Chapter 4

Power Estimation in Strip Rolling Process

4.1 Work and energy principles for estimating power in metal forming processes.
4.2 Slap rolling.
- 4.2.1 Rolling technology.
- 4.2.2 Flat rolling load estimation.
- 4.2.3 Effective strain and effective stress in strip rolling.
- 4.2.4 Rolling load and torque estimation.

4.1 Work and energy principle for estimating power on metal forming processes.

- The work and energy method is an approximate technique of estimating the forces/torque and power required in metal forming processes.

- The technique is based on the assumption that the material is homogeneous and the friction condition is neglected in the power estimation (i.e. ideal work).

- The applied force/torque assumed to be acting directly normal or parallel to cross-section area. For example, the maximum load, P_{max} , applied for compressing a cylinder can be approximated as $P_{max}=\sigma_{yield} A_{max}$, where σ_{yield} is the yielding strength and A_{max} is the area of specimen at maximum strain.

- The principle of approximating the force/torque required is based on equating the work of external applied force to the internal energy. The work due to external force is expressed as;

4.1 Work and energy principle for estimating power on metal forming processes.

The principle of approximating the force/torque required is based on equating the work of external applied force to the internal energy. The work due to external force is expressed as;

$$W_e = P_e . l_e = p_e A_e l_e = p_e V \qquad \text{Eq. 4.1}$$

Where, W_e work due to external force; P_e external force; l_e displacement of the external force; A_e cross-section area over which the external force/pressure acts; and p_e *is the* external pressure.

The work due to internal work can be obtained from Eq. 3.35 and given as follows;

$$W_i = V \frac{K}{1+n} (\bar{\varepsilon}_2^{\,n+1} - \bar{\varepsilon}_1^{\,n+1}) \qquad \text{Eq. 4.2}$$

From equation 4.1 and 4.2 we can obtain the required pressure;

$$p_e = \frac{K}{1+n} (\bar{\varepsilon}_2^{\,n+1} - \bar{\varepsilon}_1^{\,n+1}) \qquad \text{Eq. 4.3}$$

4.1 Work and energy principle for estimating power on metal forming processes.

The power of the acting force can be obtained by multiplying the acting force (or torque) by its linear velocity (or angular velocity), which represent the input work per unit time, and given as follows;

$$Power = P_e . v_e$$

$$Power = T_e . w_n \quad \text{Eq. 4.4}$$

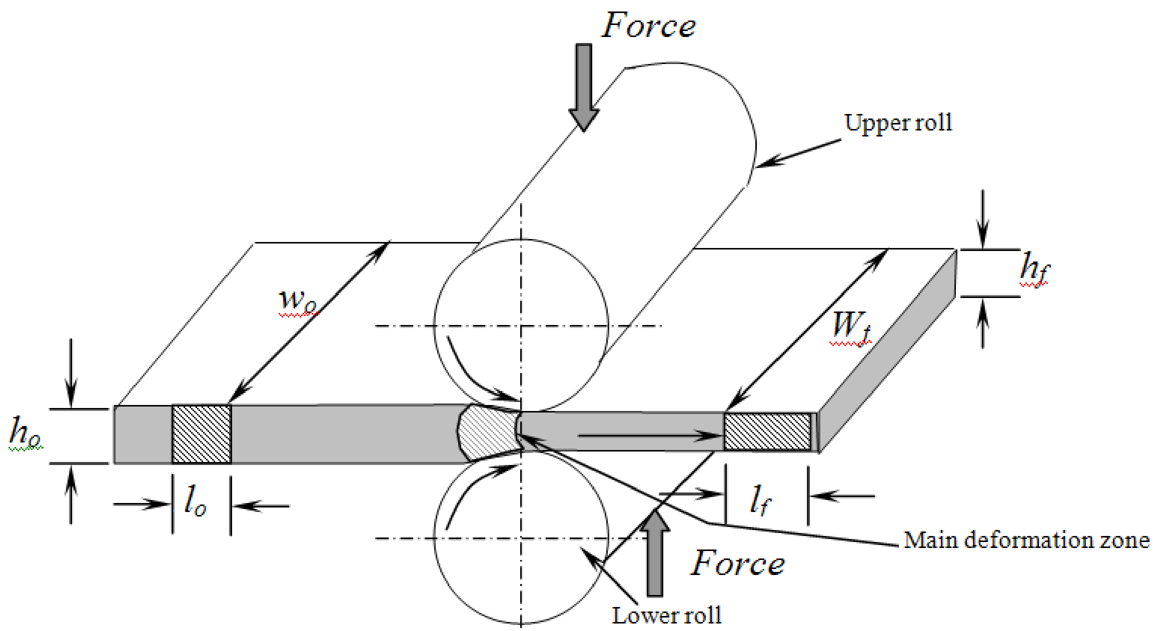
Where P_e the external force; T_e the external torque; v_e linear velocity and w_e angular speed.

4.2 Slap Rolling

4.2.1 Rolling technology

Description; The rolling process is conducted for many applications e.g. sheet metal rolling, plate (or slap) rolling, structural beam rolling, etc. Fig. 4.1 shows a diagrammatic sketch for slap rolling process where the work piece passes between two rolls; upper and lower rolls having a gap (h_2) less than the initial strip thickness(h_1).

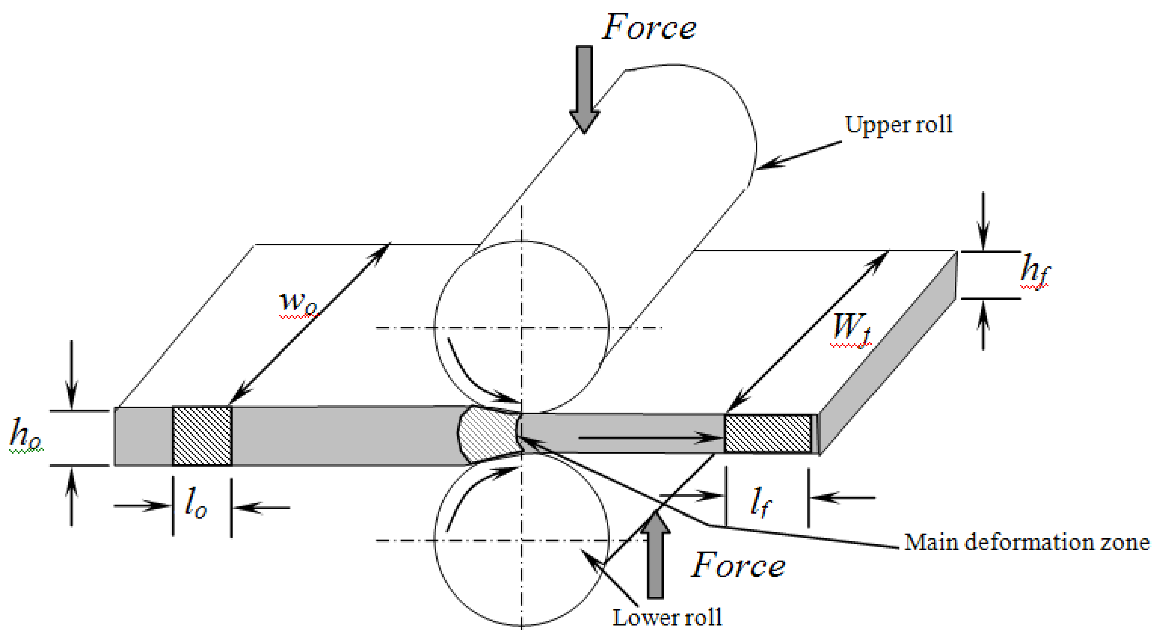
Since the main deformations are along rolling direction and through strip thickness, while the strip width is nearly constant (strain along width is nearly constant i.e. $w_o = w_f$, $ln(w_f / w_o) = 0$), the rolling process is treated as a plane strain condition.



4.2 Slap Rolling

4.2.1 Rolling technology

Rolling is one of the metalworking processes that can be run as hot or cold working. The main difference between hot and cold rolling is that in hot rolling the rolling process is carried out at elevated temperature (above room temperature). While cold rolling is carried out at room temperature. Hot rolling is more important than cold-rolling process.



