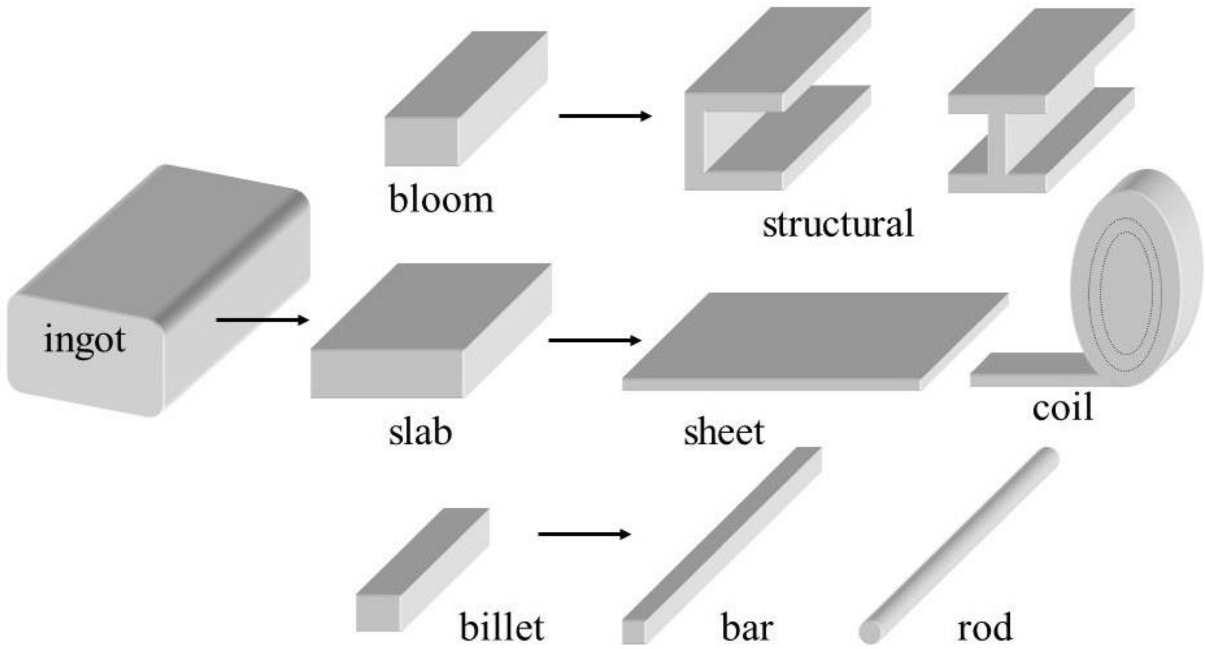
Bulk Deformation Processes

- The initial form is bulk rather than sheet including cylindrical bars and billets, rectangular billets and slabs. Figure (3-10) shows some steel products made in rolling mill.



