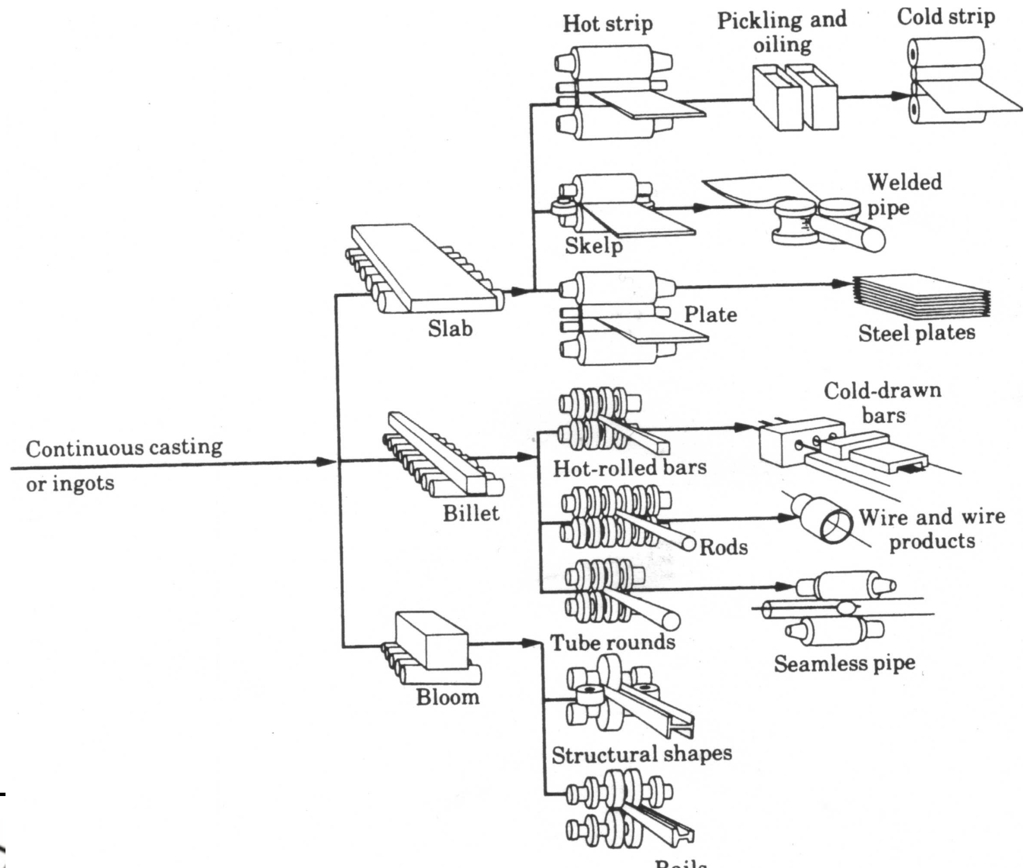
Rolling

Outline

- Rolling Introduction
- Rolling Analysis
- Rolling Defects

Rolling Introduction

- Process typically used to produce basic shapes e.g. flat plates, sheets, railway tracks, I-sections, etc.



Foil: < 0.2 mm

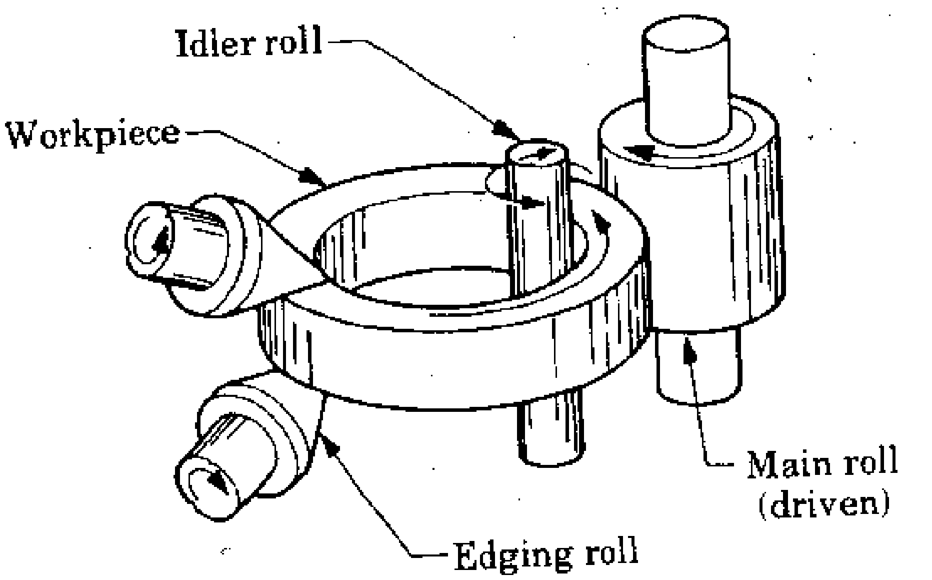
Sheet: 0.2 ~ 6 mm

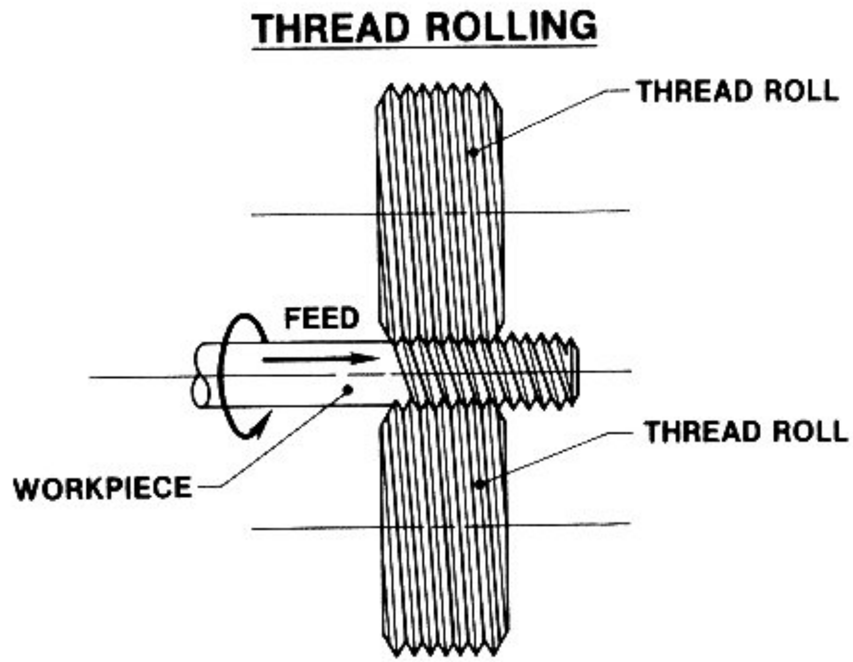
Plate: > 6 mm

Source: http://www/world-aluminum.org/

Rolling Introduction

- More complex geometries also possible e.g. rings, threads, etc.