4.2 Slap Rolling

4.2.1 Rolling technology

About 90% of all metal produced annually in the world through rolling process. Fig. 4.2 shows some of the semi finished products (e.g. structure shape, rails, bars, pipe, plates, strip,etc.) that can be produced by rolling process.

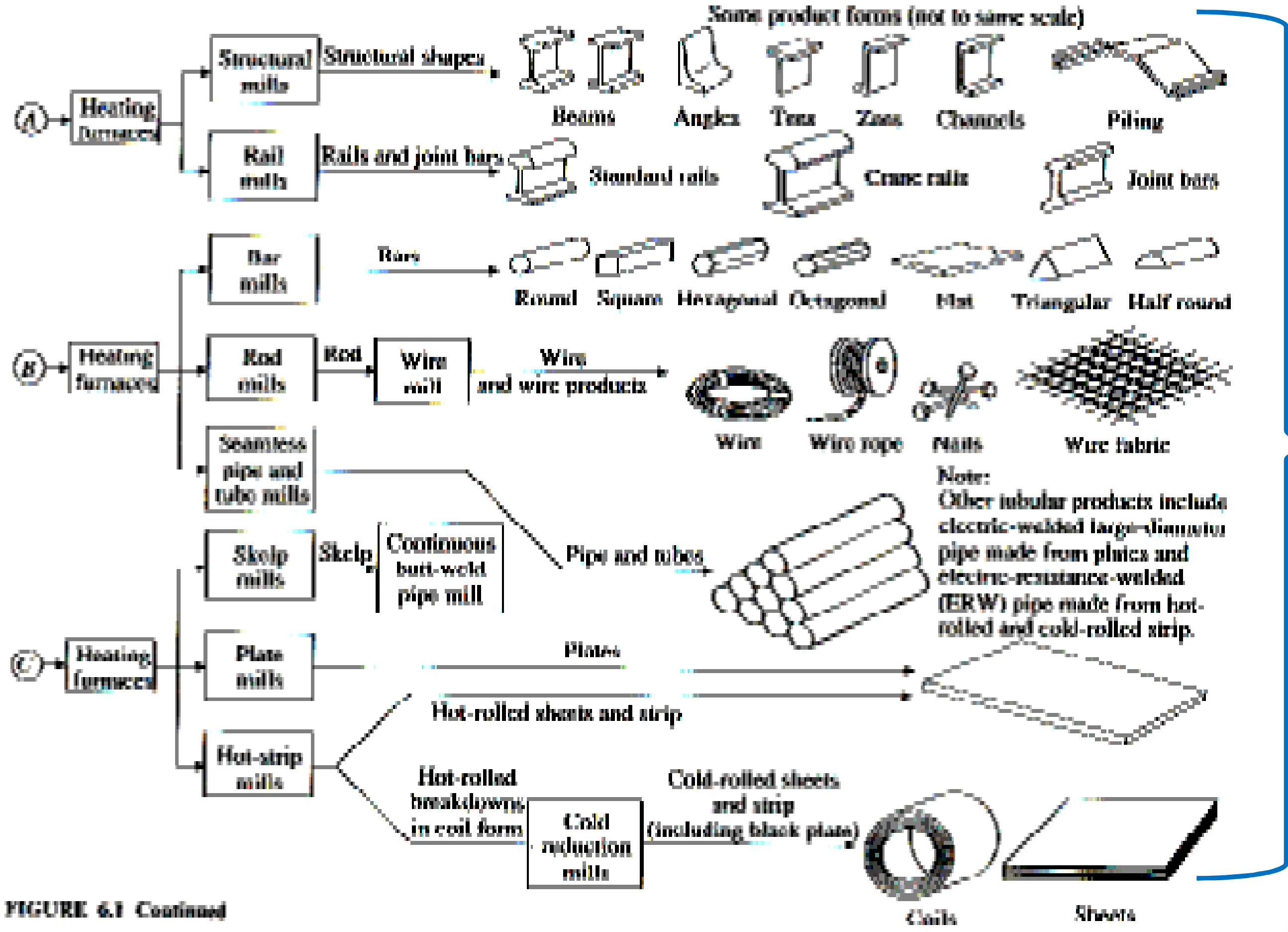


FIGURE 6.1 Continued

Products with raw material from rolling process

4.2 Slap Rolling

4.2.1 Rolling technology

Ferrous metals are usually hot-rolled while non-ferrous metals are commonly cold-rolled.

Rolling products are usually used as raw material for different manufacturing processes. For example, the wire product is used to manufacture wire baskets, rods are used in manufacturing bolts and nuts.

