Tutorial 3

Rolling

FORCES AND GEOMETRY

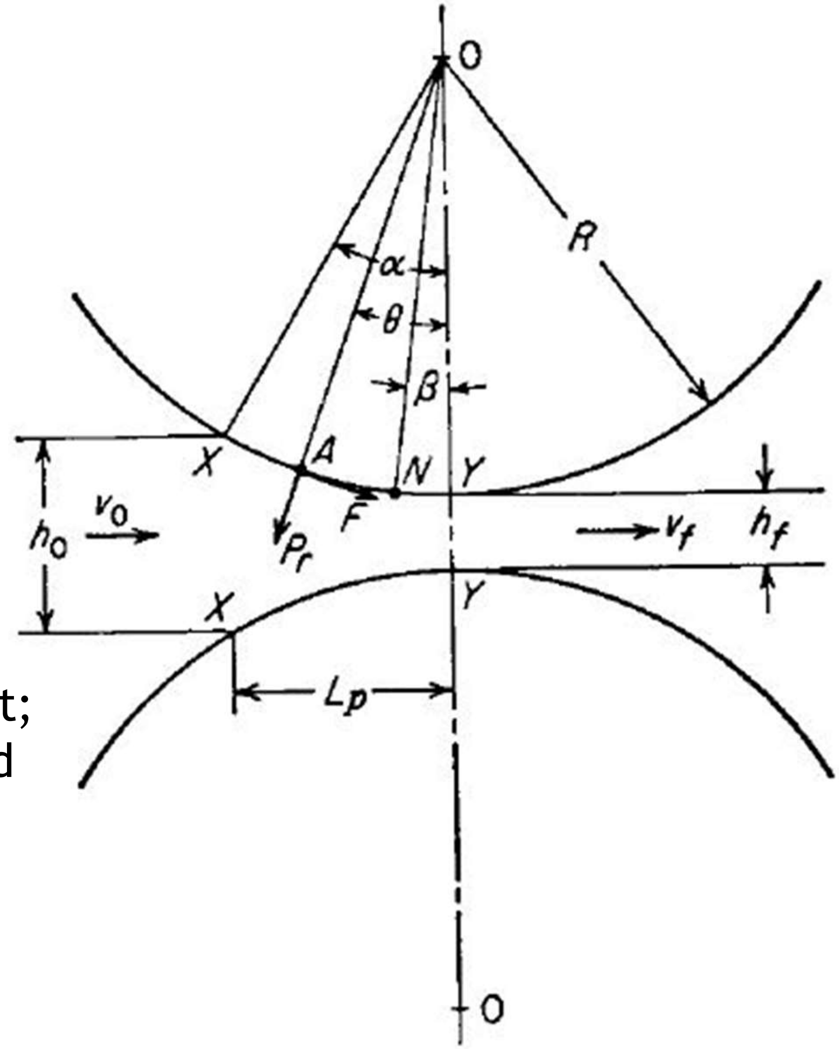
volume constancy,
(width, b)

$$bh_0v_0 = bhv = bh_fv_f$$

N - neutral/ no-slip point
P_r - radial force
F - tangential frictional force
before N, v < v_r
after N, v > v_r
Vertical component of P_r is Rolling Load, P
Contact area = L_p * b; L_p - length of arc of contact;
h_0 - h_f = dell_h - rolling draft or thickness reduced

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

Specific roll pressure, p = P/A = P/(b.L_p)

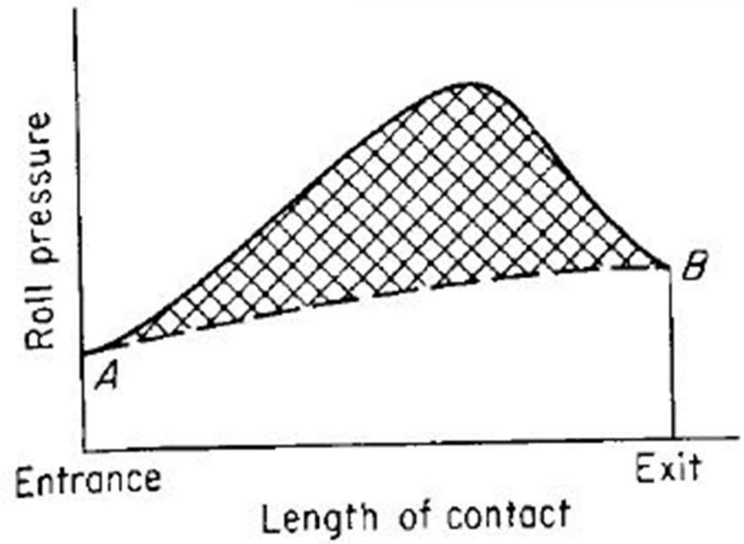


Pressure rises to a maximum at neutral point then falls.