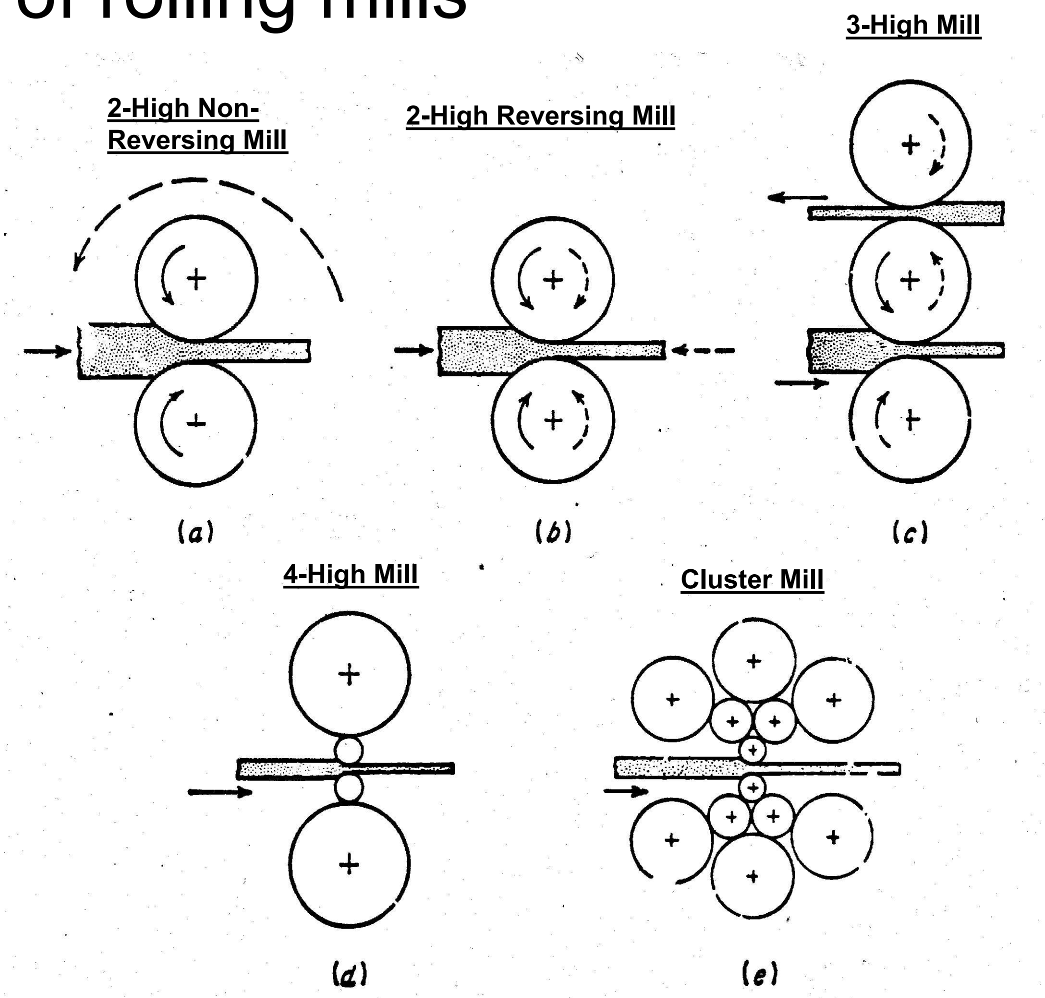




Ring Rolling

Rolling Introduction

- Types of rolling mills



Rolling Introduction

- Roller materials used
  - Cast iron
  - Forged steel

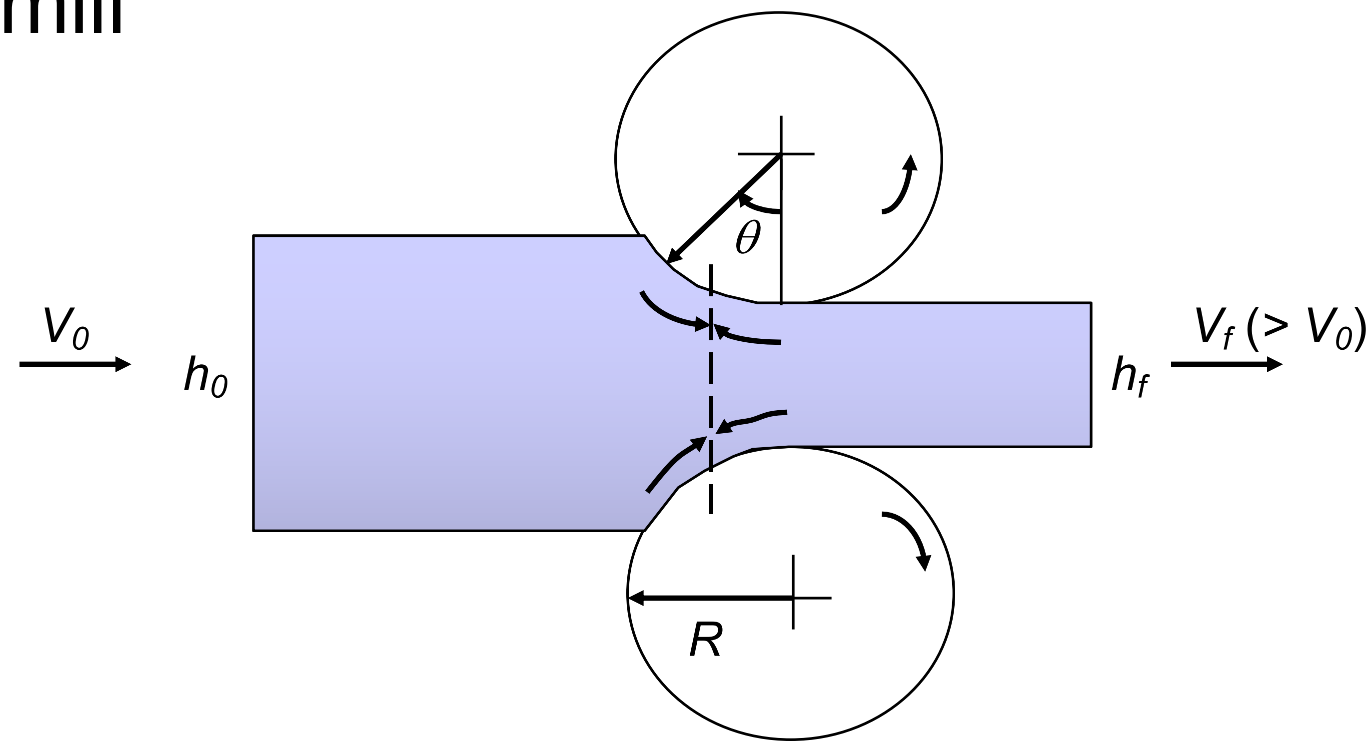
- Important properties of roller materials
  - Strength
  - Wear resistance
  - Modulus of elasticity

Rolling Analysis

- Objectives
  - Find distribution of roll pressure
  - Calculate roll separation force (“rolling force”) and torque
  - Calculate rolling power