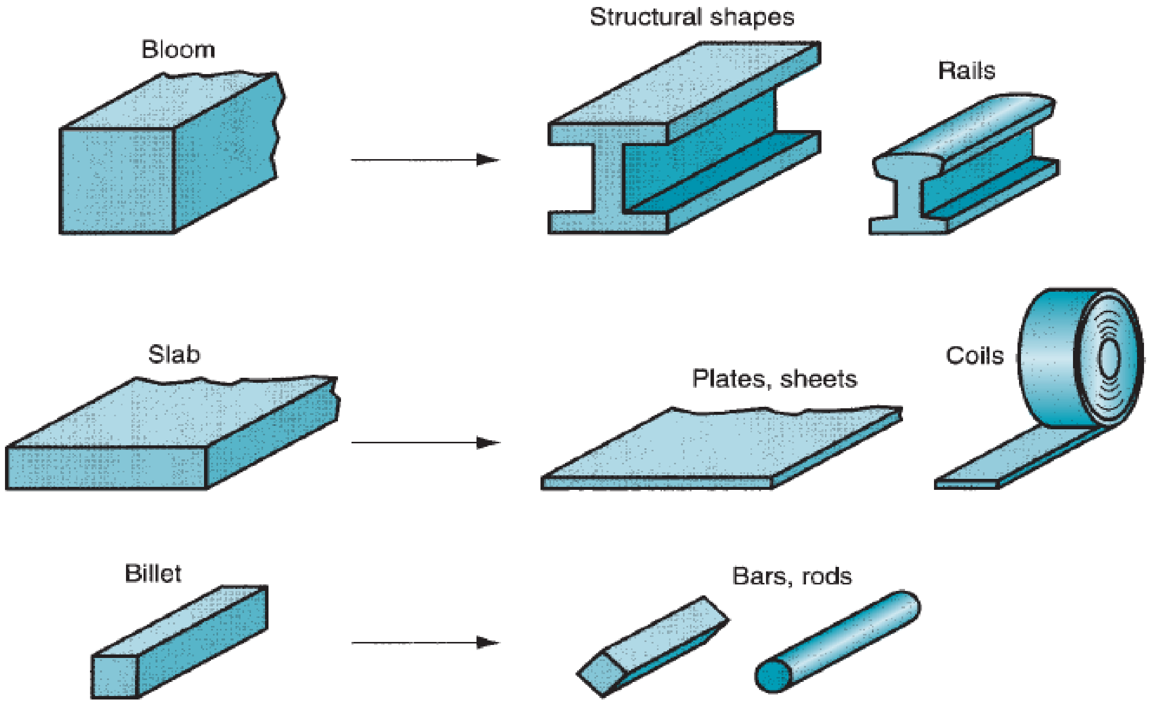


Figure (3-10) steel products made in rolling mill.

The commercial and technological importance of bulk deformation processes derives from the following:

- When performed as hot working operations, they can achieve significant change in the shape of the workpart.
- When performed as cold working operations, they can be used to increase its strength through strain hardening.
- These processes produce little or no waste as a byproduct of the operation. Some bulk deformation operations are near net shape or net shape processes.

1. Rolling Processes

Definition: it is a deformation process in which the thickness of the w.p. is reduced by compressive forces exerted by two opposing rolls as illustrated in figure (3-11).

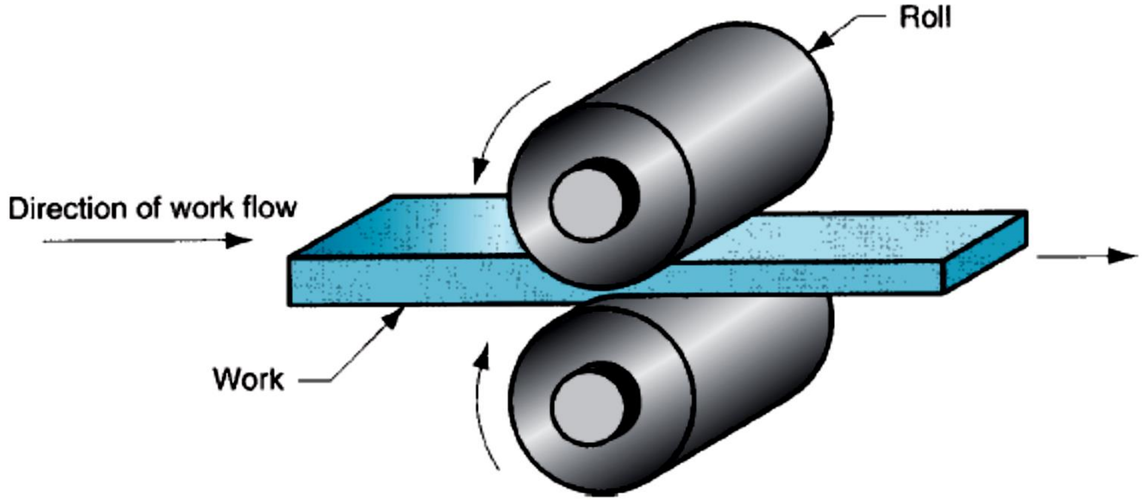


Figure (3-11) The Rolling Process (Flat Rolling).

