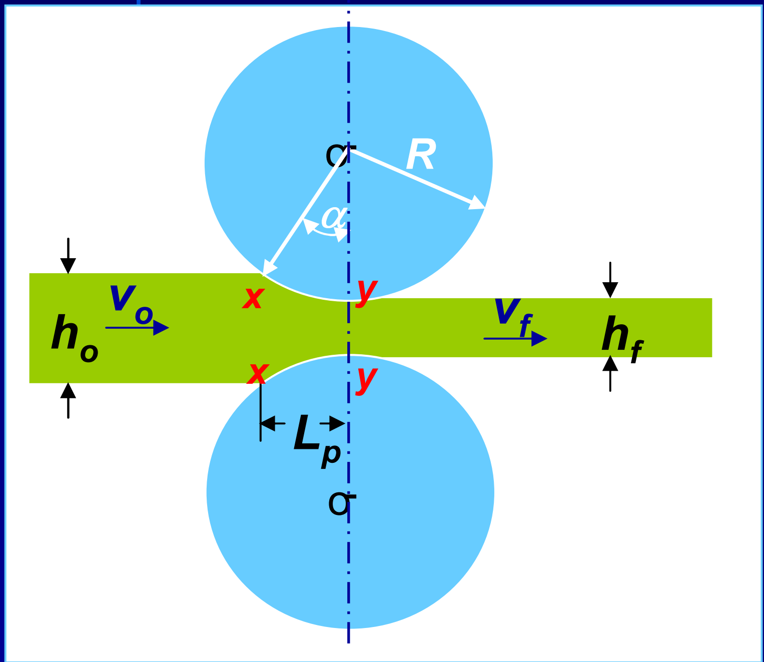
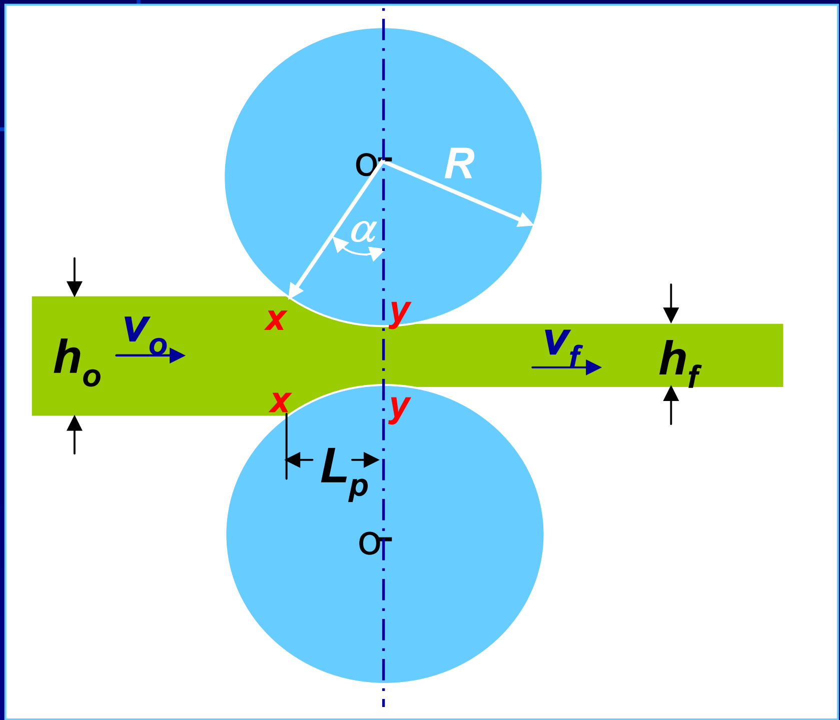
Fundamental concept of metal rolling