Flat Rolling Analysis

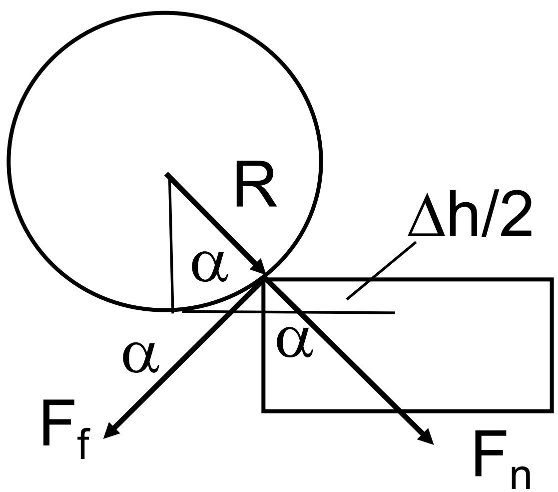
- Consider rolling of a flat plate in a 2-roll mill



Width of plate w is large → plane strain

Processing limits

- The material will be drawn into the nip if the horizontal component of the friction force (F_f) is larger, or at least equal to the opposing horizontal component of the normal force (F_n).



$$F_f \cos\alpha \geq F_n \sin\alpha$$

$$F_f = \mu \cdot F_n$$

$$\tan\alpha = \mu$$

μ = friction coefficient

Processing limits

Also

$$\cos\alpha = \frac{R - \frac{\Delta h}{2}}{R} = 1 - \frac{\Delta h}{2R}$$

and $\Delta h << R$

$$\sin\alpha = \sqrt{1 - \cos^2\alpha}$$

$$\sin\alpha = \sqrt{1 - 1 + \frac{\Delta h}{2R} - \cancelto{0}{\left(\frac{\Delta h}{2R}\right)^2}} \qquad \sin\alpha \approx \sqrt{\frac{\Delta h}{R}}$$

$$\tan\alpha = \sqrt{\frac{\frac{\Delta h}{R}}{1 - \frac{\Delta h}{R} + \left(\frac{\Delta h}{2R}\right)^2}} \cong \sqrt{\frac{\Delta h}{R - \Delta h}} \approx \sqrt{\frac{\Delta h}{R}}$$