Why no sharp peak in the graph? Neutral point is not a line but a plane!

Features of the graph:

1. Area under the curve is proportional to rolling load
2. Shaded region denotes force required to overcome frictional forces
3. Unshaded portion represents the force required to deform metal



Angle between entrance plane and centerline of rolls is the bite angle, a

Equating the horizontal components of the radial and tangential forces, we get F = mu.P_r

$$F \cos\alpha = P_r \sin\alpha$$

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

$$F = \mu P_r$$

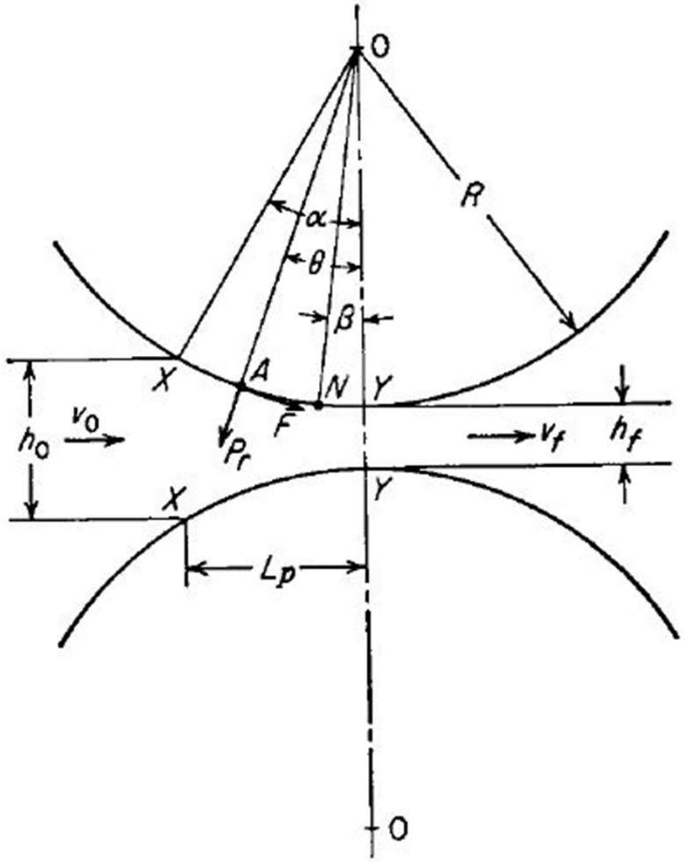
$$\mu = \tan\alpha$$

MAX. THICKNESS REDUCTION

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

$$\mu \geq \tan\alpha = \sqrt{\Delta h/R}$$

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



Solve Quickly!

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 $\mu = 0.5$?