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

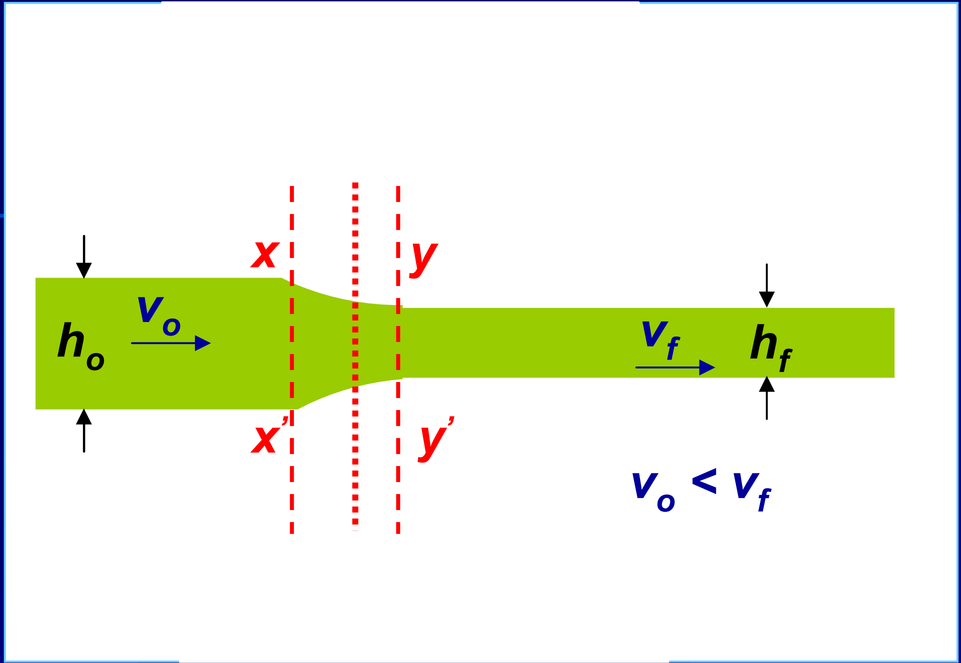


- A metal sheet with a thickness h_o enters the rolls at the entrance plane *xx* with a velocity v_o.
- It passes through the roll gap and leaves the exit plane *yy* with a reduced thickness h_f and at a velocity v_f.
- Given that there is ***no increase in width***, the vertical compression of the metal 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

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

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

$$v_o h_o = v_f h_f$$

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*.

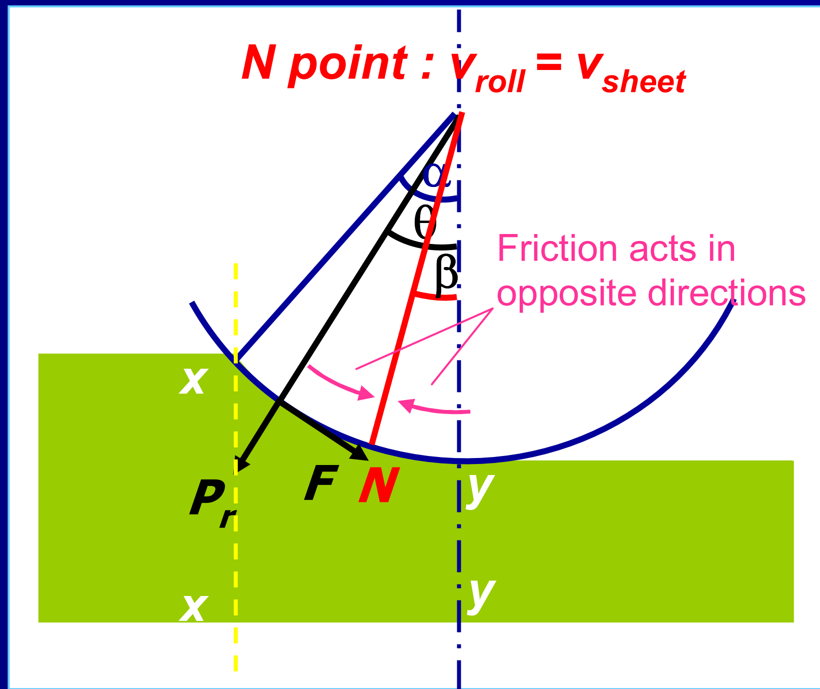
$$\frac{v_o}{v_f} = \frac{h_f}{h_o} \quad \text{...Eq.2}$$