Maximum Draft

So, approximately

$$(\tan\alpha)^2 = \mu^2 = \frac{\Delta h}{R}$$

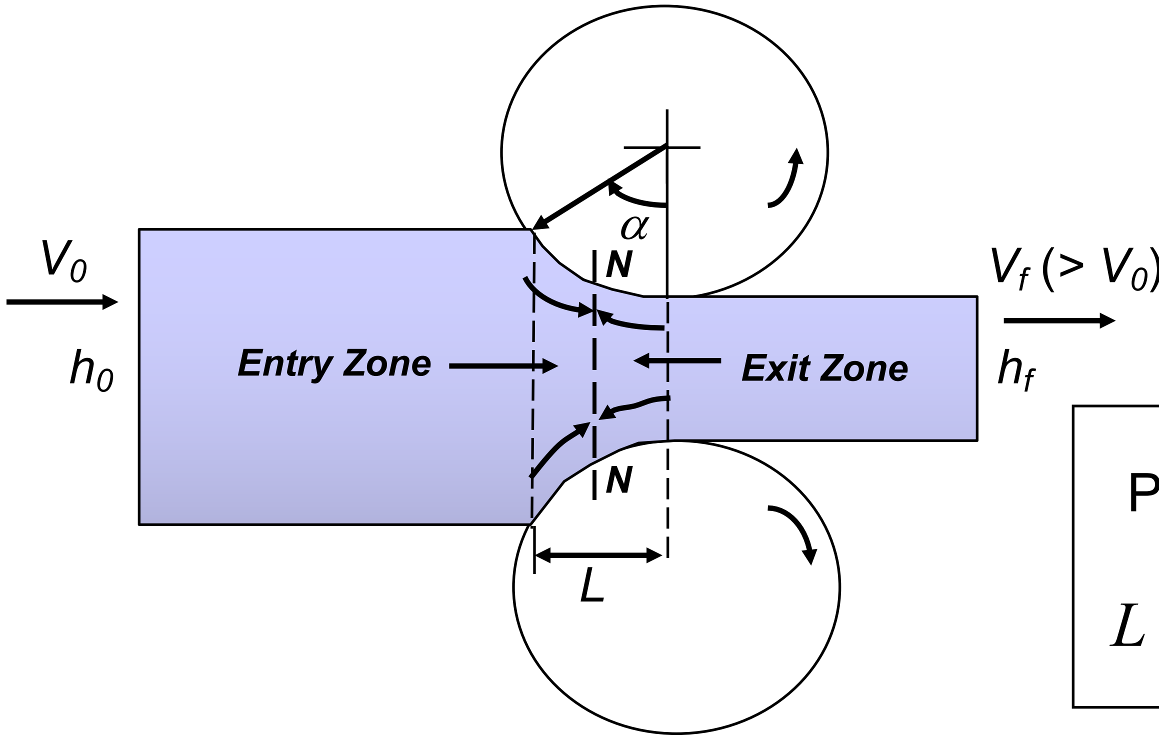
Hence, maximum draft

$$\Delta h_{\max} = \mu^2 R$$

Maximum angle of acceptance

$$\phi_{\max} = \alpha = \tan^{-1}\mu$$

Flat Rolling Analysis

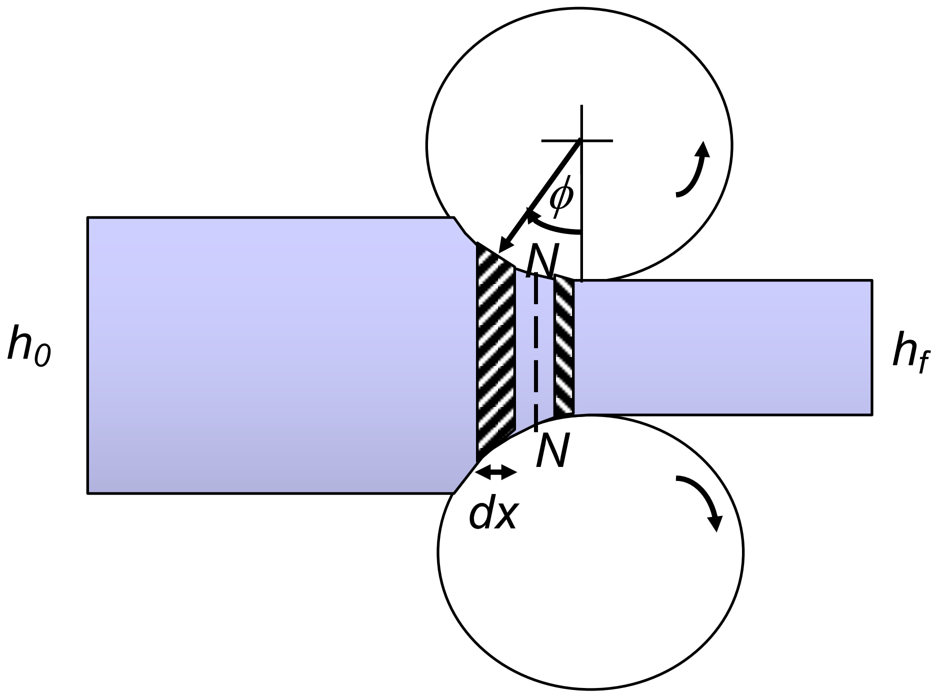


Projected contact length, L

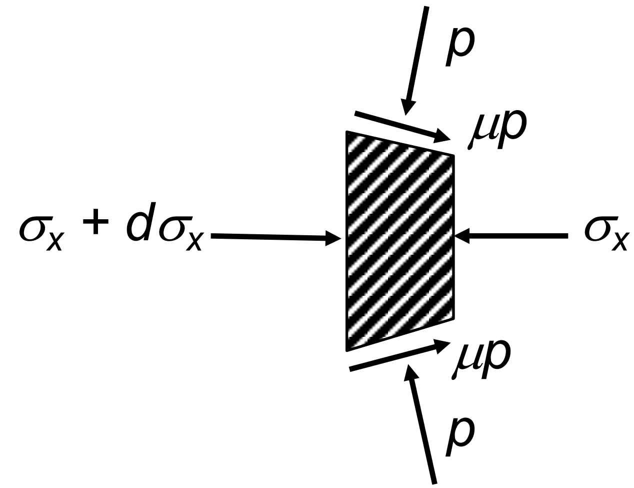
$$L \simeq \sqrt{R\left(h_0 - h_f\right)} = \sqrt{R\Delta h}$$

- Friction plays a critical role in enabling rolling → cannot roll without friction; for rolling to occur $\mu \geq \tan\alpha$
- Reversal of frictional forces at neutral plane (*NN*)

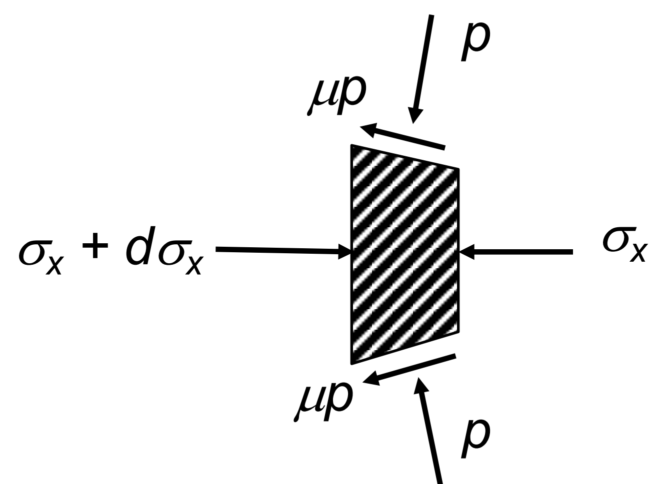
Flat Rolling Analysis



Stresses on Slab in Entry Zone

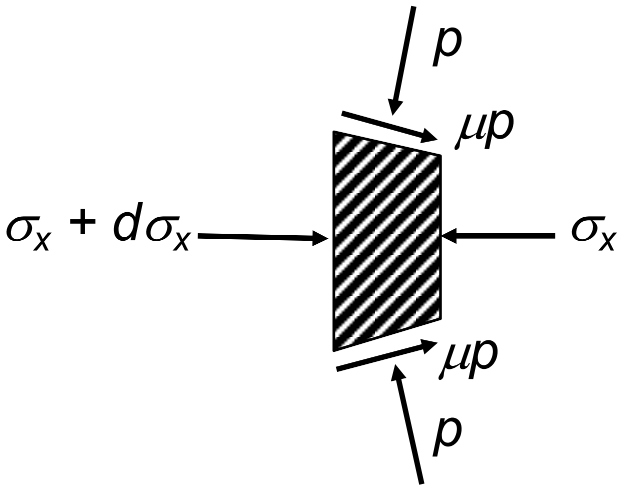


Stresses on Slab in Exit Zone

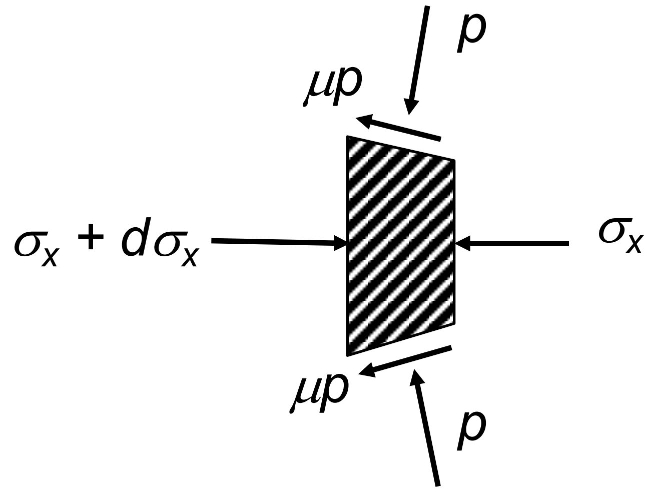


Flat Rolling Analysis

Stresses on Slab in Entry Zone



Stresses on Slab in Exit Zone



Using slab analysis we can derive roll pressure distributions for the entry and exit zones as:

$$\boxed{p = \frac{2}{\sqrt{3}} Y_f \frac{h}{h_0} e^{\mu(H_0 - H)}}$$

Entry Zone

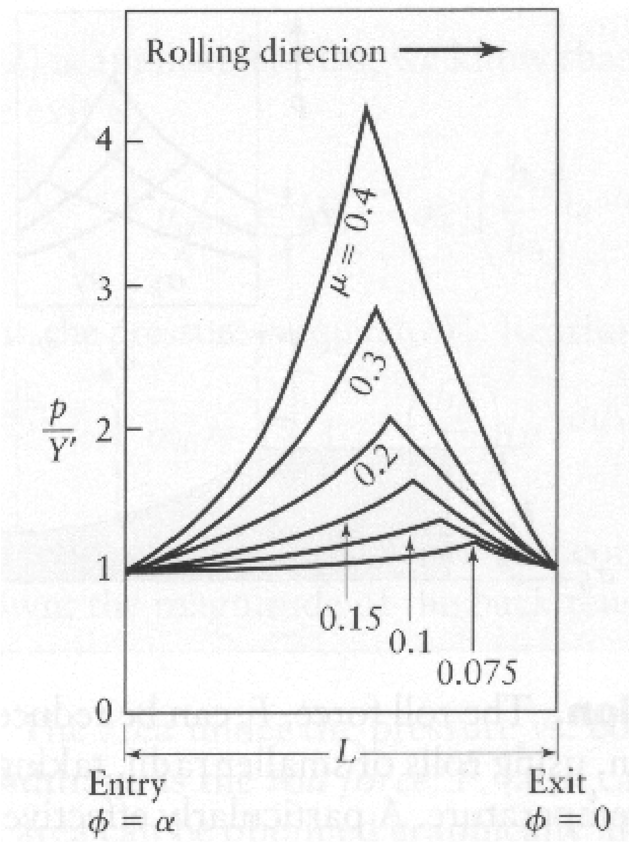
$$H = 2\sqrt{\frac{R}{h_f}} \tan^{-1}\left(\sqrt{\frac{R}{h_f}}\phi\right)$$