ELASTIC DISTORTION

1. BENDING OF ROLL
2. ROLL FLATTENING

$$R' = R\left[1 + \frac{CP'}{b(h_0 - h_f)}\right]$$

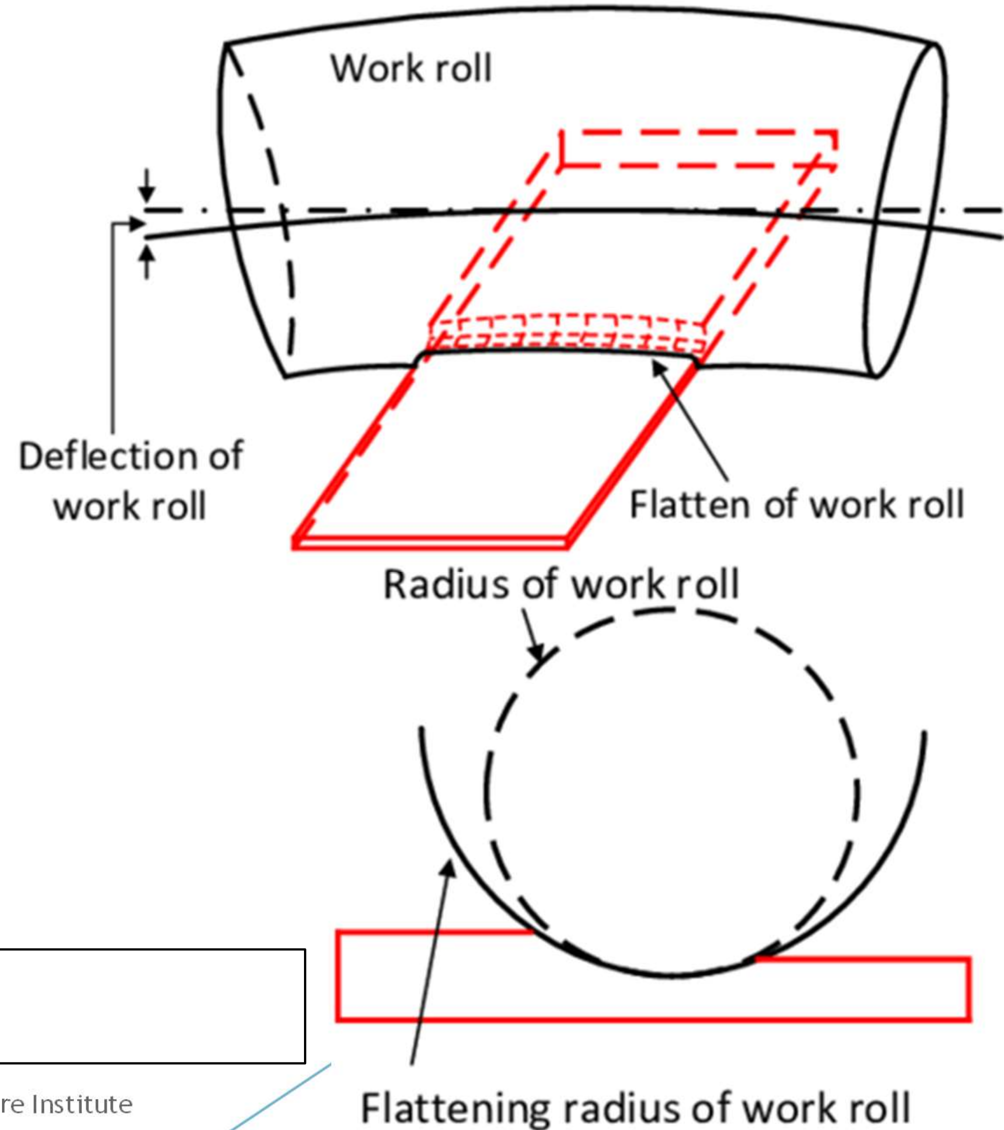
Roll flattening calculations are iterative

R' - new roll radius after roll flattening

P' - rolling load based on deformed roll radius

C = 16(1- nu^2)pi.E [roll material parameter]

C = 2.16e-11 Pa^-1 for steel rolls



Answers to the Qn in previous slide:

(i) cold rolling: dell_h_max = 1.92 mm; (ii) hot rolling: dell_h_max = 75 mm

ROLLING LOAD ANALYSIS

Major parameters in rolling:

1. Roll Diameter
2. Deformation resistance of metal
3. Friction between rolls and workpiece
4. Presence of front and/or back tension in the plane of sheet

Rolling Load, P = p.b.L_p

= Yb(R.dell_h)½;

Y - flow stress in plane strain condition

Using slab analysis, the equation of average roll pressure is obtained as follows,

$$\bar{p} = \frac{\left[Y - \frac{(T_b+T_f)}{2}\right]}{\frac{\mu L_p}{\bar{h}}}\left[e^{\frac{\mu L_p}{\bar{h}}} - 1\right]$$

$\bar{p}$ - average rolling pressure

Y - plane strain flow stress

T_b, T_f - back/front tensile stress

$\bar{h}$ - average sheet thickness

$$\bar{h} = \frac{h_0 + h_f}{2}$$

Now, $P = \bar{p}\, b \sqrt{R \Delta h}$

Question 1 - Roll Pressure without Roll Flattening

Consider the rolling of a sheet 15-cm wide from a thickness of 1.8mm to 1.2mm in a single pass by steel rolls 20 cm in diameter. Assume a friction coefficient of 0.10 and a flow stress of 125 MPa. Calculate the roll pressure if roll flattening is neglected.