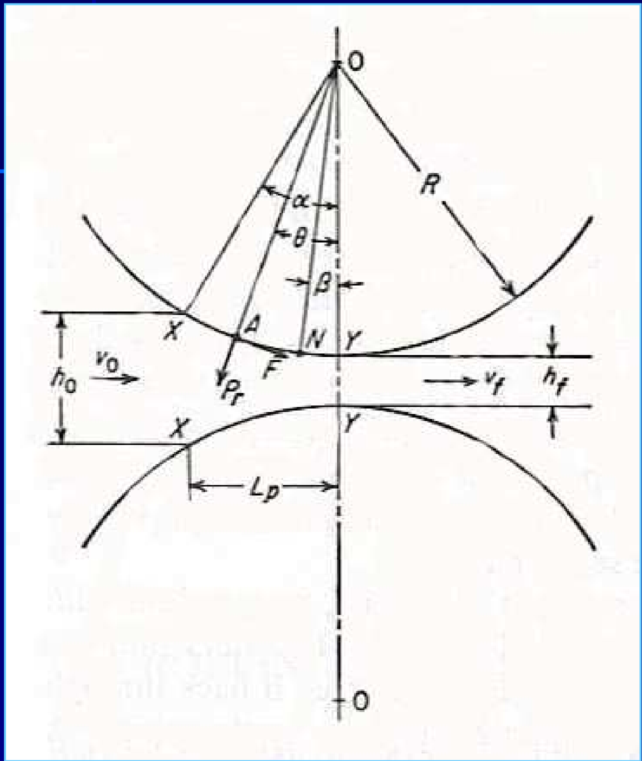
• At only one point along the surface of contact between the roll and the sheet, two forces act on the metal: 1) ***a radial force*** P_r and 2) ***a tangential frictional force*** ***F***.

• 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 fore 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.

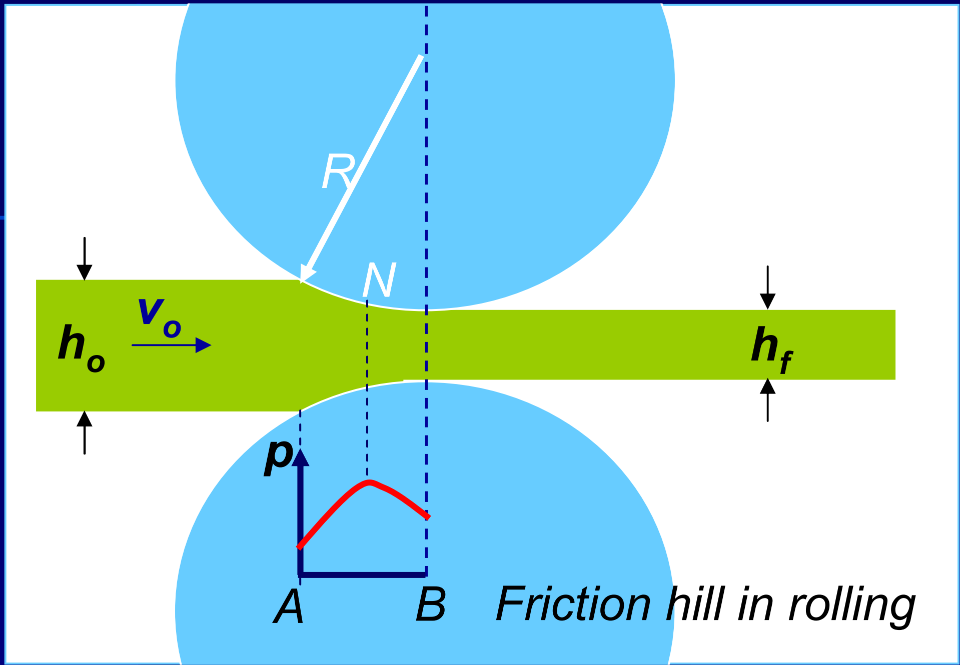
$$p = \frac{P}{bL_p} \qquad \text{...Eq.3}$$

Where ***b*** is the width of the sheet.

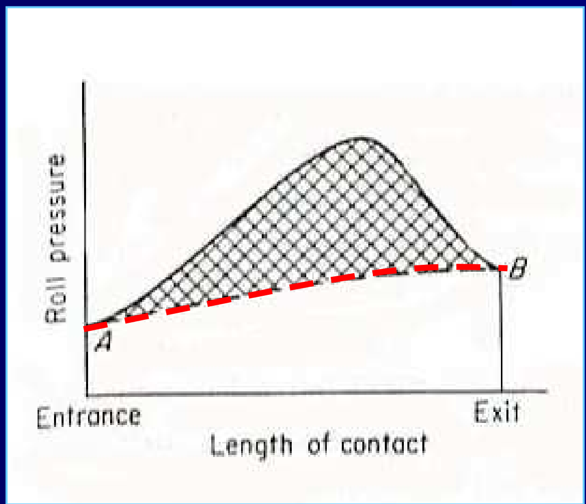
L_p is the projected length of the arc of contact.