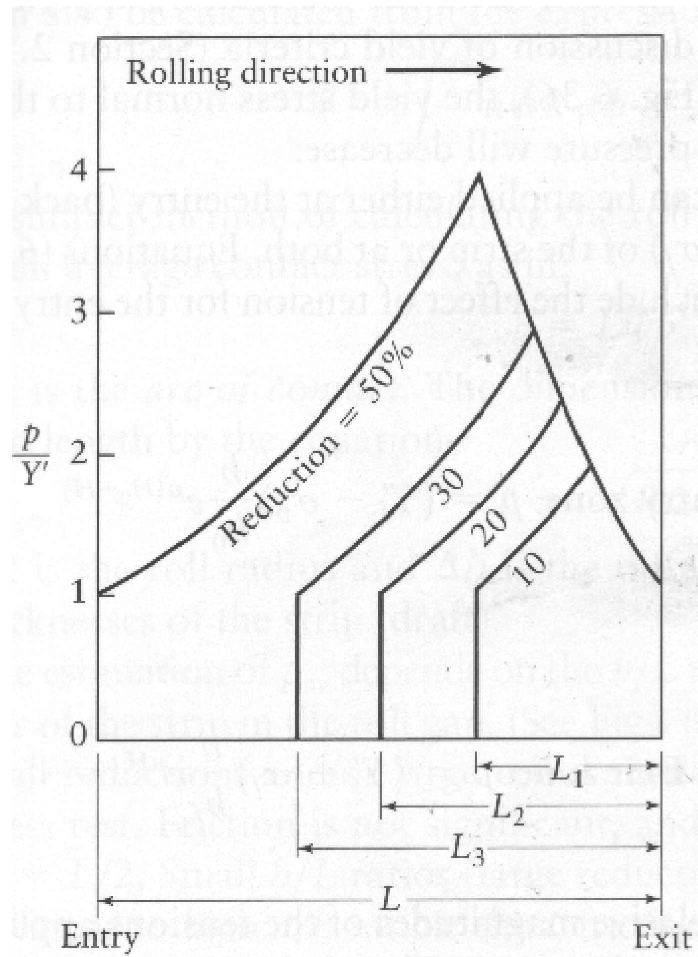
$$H_0 = H @ \phi = \alpha$$

$$\boxed{p = \frac{2}{\sqrt{3}} Y_f \frac{h}{h_f} e^{\mu H}}$$

Exit Zone

Flat Rolling Analysis





Effect of Coeff. of Friction

Effect of % Reduction

Flat Rolling Analysis

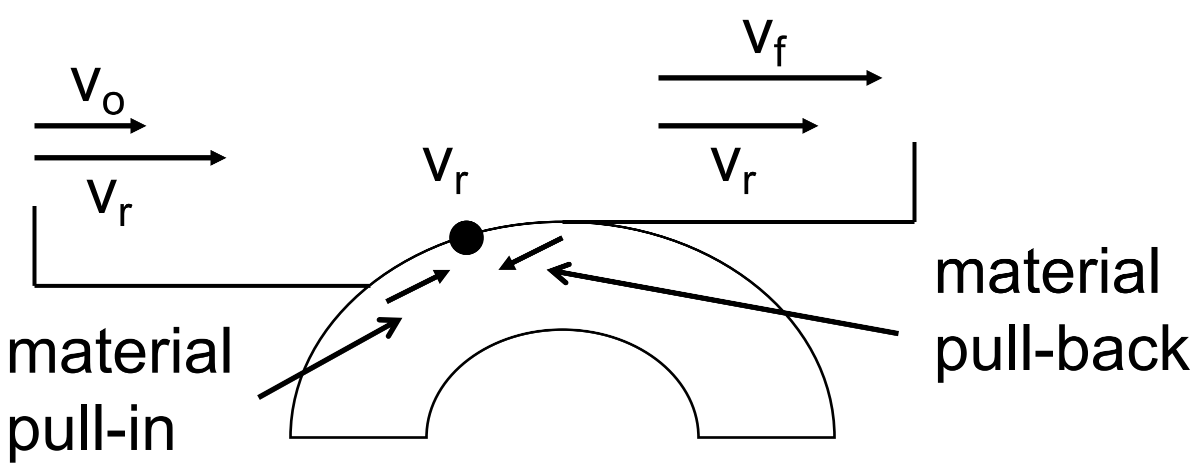
- Rolling force (also called roll-separating force), F = (area under the pressure vs. contact length curve) x (width of sheet)
- Mathematically,

$$F = \int_0^{\alpha} p\,dA = \int_0^{\phi_N} w p_{exit} R\,d\phi + \int_{\phi_N}^{\alpha} w p_{entry} R\,d\phi$$

Where ϕ_N is the location of the neutral plane

Zero slip (neutral) point

- Entrance: material is pulled into the nip
  - roller is moving faster than material
- Exit: material is pulled back into nip
  - roller is moving slower than material



System equilibrium

- Frictional forces between roller and material must be in balance.
  - or material will be torn apart
- Hence, the zero point must be where the two pressure equations are equal.

$$\frac{h_0}{h_f} = \frac{exp\left(\mu(H_0 - H_n)\right)}{exp\left(\mu H_n\right)} = exp\left(\mu\left(H_0 - 2H_n\right)\right)$$

Neutral Point

$$\phi_N = \sqrt{\frac{h_f}{R}} \tan\left(\frac{H_N}{2} \sqrt{\frac{h_f}{R}} \right), \; H_N = \frac{1}{2}\left(H_0 - \frac{1}{\mu} \ln \frac{h_0}{h_f} \right)$$

Flat Rolling Analysis

- Average rolling force,

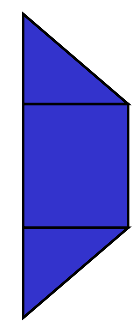
$$F_{avg} = Lwp_{avg} = Lw\left[\frac{2}{\sqrt{3}}\bar{Y}_f\left(1+\frac{\mu L}{2h_{avg}}\right)\right]$$

Where *w* is the width of sheet and h_{avg} is the average thickness of sheet = $0.5(h_0 + h_f)$

$$\bar{Y}_f \varepsilon = \int_0^{\varepsilon} K\varepsilon^n d\varepsilon = \frac{K\varepsilon^{n+1}}{n+1}$$