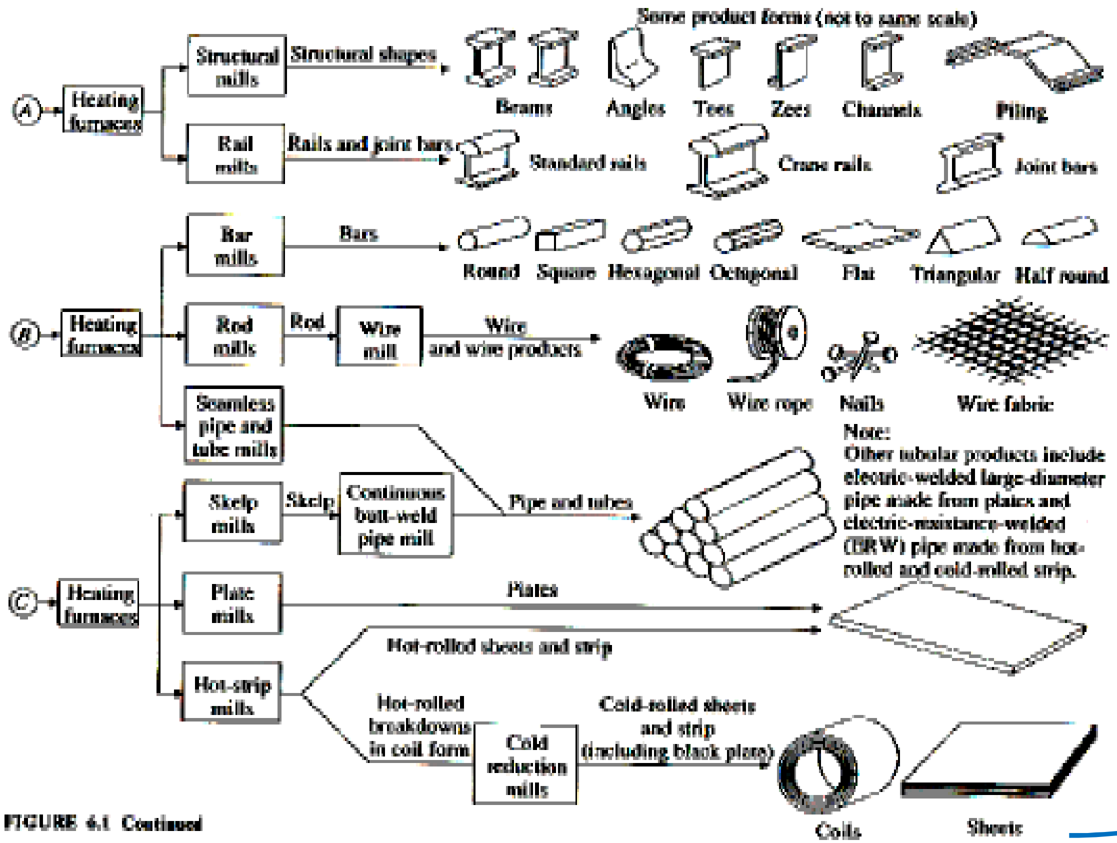


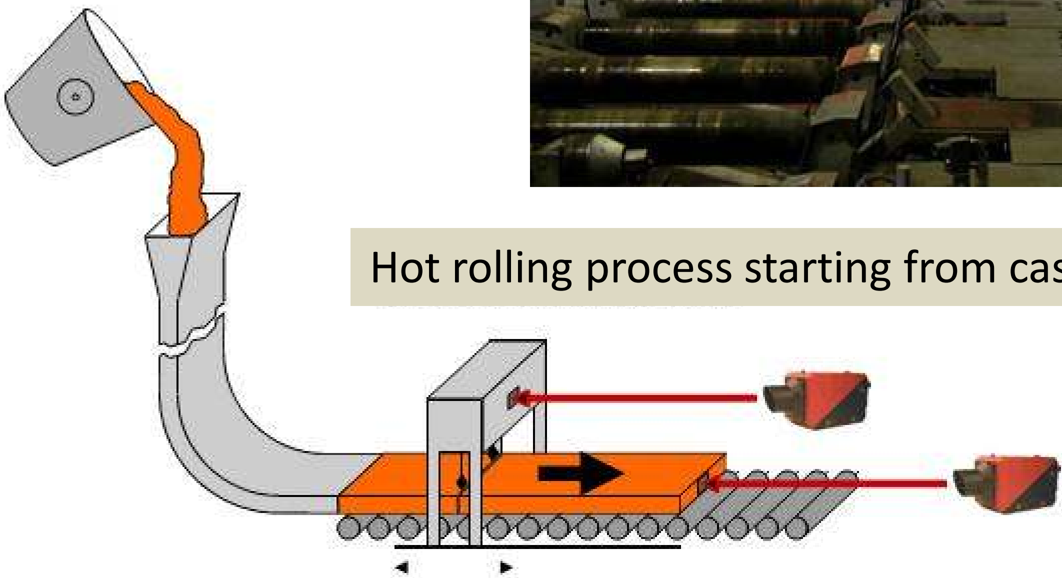
FIGURE 4.1 Continued

Products with raw material from rolling process

4.2 Slap Rolling

4.2.1 Rolling technology

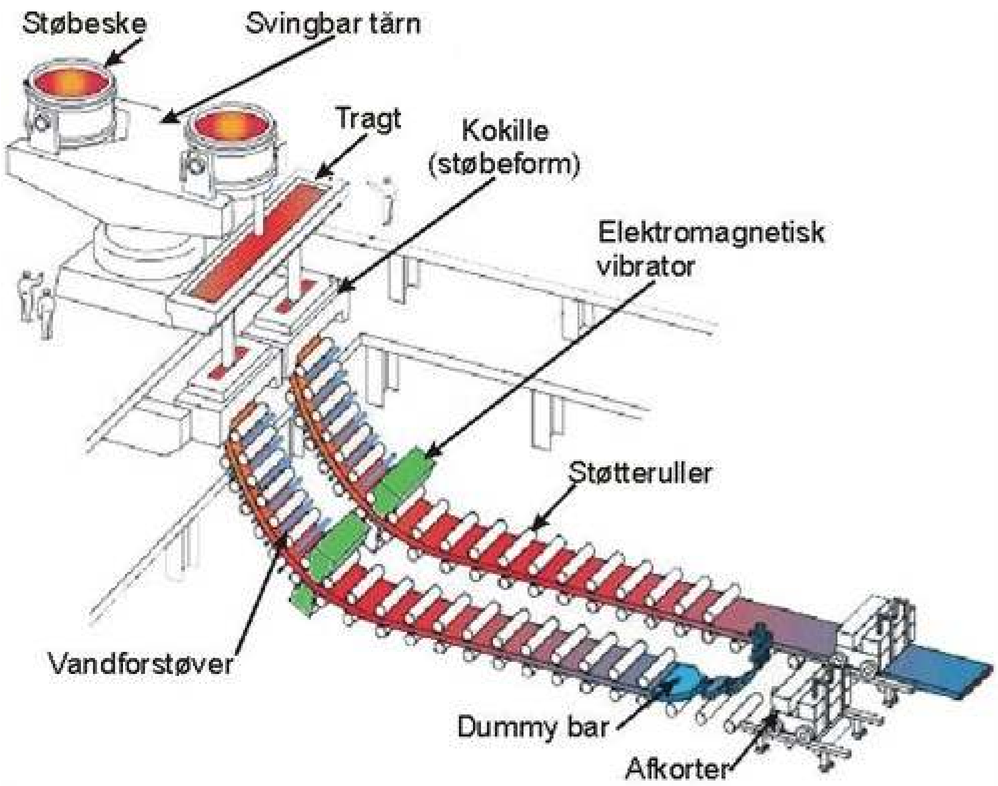
Hot rolling process starting from casting



4.2 Slap Rolling

4.2.1 Rolling technology

Flow diagram of steel making (Rolling Process)

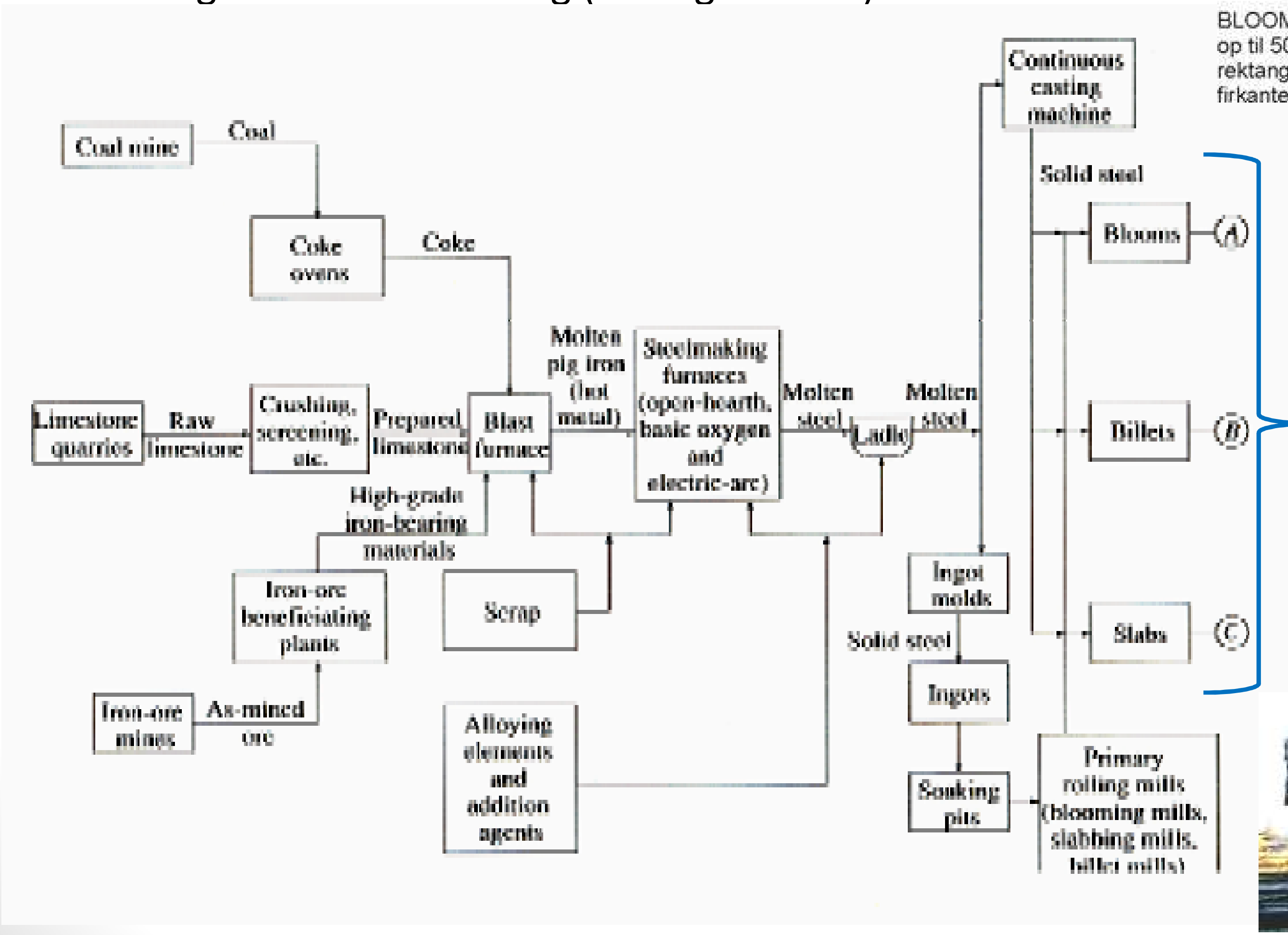


Hot rolling process starting from casting

4.2 Slap Rolling

4.2.1 Rolling technology

Flow diagram of steel making (Rolling Process)