Hot Rolling:

- It is preferred owing to large amount of deformation required.
- It is generally free of residual stresses.
- Its properties are isotropic.
- The product cannot be held to close tolerances (disadvantage).
- The surface has a characteristic oxide scale (disadvantage).

Cold Rolling:

- Strengthens the metal.
- Permits a tighter tolerance on thickness.
- The surface of cold-rolled sheet is absent of scale and superior to the corresponding hot-rolled product.

Refer to figure (3-10) to explain the following items:

- **Ingot:** casted metal block ready for forming operations.
- **Bloom:** rolled from ingots and having sq. cross sec. (150mmX150mm) or larger.
- **Slab:** rolled from ingot or bloom and having rect. cross sec. (250mm width or more X 40mm thickness or more). Products like plates, sheets, and strips. Plates are used in shipbuilding, bridges, boilers and welded structures, tubes and pipes.
- **Billets:** rolled from bloom and having sq. cross sec. (40mm larger). Products like bars and rods.

Flat Rolling and Its Analysis:

- It involves the rolling of slabs, strips, sheets and plates of workpiece having a rectangular cross-section (width >> thickness). Figure (3-12) explains the flat rolling.

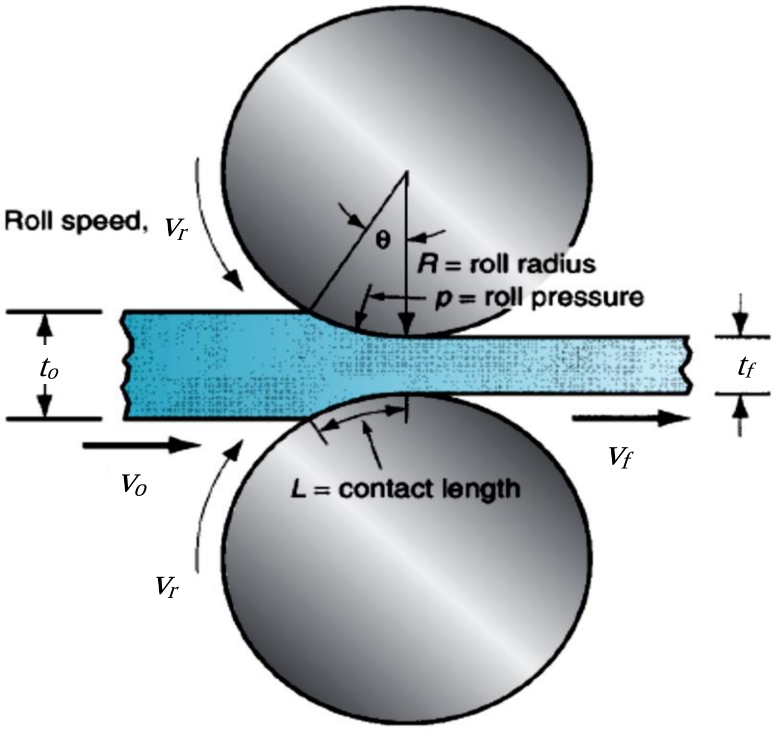


Figure (3-12) Nomenclatures of Flat Rolling (side view).

v_r: roll speed,

v_o: entering speed of w.p.,

v_f: exiting speed of w.p.,

t_o: original thickness of w.p.,

t_f: final thickness of w.p.,

θ: angle of contact with rolls.