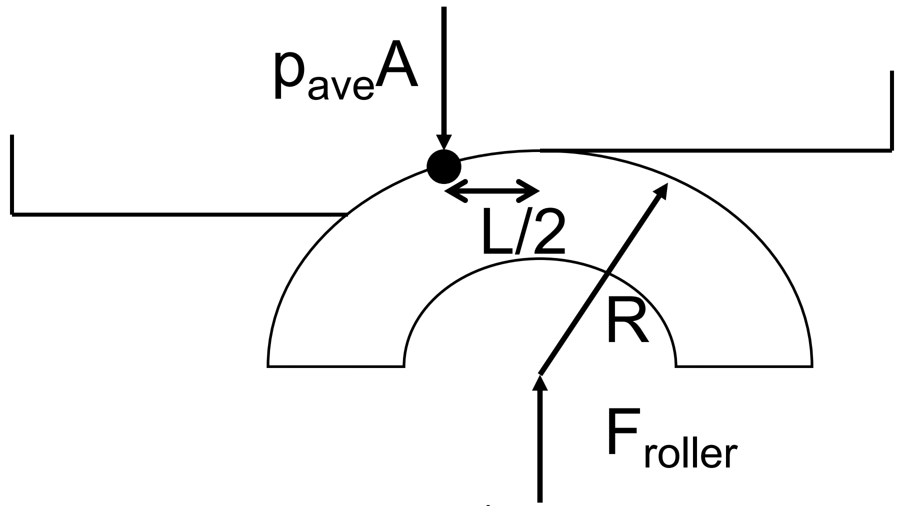
$$\bar{Y}_f = \frac{K\varepsilon^n}{n+1}$$

average flow stress:
due to shape of element



Torque

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



Δh = h_b - h_f

$$\sum F_y = 0$$
$$\therefore F_{roller} = p_{ave}A$$

$$T = \underbrace{\int_{\phi_n}^{\alpha} w\mu p R^2 d\phi}_{\text{entry}} - \underbrace{\int_{0}^{\phi_n} w\mu p R^2 d\phi}_{\text{exit}}$$

$$Torque/roller = r \cdot F_{roller} = \frac{L}{2} \cdot F_{roller} = \frac{F_{roller}L}{2}$$

Torque

- Rolling torque per roll,

$$T = Fa$$

where a is the moment arm for the roll force

$a \approx L/2$ for hot rolling, $a \approx 0.4L$ for cold rolling

Flat Rolling Analysis

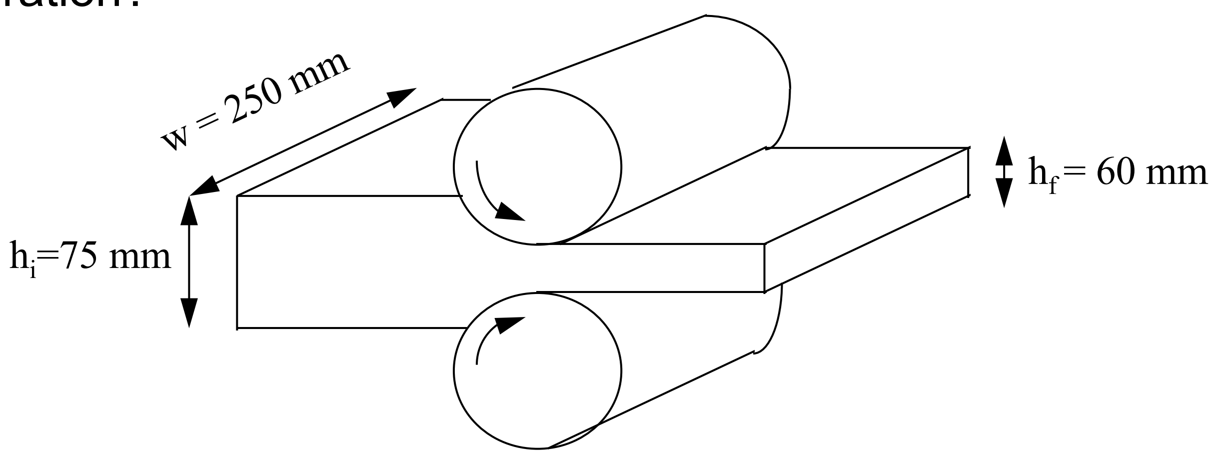
- Rolling power in KW per roll,

$$P = \omega T = \left(2\pi N / 60000\right)\left(Fa\right)$$
$$= 2\pi aFN / 60000 = \pi LFN / 60000$$

Where *N* is the roll speed in rpm, F is in N and L, a are in m.

Example Problem

A 75 mm thick by 250 mm wide slab of AISI 4135 steel is being cold-rolled to a thickness of 60 mm in a single pass. A two-high non-reversing rolling mill (shown below) with 750 mm diameter rolls made of tool steel is available for this task. The rolling mill has a power capacity of 5 MW per roll. The rolls rotate at a constant angular speed of 100 rev/min. The steel work material has the following flow curve at the rolling temperature: $\sigma_t = 1100\varepsilon_t^{0.14}$ MPa. Assume the coefficient of friction μ = 0.2. Is the available rolling mill adequate for the desired operation?



Example Problem

The rolling mill is adequate if the required power for the operation is less than or equal to the available power.

Power required per roll, $P_{roll} = \dfrac{\pi F L' N}{60000}$ **kW**

Roll separating force, $F_{avg} = (Lw)\left(\dfrac{2}{\sqrt{3}}\bar{Y}_f\right)\left(1 + \dfrac{\mu L}{2h_{avg}}\right)$

$$L = \sqrt{R\Delta h} = \sqrt{(0.375)(0.075 - 0.06)} = 0.075 \text{ m}$$

$$h_{avg} = \frac{0.075 + 0.06}{2} = 0.0675 \text{ m}$$

Example Problem

$$\bar{Y}_f = \frac{1}{\varepsilon_t}\int_0^{\varepsilon_t} \sigma_t d\varepsilon_t = \frac{1100\left(\ln\frac{75}{60}\right)^{0.14}}{1.14} = 778.96 \ \textbf{MPa}$$

$$F_{avg} = (0.075)(0.25)\left(\frac{2}{\sqrt{3}}778.96\right)\left(1 + \frac{(0.2)(0.075)}{2(0.0675)}\right) = 18.74 \ \textbf{MN}$$