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

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



Friction hill in rolling



- 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.

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***$_p$).

$$P = pbL_p = \sigma_o' b\sqrt{R\Delta h} \qquad \text{...Eq.8}$$

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.

$$\frac{\bar{p}}{\bar{\sigma}'_o} = \frac{1}{Q}\left(e^Q - 1\right) \quad \text{...Eq.9}$$

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

$\bar{h}$ = the mean thickness between entry and exit from the rolls.

From *Eq.8*,

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

We have

$$P = \frac{2}{\sqrt{3}}\bar{\sigma}_o\left[\frac{1}{Q}\left(e^Q - 1\right) b\sqrt{R\Delta h}\right] \quad \text{...Eq.10}$$

Roll diameter ⇧ ***Rolling load*** ⇧

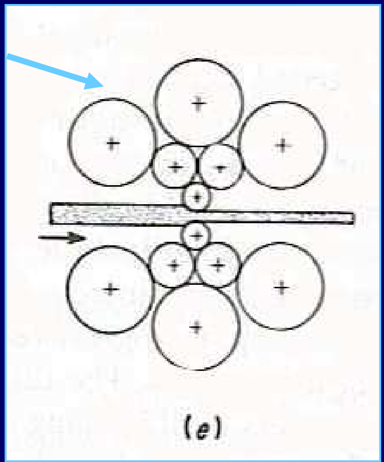
•Therefore the ***rolling load P*** increases with the roll radius $R^{1/2}$, depending on the contribution from the friction hill.

• 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.

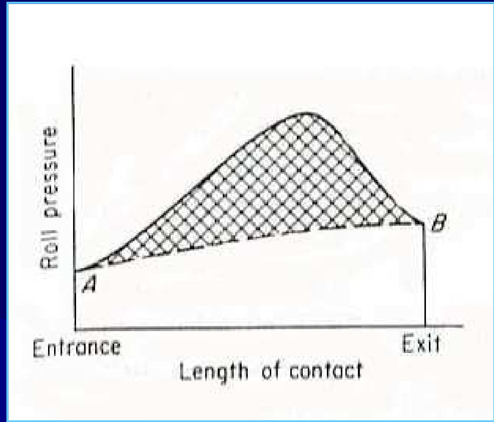
• ***Small-diameter rolls*** which are properly stiffened against deflection by backup rolls can produce a greater reduction before roll flattening become significant and no further reduction of the sheet is possible.

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, 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.*

$$\frac{h_o - h_f}{h_o} x100 = 30\%$$

$$\frac{(40)-(h_f)}{(40)} x100 = 30$$

$$h_f = 28mm$$

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

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

$$Q = \frac{\mu L_p}{\bar{h}} = \frac{\mu\sqrt{R\Delta h}}{\bar{h}} = \frac{(0.30)\sqrt{450x12}}{(34)} = 0.65$$

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

From *Eq.10*

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

$$P = 170\left[\frac{1}{(0.65)}\left(e^{0.65} - 1\right)(0.76)\sqrt{0.45x0.012}\right] = 13.4MN$$

3) Sticky friction situation

What would be the rolling load if sticky friction occurs?

Continuing the analogy with compression in plane strain

$$\bar{p} = \sigma'_o\left(\frac{a}{2h}+1\right) = \sigma'_0\left(\frac{L_p}{4\bar{h}}+1\right)$$

From *Eq.8*,

$$P = \bar{p}\,bL_p$$

From example;

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

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

$$P = 14.6MN$$

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*** *= 2.16x10⁻¹¹ Pa⁻¹,* ***P'*** *=13.4 MPa from previous example.*

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

Where ***C = 16(1-ν²)/πE***, ***P'*** = Rolling load based on the deformed roll radius.

$$R' = 0.45\left[1 + \frac{2.16x10^{-11}(13.4x10^6)}{0.76x0.012}\right] = 0.464m$$

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

$$Q = \frac{\mu\sqrt{R\Delta h}}{\bar{h}} = \frac{0.30\sqrt{464x12}}{34} = 0.66$$

$$P'' = 170\left[\frac{1}{0.66}\left(e^{0.66} - 1\right)0.76\sqrt{0.464x0.012}\right] = 13.7MN$$

$$R'' = 0.45\left[1 + \frac{2.16x10^{-11}(13.7x10^6)}{0.76x0.012}\right] = 0.465m$$

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