1. <u>Thickness Reduction:</u>

$\mathbf{d = t_o - t_f}$ d: draft (reduced amount of thickness)

$\boldsymbol{r = \frac{d}{t_o}}$ r: reduction in single rolling operation

$\boldsymbol{r = \frac{d_1 + d_2 + d_3 + \cdots}{t_o}}$ r: reduction in a series of rolling operation

2. <u>Volume Flow of Material:</u>

- Rolling increases w.p. width (spreading is cleared with low w/t and low friction).
- Conservation of matter:

$$t_o w_o L_o = t_f w_f L_f$$

- Volume rate of material flow:

$$t_o w_o v_o = t_f w_f v_f$$

w_o: original width of w.p.,
w_f: final width of w.p.,
L_o: original length of w.p.,
L_f: final length of w.p.,

3. <u>The Slip:</u>

$$v_r > v_o$$
$$v_r < v_f$$

- The amount of slip between the rolls and the w.p. is determined by the **forward slip** ***s***:

$$s = \frac{v_f - v_r}{v_r}$$

- No-slip point (neutral point) is located on contact arc at which (v_r = speed of w.p.).
- Slipping and friction occur on either side of this point.

4. Stress and Strain:

- True strain: $$\varepsilon = \ln \frac{t_o}{t_f}$$

- Average flow stress: $$\bar{Y}_f = \frac{K\varepsilon^n}{1+n}$$

$\bar{Y}_f$: average flow stress

ε: maximum strain value during the rolling process.

5. Friction:

Figure (3-13) explains the frictional forces acting in rolling process.

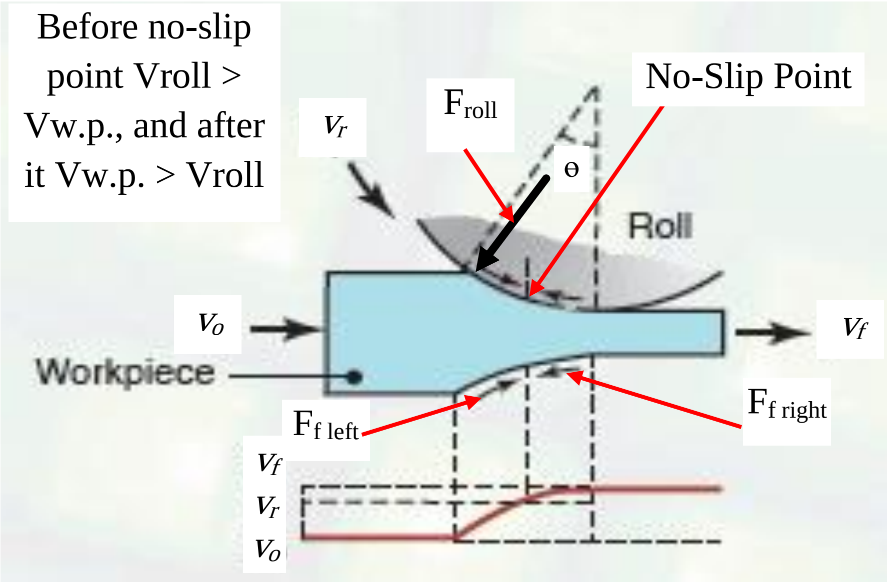


Figure (3-13) Frictional force acting along the w.p-roll interfaces

$$F_f = F_{roll}\,\mu$$

$F_{f\ left}$ > $F_{f\ right}$ always so that the net friction force and the roll speed are in the same direction from left to right to make the rolling process possible.

μ: friction coefficient,

F_f: friction force,

F_{roll}: roll force,

$F_{f\ left}$: left friction force,

$F_{f\ right}$: right friction force,

- **Maximum Possible Draft:**

$$d_{max} = \mu^2 R$$

R: roll radius.

If μ = 0.0, d=0.0 then no rolling.

μ depends on: 1- lubrication, 2- w.p. material, 3- working temperature.

- In cold rolling : μ ≈ 0.1
- In warm rolling: μ ≈ 0.2
- In hot rolling: μ ≈ 0.4

Notes:

- In hot rolling a condition is often occur called “sticking”.
- In sticking: hot w.p. surface adheres to the rolls over the contact arc. Sticking is often occur in the rolling of steels and high-temperature alloys.
- At sticking, the μ can be as high as 0.7.
- The consequences of sticking is: speed of surface layers of w.p. having the same speed of V_r and deformation of below surface is more severe in order to allow passage of the w.p. through the roll gap.