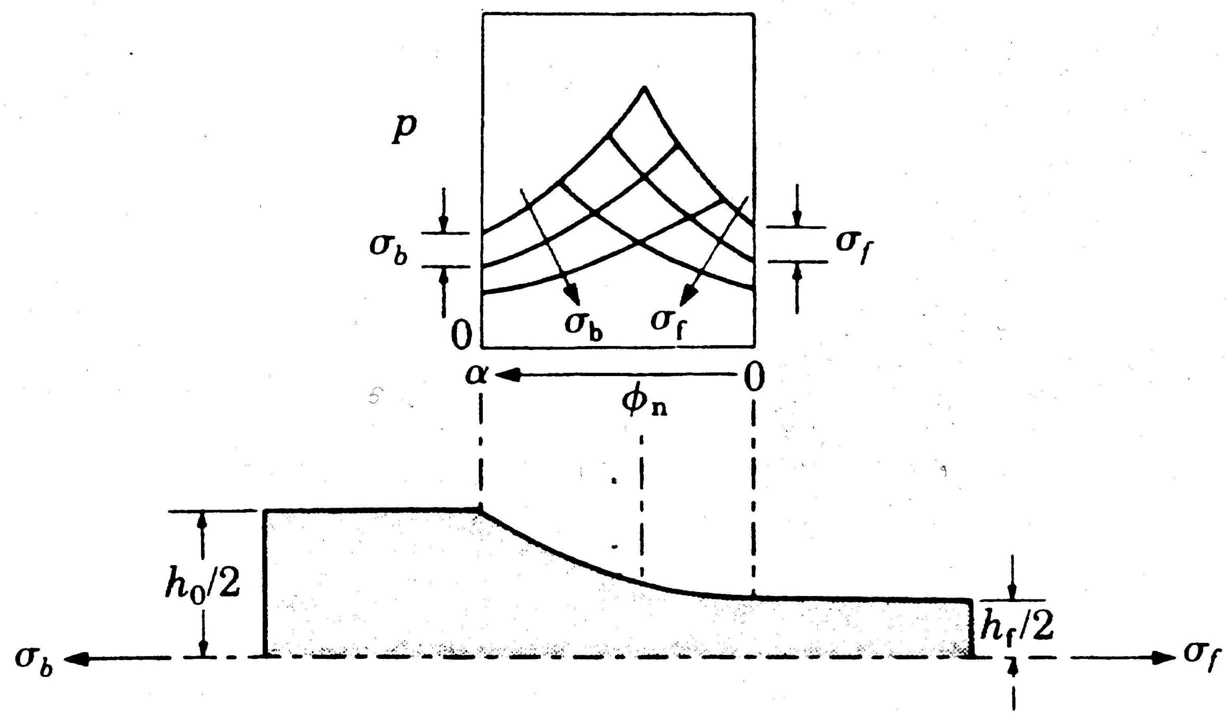
Therefore, $P_{roll} = \dfrac{\pi\left(18.74\times 10^6\right)(0.075)(100)}{60000} = 7.36 \ \textbf{MW}$

Since $P_{roll} > 5$ **MW (the available power), the rolling mill is not adequate for the operation.**

Rolling Forces

- Ways to reduce rolling forces
  - Lowering friction via use of lubricants
  - Using smaller diameter rolls
  - Taking smaller reductions
  - Increasing workpiece temperature
  - Use of front and/or back tension