Question: 1

Given:

$b = 15\ cm = 150\ mm$

$h_0 = 1.8\ mm$

$h_f = 1.2\ mm$

$D = 20\ cm$

$R = 10\ cm = 100\ mm$

$\mu = 0.1$

$Y = 125\ MPa$

(a) $$\bar{p} = \frac{Y}{\frac{\mu L_p}{\bar{h}}}\left[e^{\frac{\mu L_p}{\bar{h}}} - 1\right]$$

$$L_p = \sqrt{R \Delta h} = \sqrt{100(1.8 - 1.2)}$$

$$= 7.7\ mm$$

$$\bar{h} = \frac{h_0 + h_f}{2} = \frac{1.8 + 1.2}{2} = 1.5\ mm$$

$$\frac{\mu L_p}{\bar{h}} = \frac{0.1 \times 7.7}{1.5} = 0.5133$$

$$\Rightarrow \bar{p} = \frac{125}{0.5133}\left[e^{0.5133} - 1\right]$$

$$\bar{p} = 163.35 \text{ MPa}$$

The roll pressure, for above considered case, if roll flattening is neglected, is., $\bar{p} = 163.35$ MPa.

Rolling Load, P.

$$P = \bar{p} . b\sqrt{R\Delta h}$$

$$= 163.35 \times 150 \times 7.7$$

$$= 188669.25 \text{ N}$$

$$= 188.67 \text{ kN}$$

Practice Problem - Roll pressure - Try later!

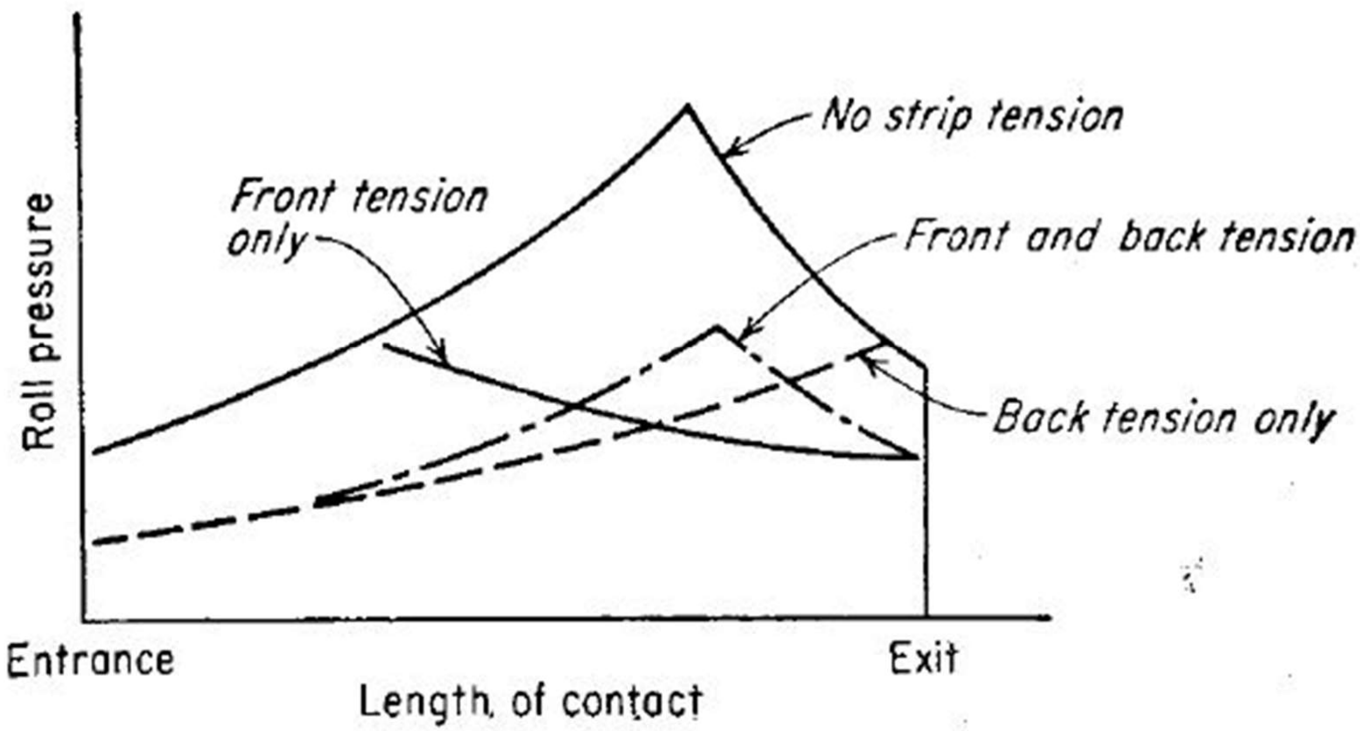
The plane-strain flow stress of a metal is 200 MPa. A sheet 0.60 m wide and 3 mm thick is to be cold rolled to 2.4 mm in a single pass using 30 cm diameter rolls. Assuming a coefficient of friction is 0.075,