4.2 Slap Rolling

4.2.1 Rolling technology

Flow diagram of steel making (Rolling Process)

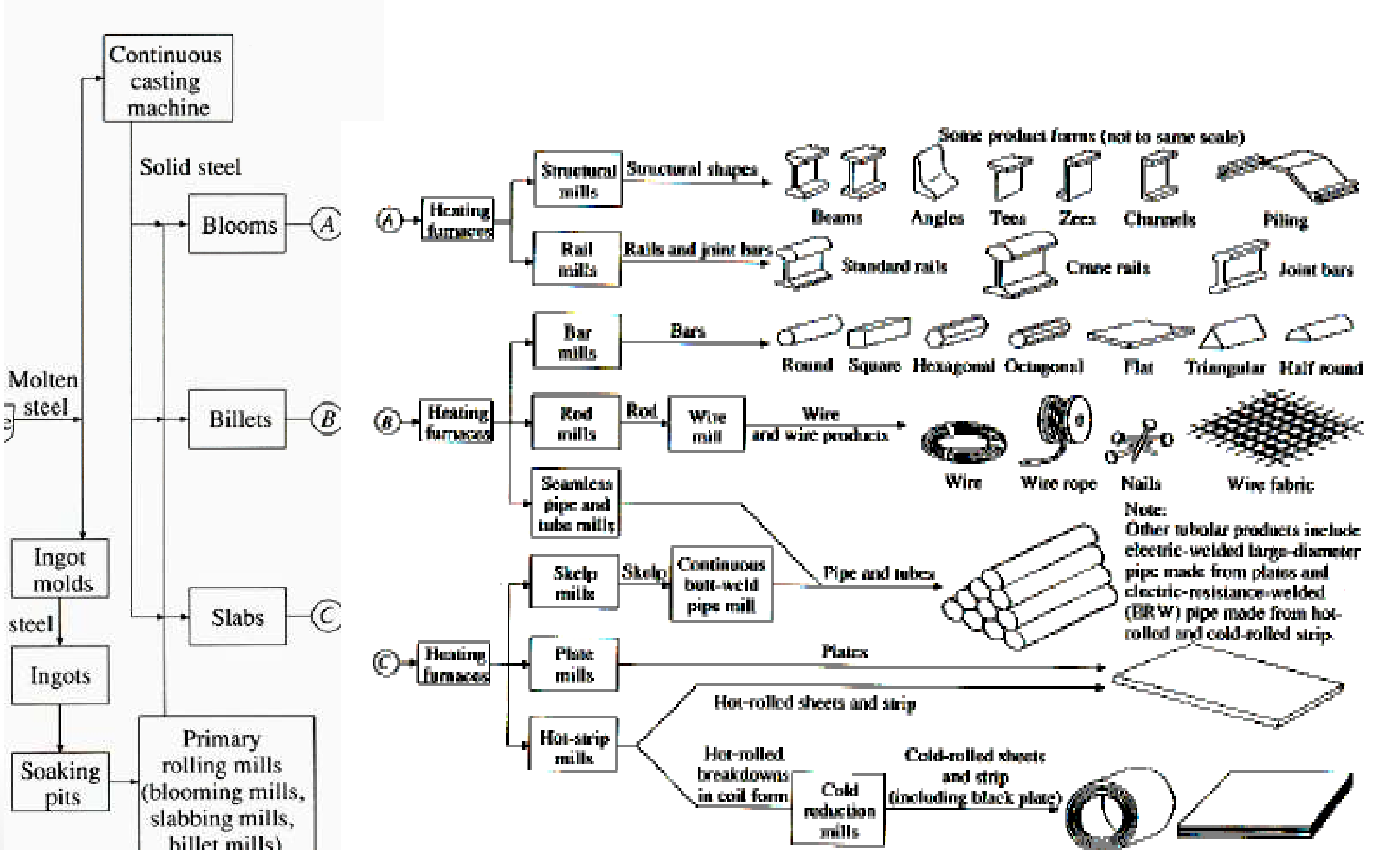


FIGURE 4.1 Continued

4.2 Slap Rolling

4.2.1 Rolling technology

- Strain hardening is involved in cold rolling process, while it does not exist in hot rolling. Hot rolling depends on work piece temperature and strain rate and the process involves annealing condition.

- Friction condition is very high between roll and work piece in cold rolling process where lubrication is necessary in such case.

- Sliding friction condition exists between roll and work piece in cold rolling, while a sticking friction condition exists in case of hot rolling.

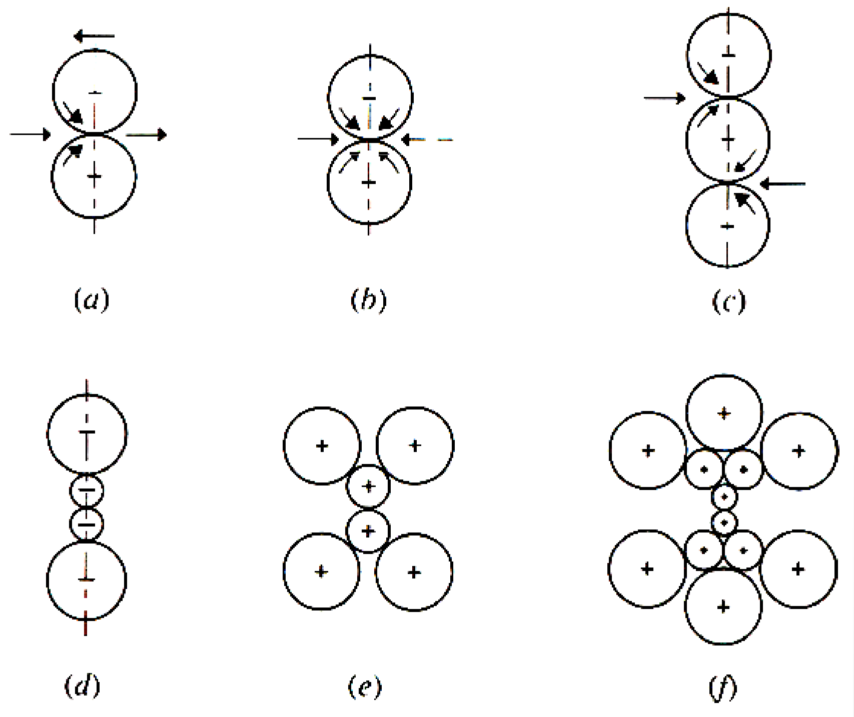
4.2 Slap Rolling

4.2.1 Rolling technology

Rolling mill (machines); rolling process is carried out on **a machine called rolling mill**. The rolls are usually flat type when rolling flat strip, and deformed rolls in case of structure or round stripes/channels. The rolls are assembled in housing and the entire unit called rolling stand.