6. Roll Force:

- The roll force is required to maintain separation between the two rolls.
- It can be calculated by integrating the unit roll pressure over the roll-w.p contact area as in figure (3-14):

$$F_{roll} = w\int_0^L p\,dL$$

w**:** width of w.p. being rolled

p: roll pressure

L: contact length

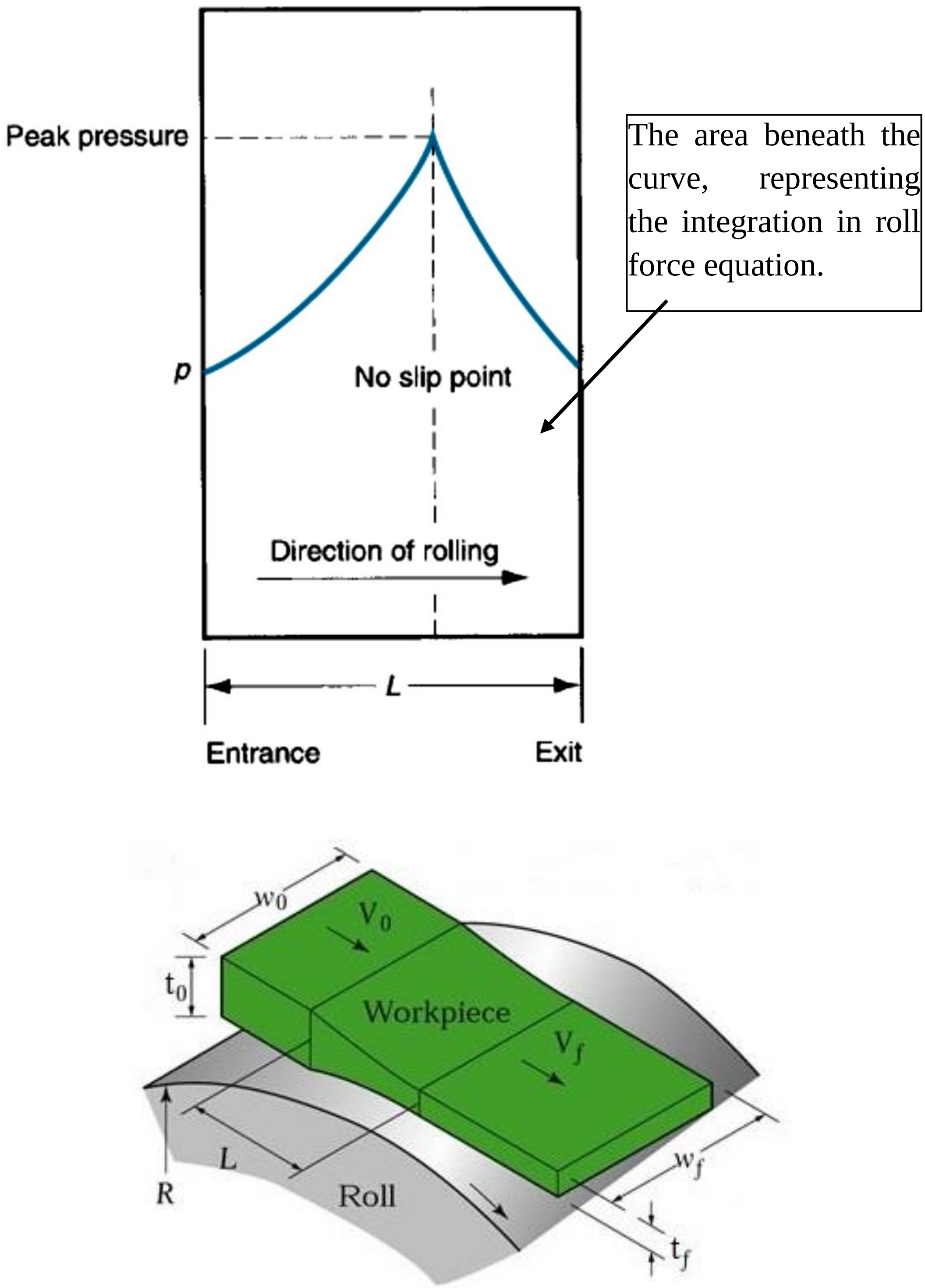


Figure (3-14) pressure variation in flat rolling

- For low frictional conditions, the roll force can be calculated as:

$$F_{roll} = \overline{Y}_f \, wL$$

$\overline{Y}_f$**:** average flow stress experienced by the w.p. in the roll gap

- For the higher frictional conditions, the roll force can be calculated as:

$$F_{roll} = \overline{Y}_f \, wL\left(1 + \frac{\mu L}{2t_{av}}\right)$$

t_{av}: average thickness of w.p. ($t_{av}=(t_o+t_f)/2$)