a) Compute the roll pressure.

b) If front tension of 75 MPa were applied, what would be the average roll pressure?

Answer: (a) 988MPa, (b) 803 MPa

EFFECT OF STRIP TENSION ON ROLL PRESSURE



THEORIES OF COLD ROLLING

Roll entrance to neutral point:

$$p_r = \frac{\sigma_0' h}{h_0}\left(1 - \frac{\sigma_{xb}}{\sigma_{01}'}\right) e^{\mu(H_1 - H)} \qquad (17\text{-}19)$$

Neutral point to roll exit:

$$p_r = \frac{\sigma_0' h}{h_f}\left(1 - \frac{\sigma_{xf}}{\sigma_{02}'}\right) e^{\mu H} \qquad (17\text{-}20)$$

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

Subscript 1 refers to a quantity evaluated at the roll-entrance plane, and subscript 2 refers to a quantity evaluated at the roll-exit plane.

THEORIES OF HOT ROLLING

1. Ford and Alexander, slip - line field analysis of hot - rolling in non - ferrous alloys and steels

$$P = kbL_p\left(\frac{\pi}{2} + \frac{L_p}{h_0 + h_f}\right)$$

$$M_T = kbL_p^2\left(1.60 + 0.91\frac{L_p}{h_0 + h_f}\right)$$

2. Denton and Crane, hot forging of a slab between perfectly rough platens analogy

Hot-rolling:

$$P = kbL_p\left[1.31 + 0.53\frac{L_p}{(h_0 h_f)^{1/2}}\right]$$

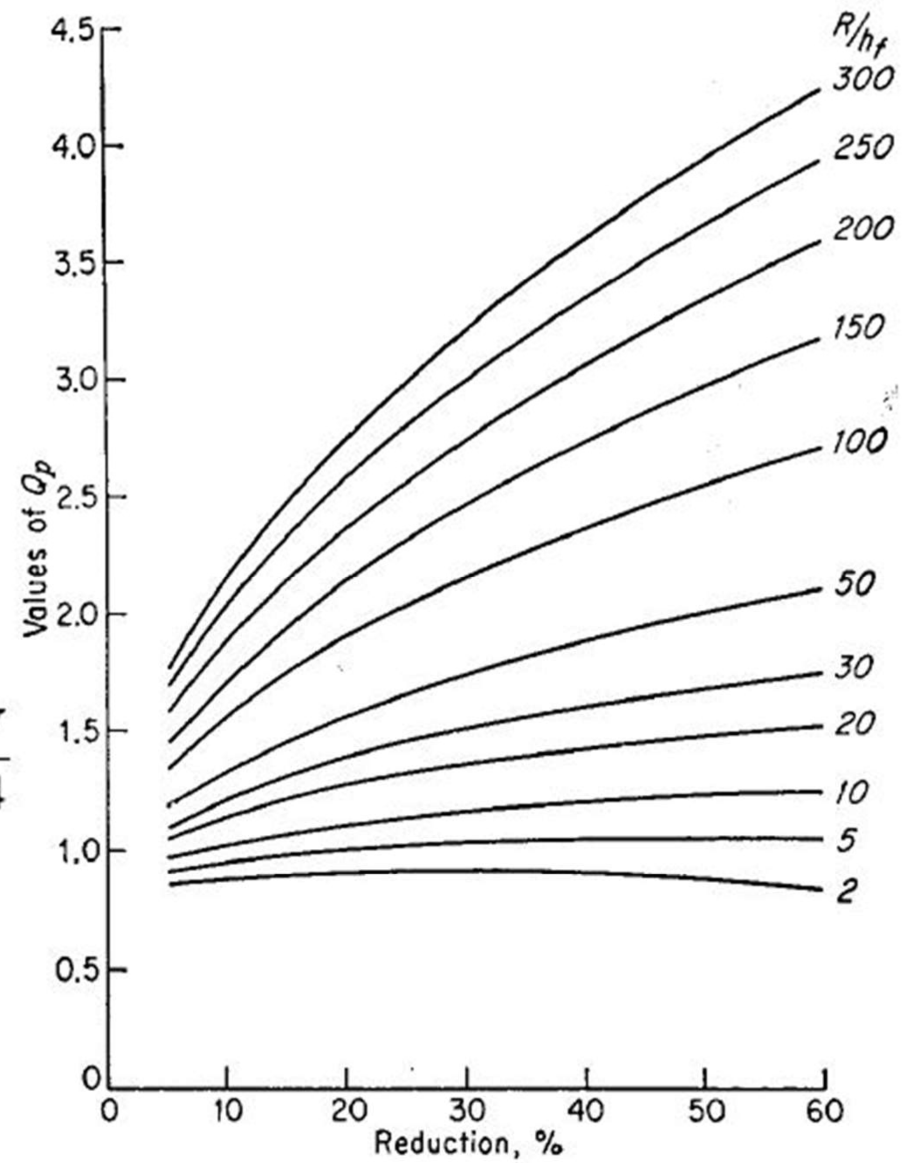
Hot-forging:

$$P = kbw\left[1.5 + 0.5\frac{b}{h}\right]$$

3. Sims relation (shortened form of Orowan's equation and further mathematical simplification)

$$P = \sigma_0' b \left[R(h_0 - h_f)^{1/2} \right] Q_p$$

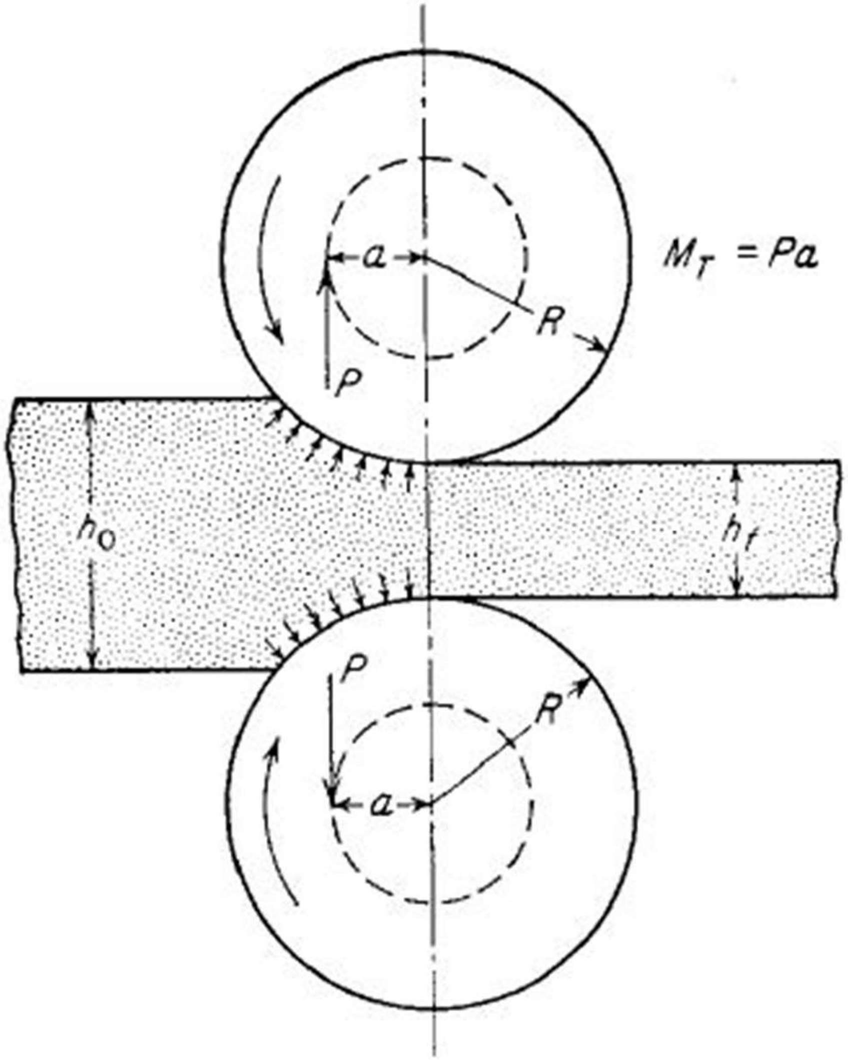
$$Q_p = \sqrt{\frac{h_0}{4\Delta h}} \left[\pi \tan^{-1} \sqrt{\frac{\Delta h}{h_f}} - \sqrt{\frac{R}{h_f}} \ln \frac{h_n^2}{h_0 h_f} \right] - \frac{\pi}{4}$$