Typical arrangement of rolls in a rolling mill.

a) 2-high single pass or pull over;
b) 2-high reversing mill;
c) 3-high mill;
d) 4-high mill;
e) 6- and
f) 12-high cluster roll mill



4.2 Slap Rolling

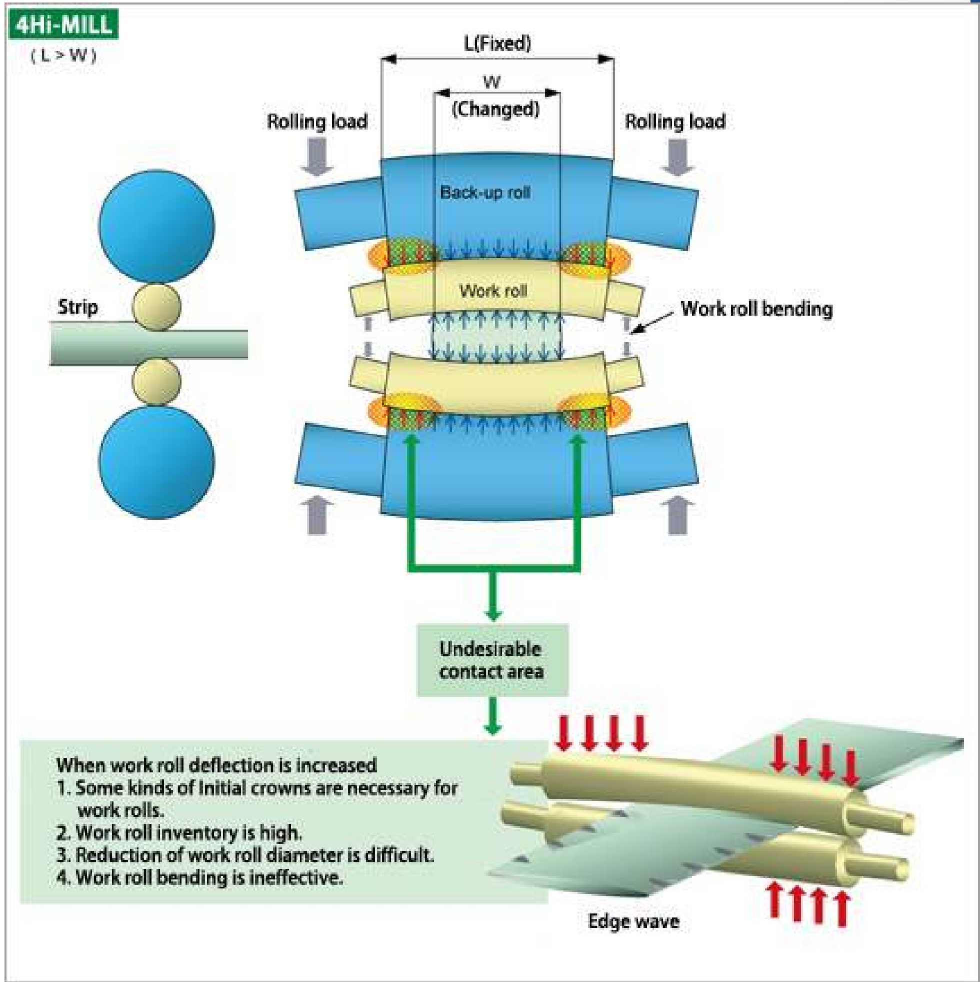
4.2.1 Rolling technology

Rolling mill (machines);

➢For example, a rolling mill have two rolls in its stands called *two-roll* mill. Similarly, A *three-high mill* has three rolls,etc.

➢The rolls that are in contact with the work-piece are called *working rolls*, while those idles and supporting the work-piece are called *backup rolls*.

➢ Different roll diameters are commonly used for more support and for avoiding roll deflection, which results in defect rolling product.



4.2 Slap Rolling

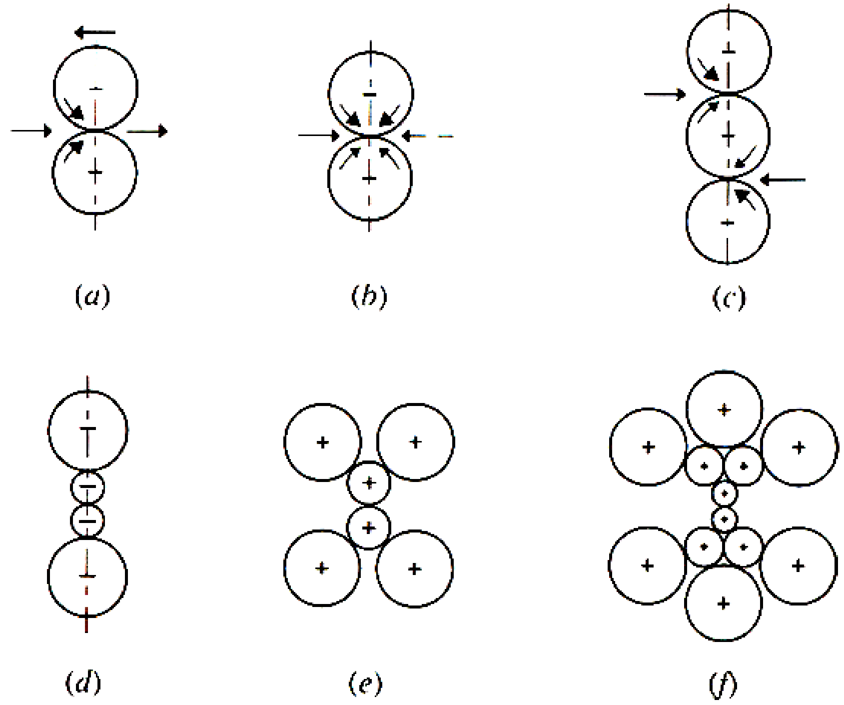
4.2.1 Rolling technology

Rolling mill (machines);

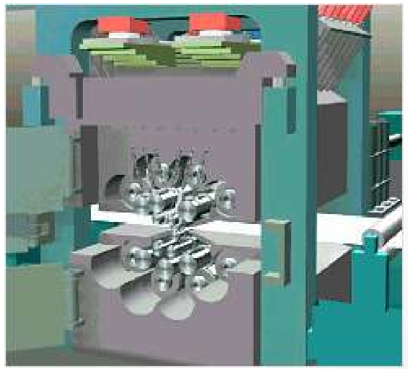
- In rolling mill, the working rolls are rotating in opposite direction when rolling follow in one direction.

- Some of the mills have *reversing* working rolls for each pass (small mills). In this case, the metal rolled back and forth, while gap between th driving rolls is frequently adjusted to achieve the desired strip thickness.

- One disadvantage of reversing rolls that each reversing time requires overcoming the inertial forces which may results in fatigue stresses and decrease the life of rolling mill.



6 High mill (type d)



cluster roll mill (type f)

4.2 Slap Rolling

4.2.1 Rolling technology

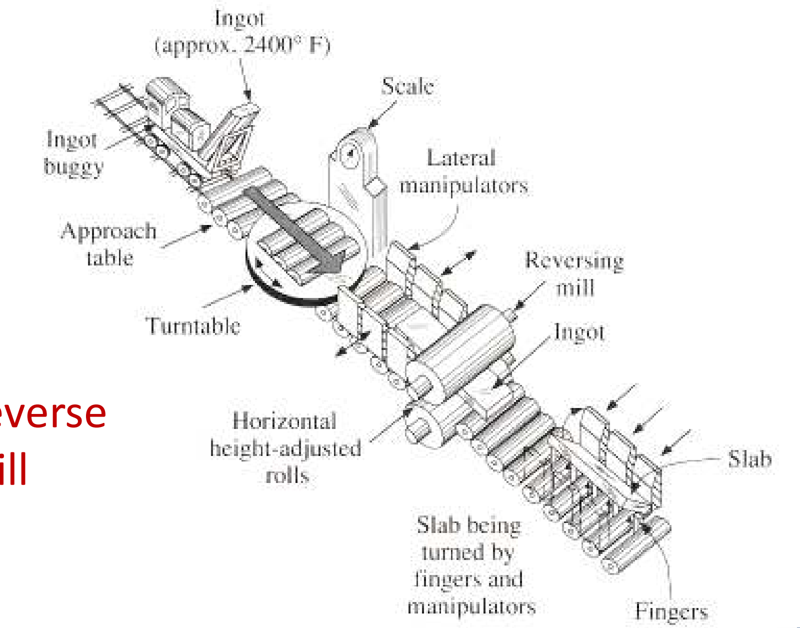
Rolling mill (machines);

➢ In rolling mill, the working rolls are rotating in opposite direction when rolling follow in one direction.