- By aiding of figure (3-15), the contact length L can be determine as:

$$L = \sqrt{R(t_o - t_f)}$$

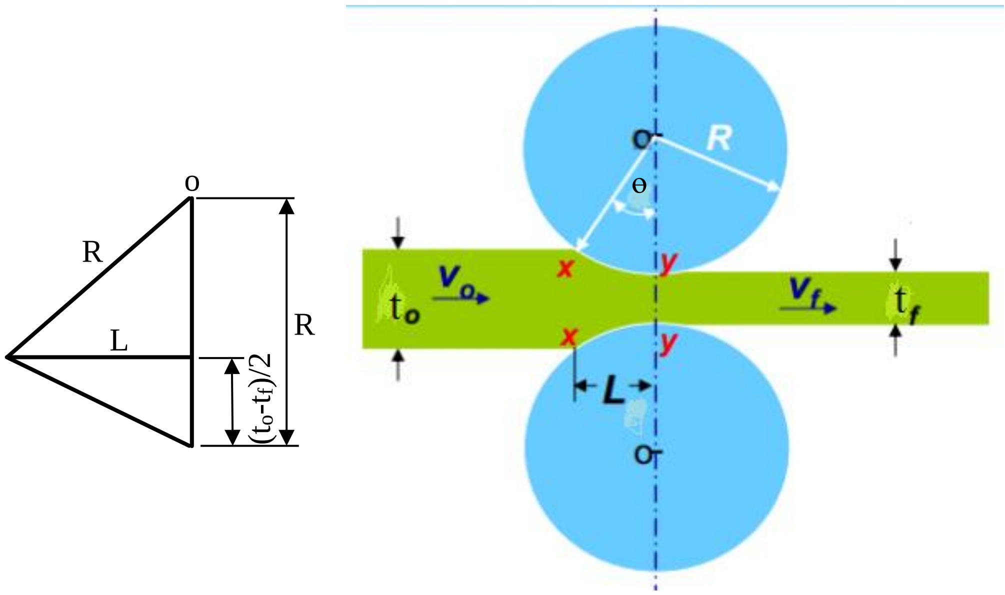


Figure (3-15) Contact length in flat rolling.

7. <u>Torque and Power:</u>

a- Torque:

- It is estimated by assuming that the roll force acts in the middle of the contact arc (this results in a moment arm of 0.5L):

Then the torque per roll is: $T = 0.5F_{roll}L$

- It is found that **(0.5L moment arm)** is good estimate for hot rolling and **(0.4L moment arm)** is a better estimate for cold rolling.

b- Power:

- It is given by:

$$P = T\omega$$

$$\omega = 2\pi N/60$$

$$P = 0.5F_{roll}L\ \frac{2\pi N}{60}$$

$$\therefore P = \frac{\pi N F_{roll} L}{60} \quad \textbf{per roll}$$

And

$$P = \frac{2\pi N F_{roll} L}{60} \quad \textbf{for 2 rolls}$$

T: roll torque (N.m)