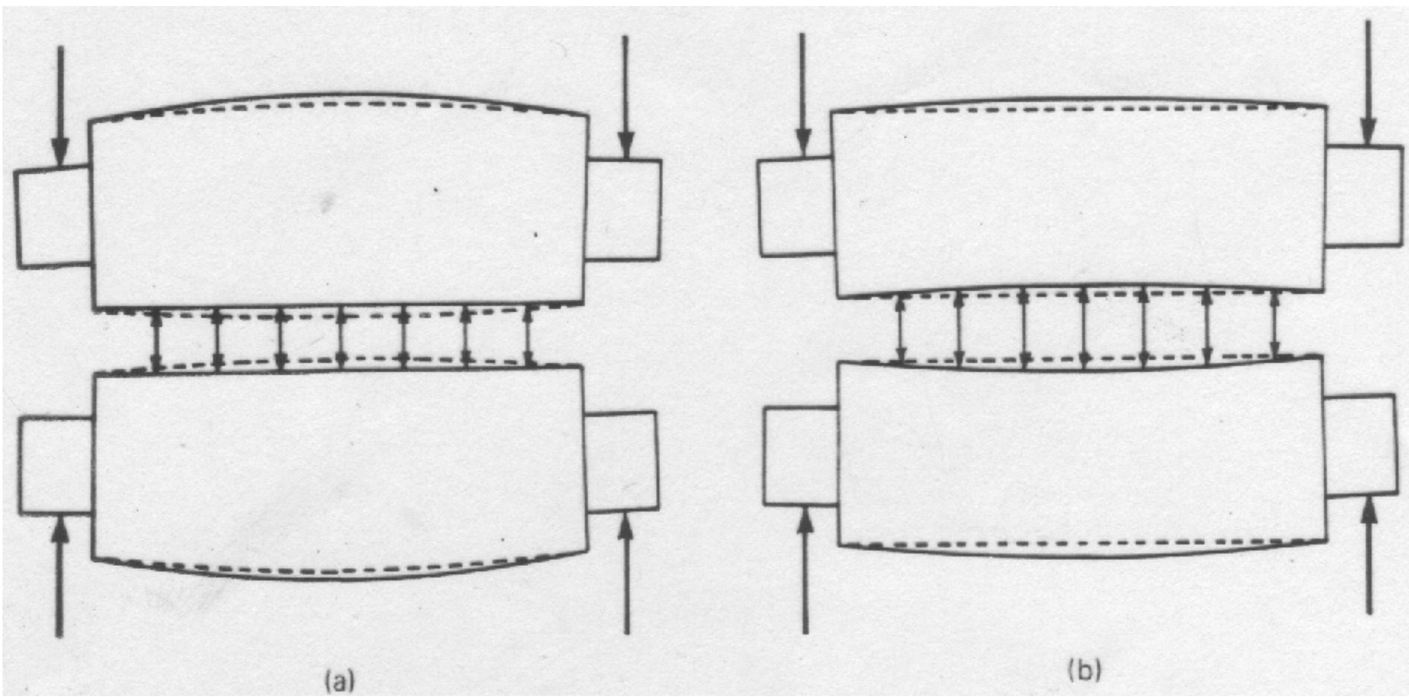
Front & Back Tension



Lowers apparent yield strength of material → lowers roll force

Rolling Defects

- Roll bending
- Remedy: roll camber

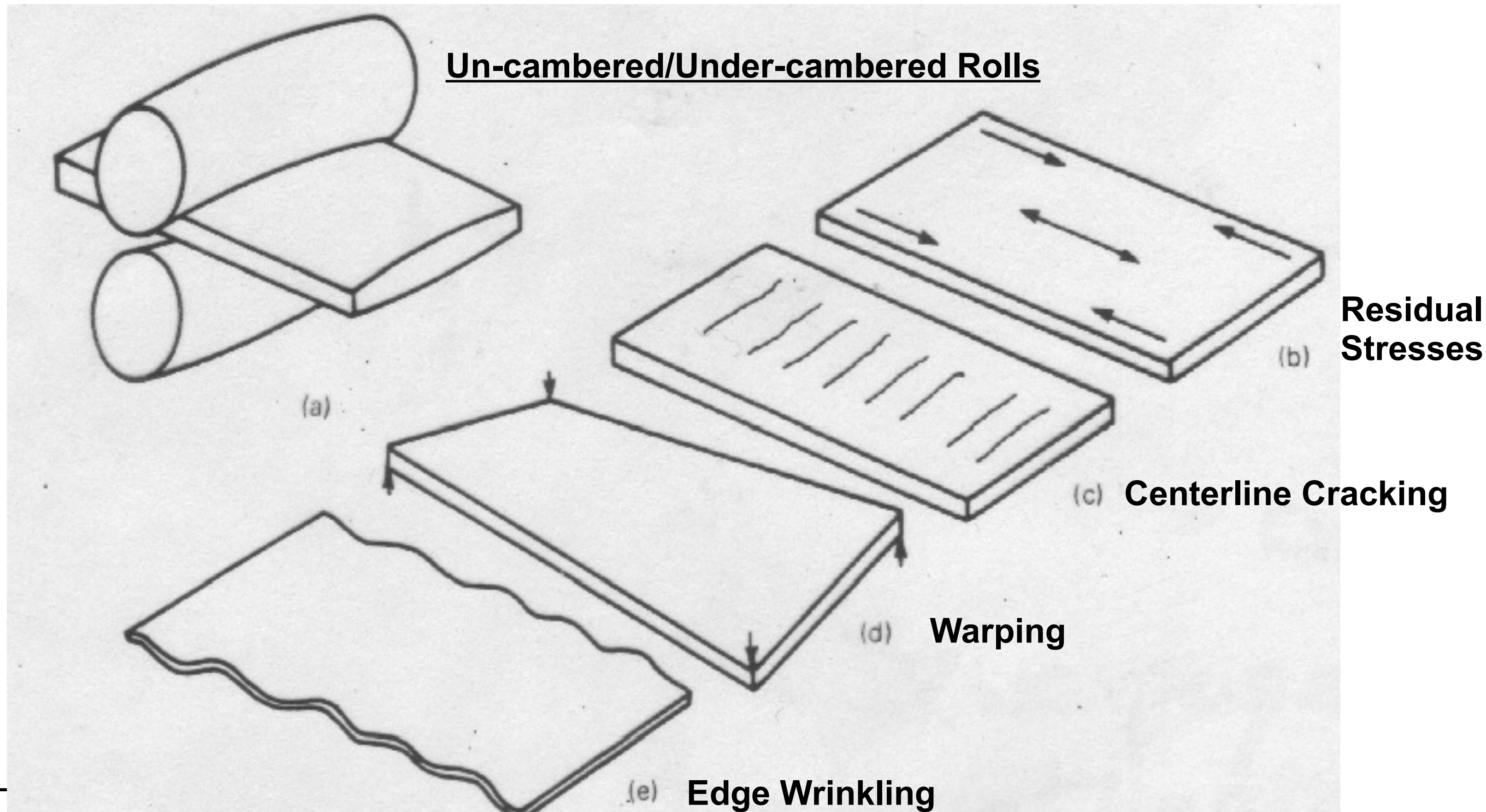


Cambered Rolls **Un-Cambered Rolls**

Source: Metal Forming, W.F. Hosford & R.M. Caddell, 1993

Rolling Defects

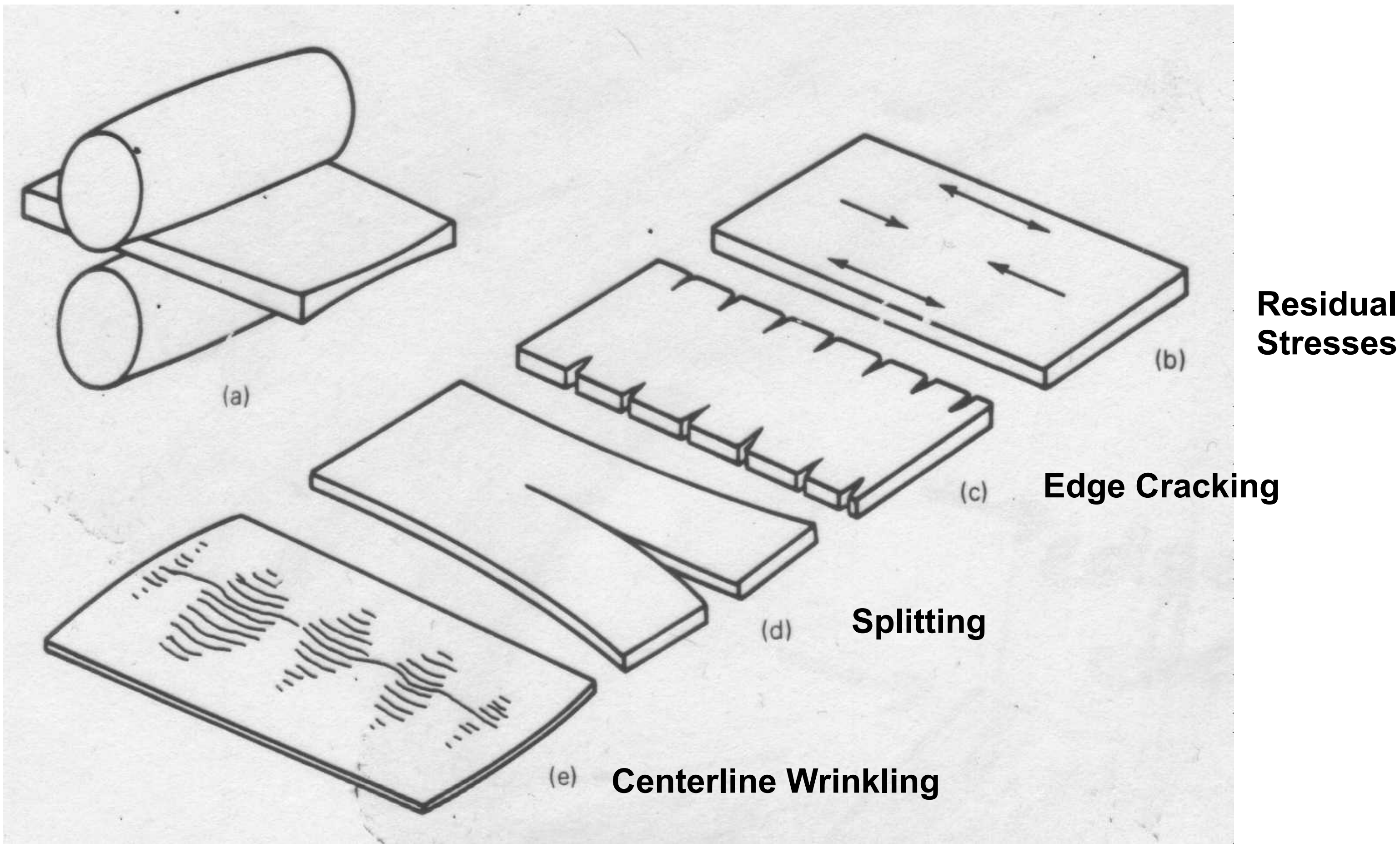
- Un-cambered or under-cambered rolls



Source: Metal Forming, W.F. Hosford & R.M. Caddell, 1993

Rolling Defects

- Over-cambered rolls



Source: Metal Forming, W.F. Hosford & R.M. Caddell, 1993

Rolling Defects

- Roll flattening: similar to tyre flattening
  - Due to elasticity of rolls
  - Increases roll radius and hence rolling force
- Remedy
  - Choose rolls with high elastic modulus
  - Reduce rolling force

Summary

- Rolling Introduction
  - Rolling mill types
- Rolling analysis
  - Roll pressure, rolling force, torque
- Rolling defects
  - Roll bending, flattening, etc.