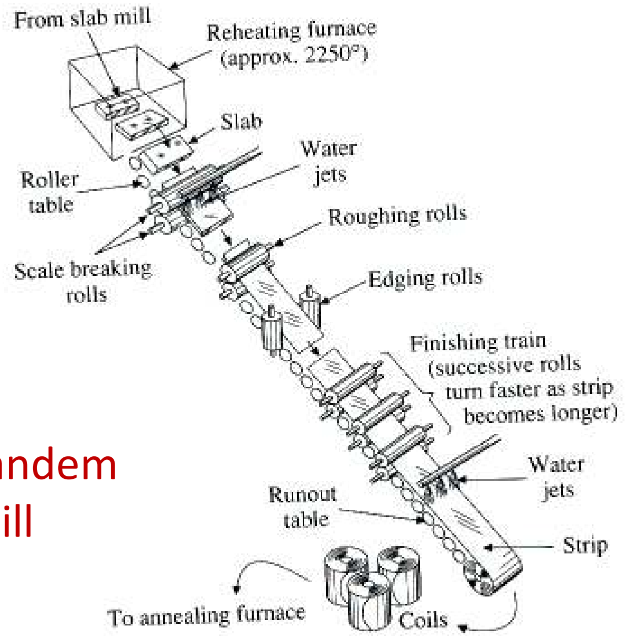
➢Some of the mills have *reversing* working rolls for each pass (small mills). In this case, the metal rolled back and forth, while gap between the driving rolls is frequently adjusted to achieve the desired strip thickness.

➢One disadvantage of reversing rolls is that each reversing time requires overcoming the inertial forces which may results in fatigue stresses and decrease the life of rolling mill.

Reverse Mill



Tandem mill



4.2 Slap Rolling

4.2.2 Flat rolling load estimation

h_o ; Strip thickness before rolling,	h_f ; Strip thickness after rolling,
R ; Upper roll raduis,	α ; Bite angle,
L ; Projected length size of the strip-roll contact area,	
l_o, l_f; Stipe length before and after the deformation,	

Assumptions:

- Rolling process can be considered as a forging process, where, roll is dispaced toward a flat strip, i.e. rolling force due to roll forging.
- The friction condition between roll and strip is neglected.
- Rolling process can be analyzed as plan strain condition, where the strain along strip is nearly zero, i.e. $w_o = w_f$.

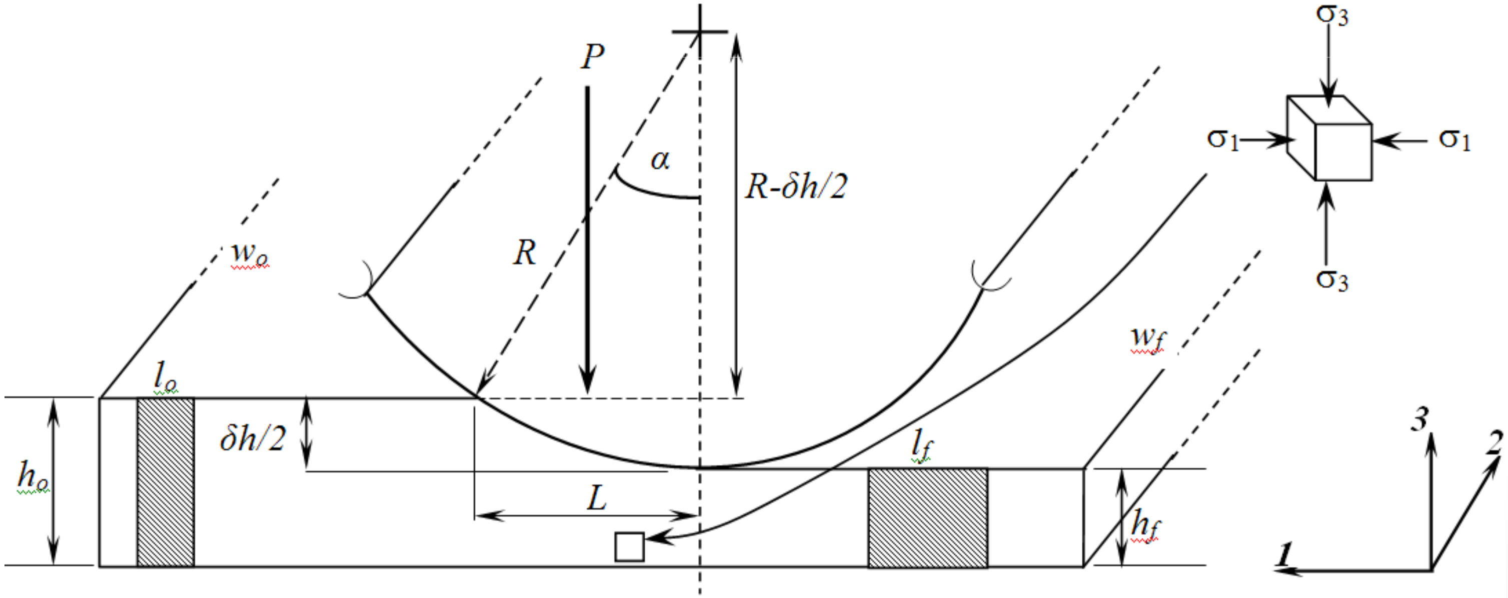


Fig. 4.5 Strip rolling sketch showing all rolling terms used in load estimation.

4.2.3 Flat rolling load estimation- Effective strain and stress in strip rolling:

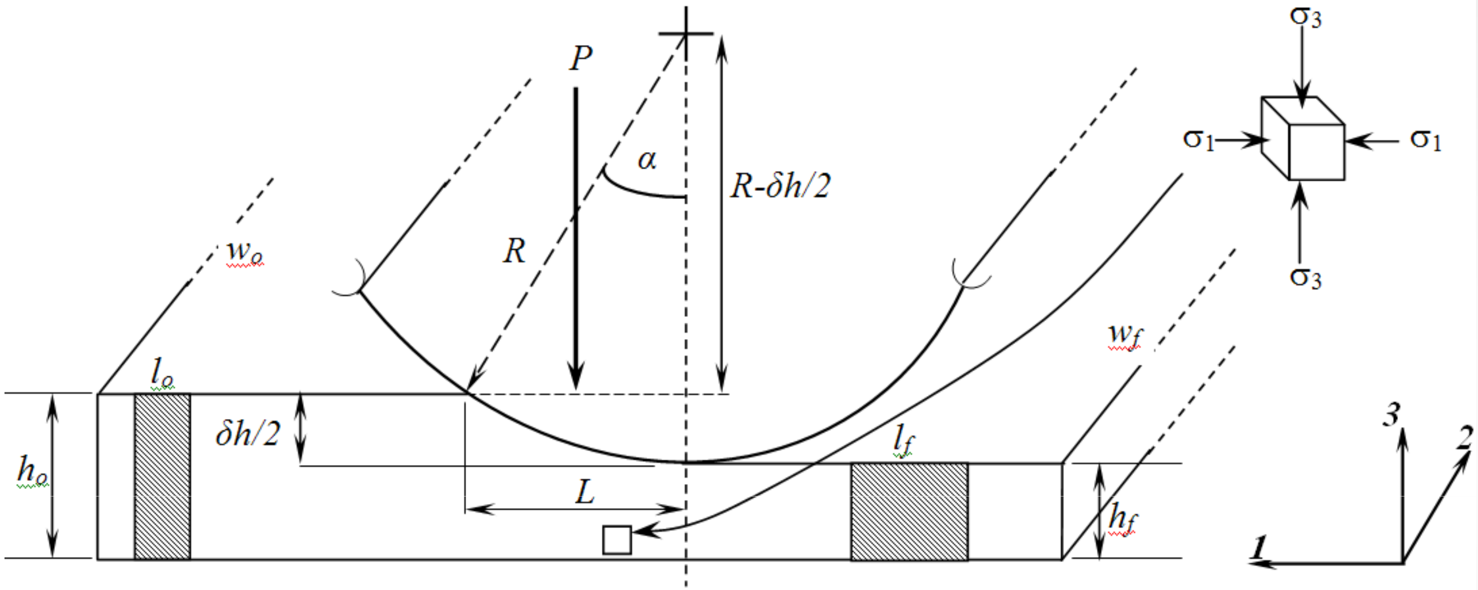


Fig. 4.5 Strip rolling sketch showing all rolling terms used in load estimation.