ω: angular velocity of roll (rad/s)

N: rotational velocity of roll (rpm)

P: rolling power (W)

Example (1):

A 300-mm-wide strip 25-mm thick is fed through a rolling mill with two powered rolls each of radius =250 mm. The w.p. thickness is to be reduced to 22 mm in one pass at a roll speed of 50 rev/min. The w.p. material has a flow curve defined by K=275 MPa and n=0.15, and the coefficient of friction between the rolls and the w.p. is assumed to be 0.12. Determine if the friction is sufficient to permit the rolling operation to be accomplished. If so, calculate the roll force, torque, and horsepower.

Solution:

$d = t_o - t_f = 25 - 22 = 3mm$

$d_{max} = \mu^2 R = (0.12^2)(250) = 3.6mm$

Since $\mathbf{d_{max} > d}$ then the rolling process is feasible. ***Answer***

Since the friction coefficient is low then we can use the equation:

$$\boldsymbol{F_{roll} = \bar{Y}_f\, wL}$$

$$\boldsymbol{L = \sqrt{R(t_o - t_f)} = \sqrt{(250)(3)} = 27.4mm}$$

$$\boldsymbol{\bar{Y}_f = \frac{K\varepsilon^n}{n+1}\ , \qquad \varepsilon = \ln\frac{t_o}{t_f} = \ln\frac{25}{22} = 0.128}$$

$$\boldsymbol{\bar{Y}_f = \frac{(275)(0.128^{0.15})}{0.15+1} = 175.7MPa}$$

$$\boldsymbol{\therefore\ F_{roll} = (175.7)(300)(27.4) = 1444.254kN}\ \text{Answer}$$

$$\boldsymbol{T = 0.5F_{roll}L = 0.5(1444.254)\left(\frac{27.4}{1000}\right) = 19.8kN.m}\ \text{Answer}$$

$$\boldsymbol{P = \frac{2\pi NF_{roll}L}{60} = \frac{2\pi(50)(1444.254)(27.4)(10^{-3})}{60} = 207.1kW}\ \text{Answer}$$

or 1horsepower= 745.7 W

$$\boldsymbol{\therefore HP = \frac{207.1(10^3)}{745.7} = 278hp}\ \text{Answer}$$

Example (2):

A 9" wide 6061-O aluminum strip is rolled from a thickness of 1" to 0.8". If the roll radius is 12" and the roll rpm is 100. Calculate the HP required for rolling operation. Take: K=30,000psi, n=0.2.

Solution:

$$\boldsymbol{P = \frac{2\pi NF_{roll}L}{60}}$$

$$\boldsymbol{L = \sqrt{R(t_o - t_f)} = \sqrt{(12)(1-0.8)} = 1.549'' \div 39.4 = 0.0393m = 39.3mm}$$

1m=39.4in, 1in=25.4mm

Since the friction coefficient is low then we can use the equation:

$$F_{roll} = \overline{Y}_f \, wL$$

$$\overline{Y}_f = \frac{K\varepsilon^n}{n+1} \, , \qquad \varepsilon = \ln\frac{t_o}{t_f} = \ln\frac{1}{0.8} = 0.223$$

$$\overline{Y}_f = \frac{(30000)(0.223^{0.2})}{0.2+1} = 18518.3psi = (18518.3)(6894.8) = 127.7\text{MPa}$$

1psi=6894.8pa

$$\therefore \; F_{roll} = (127.7E6)(9 \div 39.4)(0.0393) = 1146.4kN$$

$$P = \frac{2\pi(100)(1146.4)(0.0393)}{60} = 472kW$$

$$\therefore HP = \frac{472(10^3)}{745.7} = 633hp$$ ***Answer***

Example (3):

A 12" wide strip is rolled from a thickness of 1" to 0.875" in one pass. The roll radius and roll speed are 10" and 50rpm respectively. Material having the following properties: K=40,000psi, n=0.15 and μ=0.12. Is this process feasible? If so, determine roll force, torque and required HP.