TORQUE AND POWER

Power Expenditure:

1. Energy needed to deform the metal
2. Energy needed to overcome frictional forces in bearings
3. Energy lost in pinion and power transmission system
4. Electrical losses in motors and generators



Calculating moment arm, a from the ratio of moment arm length to projected length of arc of contact

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

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

Torque = Total rolling load * effective moment arm; where total rolling load is 2P for 2 rolls

$$M_t = 2Pa$$

The rolling load acts on the circle whose circumference is given by 2.pi.a; hence, work is given by the product of load with the distance travelled

$$\text{Work} = 2(2\pi a)P$$

$$W = 4\pi a P N$$

Power is the rate of doing work.

Question 2 - Roll Torque

A 300 mm-wide aluminum 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 the aluminum alloy can be expressed as $140\varepsilon^{0.2}$(MPa). Determine the rolling load and the power required for this hot reduction.

Solution

Question 2

Given: aluminium alloy, hot rolling

$b = 300\ mm$

$h_o = 20\ mm$

$h_f = 15\ mm$

$D = 1\ m$, $R = 0.5\ m = 500\ mm$

$N = 100\ rpm$

$Y = 140\ \varepsilon^{0.2}\ MPa$

$$\varepsilon_t = \ln\left(\frac{h_o}{h_f}\right) = \ln\left(\frac{20}{15}\right) = 0.288$$

$$\bar{Y} = \frac{k\varepsilon^n}{n+1} = \frac{140\ (0.288)^{0.2}}{0.2+1} = 90.95\ MPa$$

$$L_p = \sqrt{R\Delta h} = \sqrt{500\ (5)} = 50\ mm$$

For aluminium (non-ferrous) alloy,
use Ford and Alexander relation.

$$k = \frac{\bar{Y}}{\sqrt{3}} = 52.51 \text{ MPa.}$$

$$P = kbL_p \left[\frac{\pi}{2} + \frac{L_p}{h_o + h_f} \right]$$

$$P = 52.51 \times 300 \times 50 \left[\frac{\pi}{2} + \frac{50}{20+15} \right]$$

$$= 2362452 \text{ N}$$

$$= 2.36 \text{ MN}$$

Similarly,

$$M_T = kbL_p^2 \left[1.60 + 0.91 \frac{L_p}{h_o + h_f} \right]$$

$$= 52.51 \times 300 \times (50)^2 \left[1.60 + 0.91 \left(\frac{50}{20+15} \right) \right]$$

$$= 114209250 \text{ N-m}$$

$$= 114.21 \text{ MN-m}$$

For hot-rolling, $\lambda = 0.5$

$$a = \lambda L_p = 0.5(50) = 25 \text{ mm}$$

Power, $W = 4\pi a P N$

$$= 4\pi(25 \times 10^{-3})(2.36 \times 10^{6}) \frac{100}{60}$$

$$= 1235693 \text{ W}$$

$$= 1.24 \text{ MW}.$$

THANK YOU!