The principle strains for rolling process; $\varepsilon_1 = \ln(l_f / l_o)$; $\varepsilon_2 = \ln(w_f / w_o) = 0$ $(plain\,strain)$

$\varepsilon_3 = \ln(h_f / h_o)$. And for volume constancy; $\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0 \quad \Rightarrow \varepsilon_1 = -\varepsilon_3$ $(where\ \varepsilon_2 = 0)$. Hence,

the effective strain can be driven as follows;

$$\bar{\varepsilon} = [\frac{2}{3}(\varepsilon_1{}^2 + \varepsilon_3{}^2)]^{\frac{1}{2}} = [\frac{2}{3}(\varepsilon_1{}^2 + \varepsilon_1{}^2)]^{\frac{1}{2}} = \frac{2}{\sqrt{3}}\varepsilon_1 = -\frac{2}{\sqrt{3}}\varepsilon_3 \qquad \text{Eq.4.5}$$

4.2 Slap Rolling

4.2.3 Flat rolling load estimation- Effective strain and stress in strip rolling:

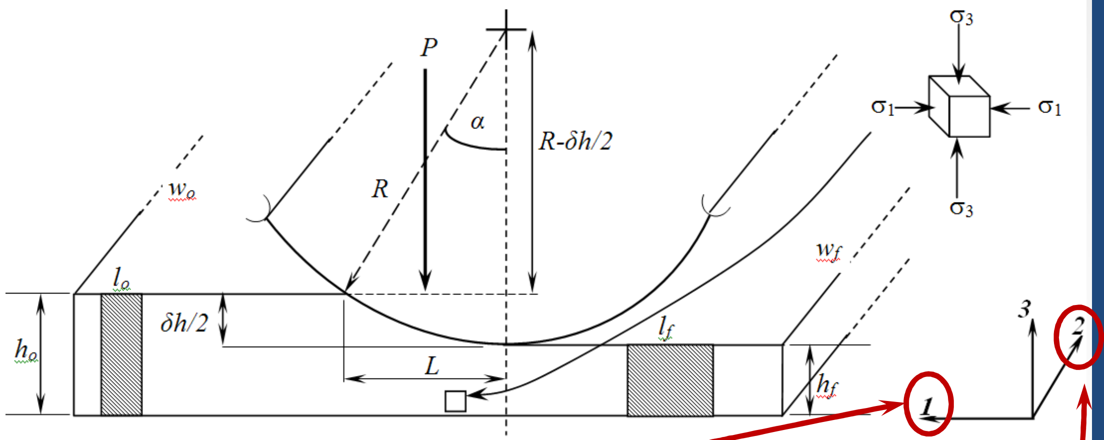


Fig. 4.5 Strip rolling sketch showing all rolling terms used in load estimation.

The principal stresses for strip rolling are given as ; $\sigma_1 = 0$ (Zero friction assumed between roll-strip contact area), $\sigma_2 = (\sigma_1 + \sigma_3)/2 = \sigma_3/2$ (for plain strain condition), while σ_3 is a results of the applied rolling force *P*. Hence, the effective stress can be drawn as follows;

$$\bar{\sigma} = \frac{1}{\sqrt{2}}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{1/2} = \frac{1}{\sqrt{2}}[(0 - \frac{\sigma_3}{2})^2 + (\frac{\sigma_3}{2} - \sigma_3)^2 + (\sigma_3 - 0)^2]^{1/2} = \frac{\sqrt{3}}{2}\sigma_3 \qquad \text{Eq.4.6}$$

The state of stress in rolling is compressive state of stress (see Fig. 4.5).

Hence, $\sigma_3 = -\frac{2}{\sqrt{3}}\bar{\sigma}$. Using the effective yield stress (Equ. 3.34), for $\bar{\sigma}$;

4.2 Slap Rolling

4.2.3 Flat rolling load estimation- Effective strain and stress in strip rolling:

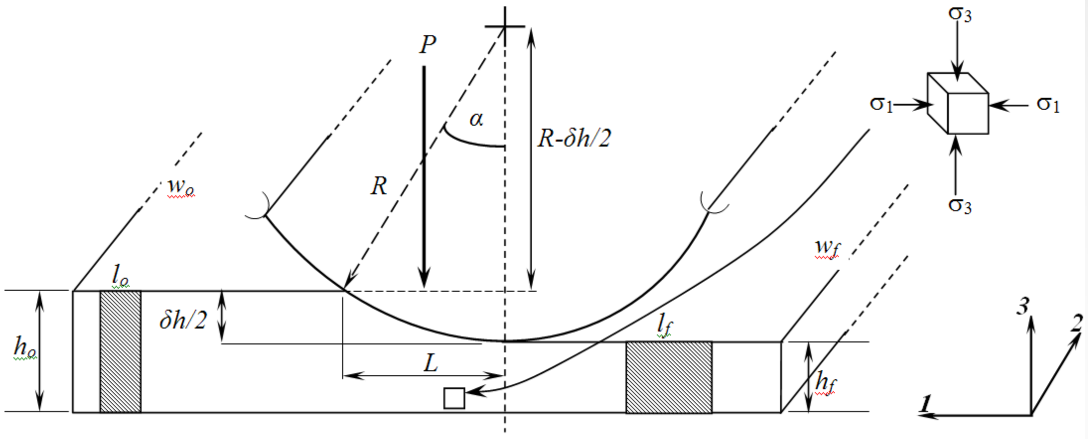


Fig. 4.5 Strip rolling sketch showing all rolling terms used in load

$$\bar{\sigma} = \frac{1}{\sqrt{2}}[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2]^{1/2} = \frac{1}{\sqrt{2}}[(0-\frac{\sigma_3}{2})^2+(\frac{\sigma_3}{2}-\sigma_3)^2+(\sigma_3-0)^2]^{1/2}$$

$$= \frac{\sqrt{3}}{2}\sigma_3 \qquad \text{Eq.4.6}$$

The state of stress in rolling is compressive state of stress (see Fig. 4.5).

Hence, $\sigma_3 = -\frac{2}{\sqrt{3}}\bar{\sigma}$. Using the effective yield stress (Equ. 3.34), for $\bar{\sigma}$;

$$\sigma_3 = -\frac{2}{\sqrt{3}}\bar{\sigma}_m \qquad \text{Eq.4.7}$$

4.2.3 Flat rolling load estimation- Effective strain and stress in strip rolling:

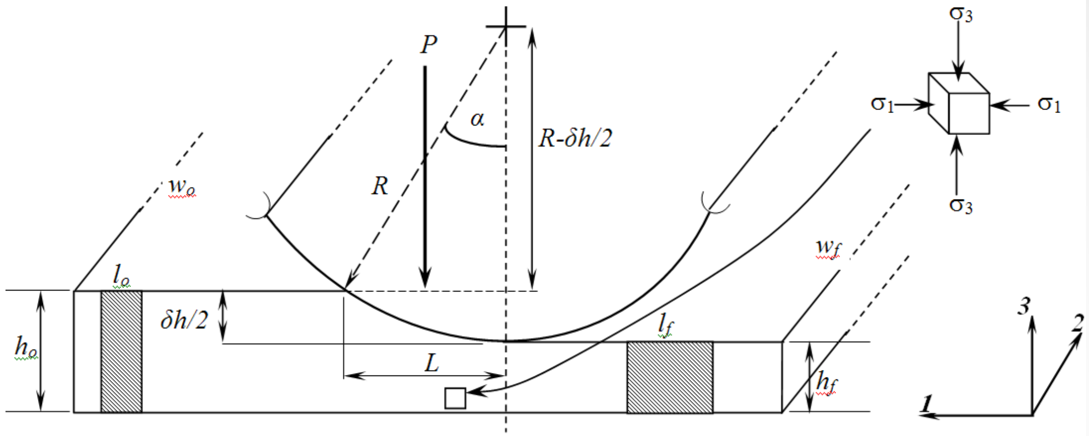


Fig. 4.5 Strip rolling sketch showing all rolling terms used in load

4.2.4 Rolling load and torque estimation ;

From Fig.4.5, the projected length size of the strip-roll contact area, L , expressed as follows;

$$L^2 = R^2 - (R - \delta h/2)^2 = \cancel{R}^2 - \cancel{R}^2 + 2\frac{\delta h}{2}R + (\cancel{\delta h})^2/4 \cong R\,\delta h \quad \text{or} \quad L \cong \sqrt{R\,\delta h} \qquad \text{Eq.4.8}$$

Too small Value, neglected

The rolling force is then P express as follows;

$P = -\sigma_3\, w L$, where: w is the strip width.