Solution:

$d = t_o - t_f = 1 – 0.875 = 0.125$in

$d_{max} = \mu^2 R = (0.12^2)(10) = 0.144$in

Since **$d_{max} > d$** then the rolling process is feasible. ***Answer***

Since the friction coefficient is low (0.12) then we can use the equation:

$$F_{roll} = \overline{Y}_f \, wL$$

$$L = \sqrt{R(t_o - t_f)} = \sqrt{(10)(0.125)} = 1.118in = 0.0284m = 28.4mm$$

$$\overline{Y}_f = \frac{K\varepsilon^n}{n+1} \, , \qquad \varepsilon = \ln\frac{t_o}{t_f} = \ln\frac{1}{0.875} = 0.134$$

$$\bar{Y}_f = \frac{(40000)(0.134^{0.15})}{0.15+1} = 25729.3psi = 177.4MPa$$

$$\therefore\ F_{roll} = (177.4)(12x25.4)(28.4) = 1535.6kN$$ Answer

$$T = 0.5F_{roll}L = 0.5(1535.6)(0.0284) = 21.8kN.m$$ Answer

$$P = \frac{2\pi N F_{roll} L}{60} = \frac{2\pi(50)(1535.6)(0.0284)}{60} = 228.3kW$$ Answer

Or

$$P = T\omega = T\frac{2\pi N}{60} = 114.144x2 = 228.3kW$$

$$\therefore HP = \frac{228.3(10^3)}{745.7} = 306hp$$ Answer

Note:

- According to maximum shear stress criterion (Tresca criterion) that yielding occurs when:

$$\sigma_{max} - \sigma_{min} = \tau_{max} = \bar{Y}_f = \frac{K\varepsilon^n}{n+1}$$

- According to the distortion-energy criterion (von Mises criterion) for the plane strain:

$$\bar{Y}_f = \frac{2}{\sqrt{3}}\frac{K\varepsilon^n}{n+1}$$ **can be also used to determine F_{roll}.**

Plane Stress: is the state of stress in which one or two of the pairs of faces on an element are free from stress.

Plane Strain: is the state of stress where one of the pairs of faces on an element undergoes zero strain.

8. Forces in Hot Rolling:

- The force in hot rolling process can be estimated approximately because of (1) variations in (μ) at elevated temperatures, (2) variations of strain-rate sensitivity (*m*) at elevated temperatures.
- The following relations are used to estimate the rolling force in hot rolling:

In case of very high friction condition we can use:

$$F_{roll} = Y_f\, wL\left(1 + \frac{\mu L}{2t_{av}}\right)$$

$$F_{roll} = Y_f wL$$

$$Y_f = C\dot{\bar{\varepsilon}}^m$$

$$\dot{\bar{\varepsilon}} = \frac{\varepsilon}{t}$$

$$\varepsilon = \ln\frac{t_o}{t_f}$$

$$t = \frac{L}{v_r}$$

$$v_r = \pi DN \text{ (m/min)}$$

$$\therefore \dot{\bar{\varepsilon}} = \frac{v_r}{L}\ln\frac{t_o}{t_f}$$

$$v_r = R\omega = \frac{D}{2}\frac{2\pi N}{60}$$

$$v_r = \frac{\pi DN}{60}\ \left(\frac{m}{s}\right)$$

$$v_r = \pi DN\ \left(\frac{m}{min}\right)$$

Torque and Power are calculated as in the preceding discussion.

Where:

$\dot{\bar{\varepsilon}}$: average strain rate

t: time required for an element to undergo this strain in the roll gap

D: roll diameter

Homework:

In hot rolling process, the following data was collected:

N=20rpm, R=20cm, t_o=40mm, t_f=35mm, C=415MPa.s, *m*=0.02, *w*=60cm, one pass rolling. Find F_{roll}, T and Power.