4.2.3 Flat rolling load estimation

The rolling force is then P express as follows;

$P = -\sigma_3 \, wL$, where: w is the strip width.

Using Eq. 4.7 and 4.8 for σ_3 and L respectively, the rolling load can be expressed as follows;

$$P = -\frac{2}{\sqrt{3}}\bar{\sigma}_m w L = -\frac{2}{\sqrt{3}}\bar{\sigma}_m w.(R\delta h)^{1/2} \qquad \text{Eq.4.9a}$$

Load calculation given in Eq. 4.9a, assuming frictionless. By 20% friction contribution, Eq. 4.9 can be rewritten as follows;

$$P^* = -(1.2)\frac{2}{\sqrt{3}}\bar{\sigma}_m w.(R\delta h)^{1/2} \qquad \text{Eq.4.9b}$$

where, $\bar{\sigma}_m = \frac{k}{n+1}[\bar{\varepsilon}_2^{\,n} - \bar{\varepsilon}_1^{\,n}]$, assuming $\bar{\varepsilon}_1$=0 and $\bar{\varepsilon}_2 = \bar{\varepsilon}$, then $\bar{\sigma}_m = \frac{k}{n+1}[\bar{\varepsilon}^{\,n}]$, where $\bar{\varepsilon} = \varepsilon_1 = \ln(l_f / l_o) = -\varepsilon_3 = -\ln(h_f / h_o)$.

4.2.3 Flat rolling load estimation

Hence, the corrected rolling load can be expressed as follows

$$P^{*} = -(1.2)\frac{2}{\sqrt{3}}[\frac{k}{n+1}(\bar{\varepsilon})^{n}]\, w.(R\,\delta h)^{1/2} \qquad \text{Eq.4.9}$$

Torque estimation on roll is expressed as follows;

$$T = P^{*}(L/2) \qquad \text{Eq.4.10}$$

The rolling power is obtained by multiplying the rolling torque by the angular speed of roll (w_n), *rad/sec*, and given as follows;

$$Power = T\, w_n = (P^{*}\frac{L}{2})\, w_n \qquad \text{Eq.4.11}$$

4.2 Slap Rolling

4.2.3 Flat rolling load estimation

Example 4.1

A rolling mill with single stand used to decrease the strip height from h_f to h_o. Roll diameter is 500 mm (i.e. R=250 mm), and driven at angular speed of n=50 rpm. Given roll width or strip width $w=1800$ mm, calculates;

a) Rolling force from h_o=2.5 mm to h_f=2.0 mm and the power required.

b) Rolling force from h_o=2.5 mm to h_f=1.75 mm and the power required.

c) Comment on the results, given material flow curve $\bar{\sigma} = 150(\bar{\varepsilon})^{0.25} N/mm^2$?

Solution:

Using Eq. 4.9, where $\varepsilon_1 = \ln(l_f/l_o)$; $\varepsilon_2 = 0$, $\varepsilon_3 = -\varepsilon_1 = \ln(h_f/h_o)$; $\bar{\varepsilon} = \frac{2}{\sqrt{3}}\varepsilon_1 = -\frac{2}{\sqrt{3}}\varepsilon_3$.

The angular speed expressed as $w_n = \frac{2\Pi}{60}(50) = 5.236\, rad/sec.$

4.2 Slap Rolling

4.2.3 Flat rolling load estimation

Example 4.1

A rolling mill with single stand used to decrease the strip height from h_f to h_o. Roll diameter is 500 mm (i.e. R=250 mm), and driven at angular speed of n=50 rpm. Given roll width or strip width w=*1800* mm, calculates;

a) Form h_o=2.5 mm to h_f=2.0 mm;

$$\varepsilon_3 = \ln 2/2.5 = -0.223\,,\ \bar{\varepsilon} = -\frac{2}{\sqrt{3}}(-0.223) = 0.2576\,,\ \bar{\sigma}_m = \frac{150}{1.25}(0.2576)^{0.25} = 85.5\,N/mm^2$$

$$P^* = 1.2(2/\sqrt{3})(85.5)(1800)(\sqrt{250(0.5)}) = 2384\,KN$$

The rolling power is calculated using Eq. 4.11 as follows;

$$L = \sqrt{R\,\delta h} = \sqrt{250*0.5} = 11.18\,mm$$

$$Power = T\,w_n = P^*\frac{L}{2}\,w_n = 2384(11.18/2)*5.236 = 69.78\,KW$$

4.2.3 Flat rolling load estimation

Example 4.1

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b) Form h_o=2.5 mm to h_f=1.75 mm;

$$\varepsilon_3 = \ln 1.75/2.5\,,\ \bar{\varepsilon} = -\frac{2}{\sqrt{3}}\ln(1.75/2.5) = 0.412\,,\ \bar{\sigma}_m = \frac{150}{1.25}(0.412)^{0.25} = 96.1\,N/mm^2$$

$$P^* = 1.2(2/\sqrt{3})(96.1)(1800)(\sqrt{250(0.75)}) = 3282.1\,KN$$

Similarly, the power calculation in current case is given below

$$L = \sqrt{R\,\delta h} = \sqrt{250*0.75} = 13.69\,mm$$

$$Power = T\,w_n = P^*\frac{L}{2}w_n = 3282.1(13.69/2)*5.236 = 117.6\,KW$$

From (a & b): clearly observed rolling load and power increase with increase of strip reduction

Problems:

4.1) A reversing mill having single rolling stand used to roll a strip from h_o=2.0*mm* to h_f=1.5*mm* and strip-width of w=500 mm, and driven at angular speed of n=50 rpm. Calculate rolling force and torque when roll diameter is changed from D_1=500 mm to D_2=300 mm. (i.e. R_1=250 mm to R_2=150 mm), given material follow stress $\bar{\sigma} = 150(\bar{\varepsilon})^{0.25} N/mm^2$?

4.2) A single stand rolling mill used to roll a strip height from h_o to h_f. Given roll diameter of 500 mm (i.e. R=250 mm), and driven at rolling angular speed of n=60 rpm. If roll width (i.e. strip width w=*1800* mm), calculates;

a) Rolling force from h_o=1.5 mm to h_f=1.0 mm and power required? Given material follow stress $\bar{\sigma} = 150(\bar{\varepsilon})^{0.25} N/mm^2$.

b) If the initial strip length is 2 meter calculate the final strip length?

Problems

4.3) A rolling stand has a power of 20 KW, driven at angular speed of 80 rpm. Given roll diameter is 300 mm (i.e. $R=150$ mm), and initial strip thickness is 3 mm and strip-width 300 mm. (Material follow stress $\bar{\sigma} = 120(\bar{\varepsilon})^{0.2} N/mm^2$)

a) Calculate the maximum reduction in strip thickness based on given rolling power?

b) If the strip length is 3 meter, calculate rolling cost of producing 100 stripes if power cost is 1.5 SR/(KW.Hr)?

4.4) Tandem mill has two rolling stands with power of 60 and 50 KW, respectively. Given roll diameter is 400 mm for all rolls. Given angular speed for each stand is 80 rpm. The initial strip thickness is 3 mm and its width 300 mm. Calculate maximum reduction of strip thickness on tandem mill? Given material follow stress $\bar{\sigma} = 120(\bar{\varepsilon})^{0.2} N/mm^2$.