Deformation Processing - Rolling

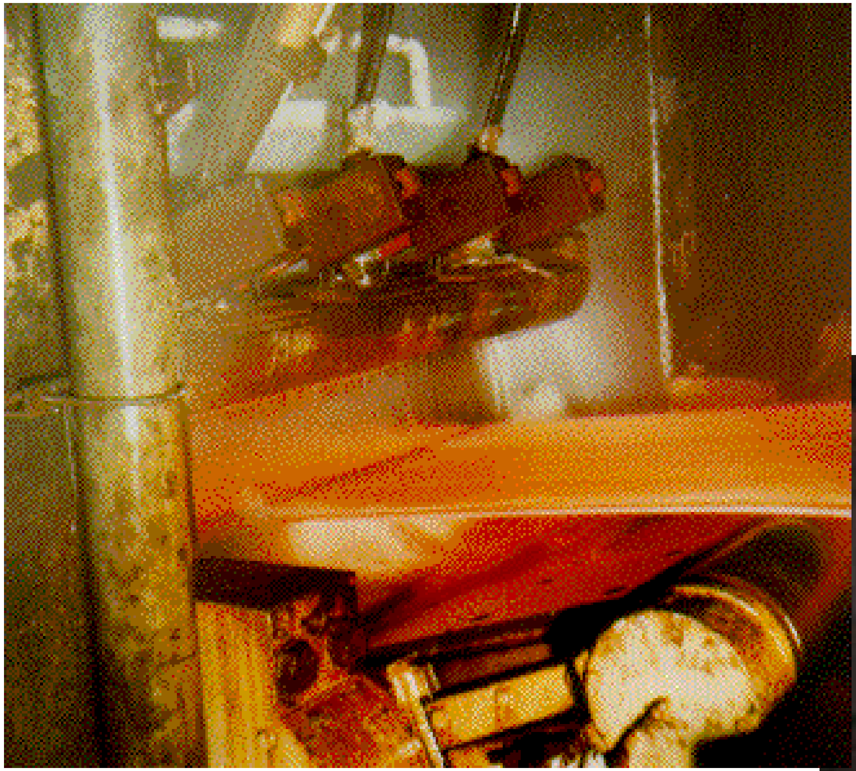
ver. 1

Prof. Ramesh Singh, Notes by Dr. Singh/ Dr. Colton

Overview

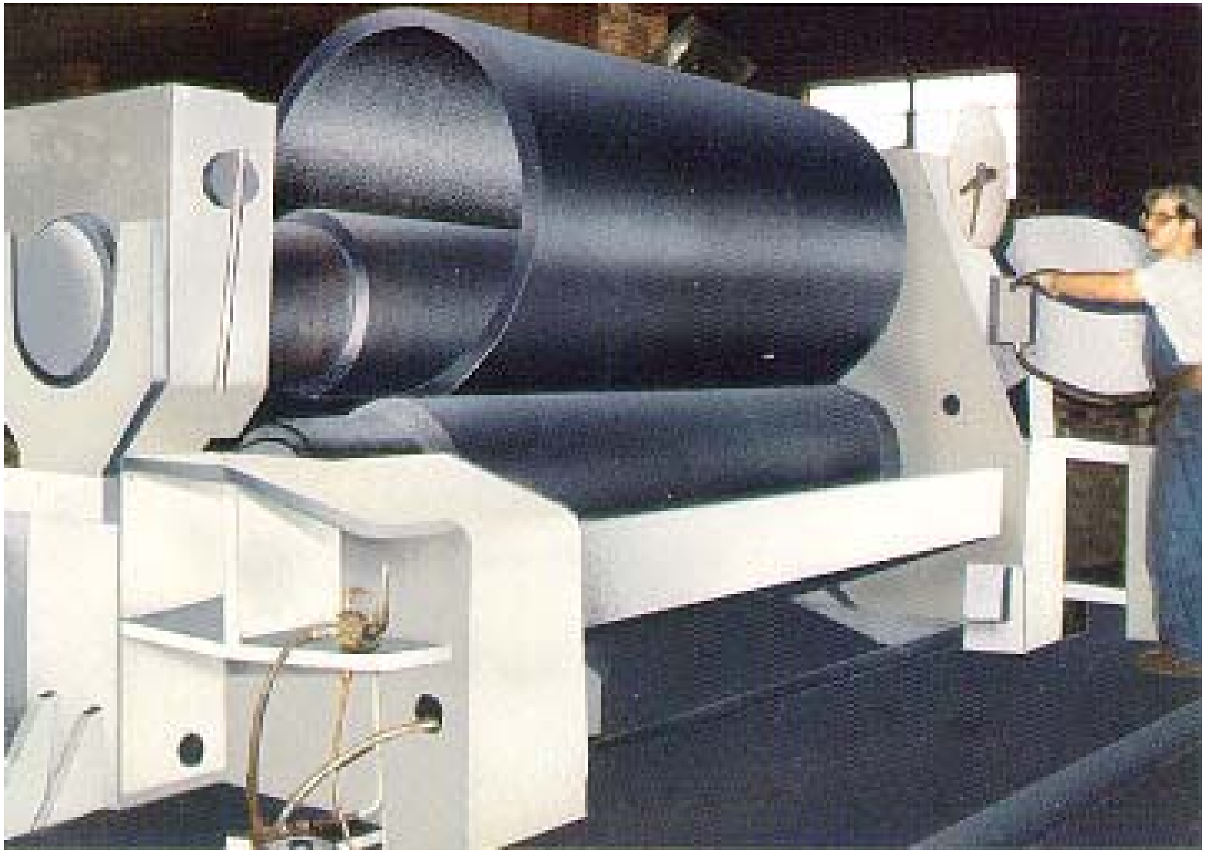
- Process
- Equipment
- Products
- Mechanical Analysis
- Defects

Process



Process

Process



Ring Rolling

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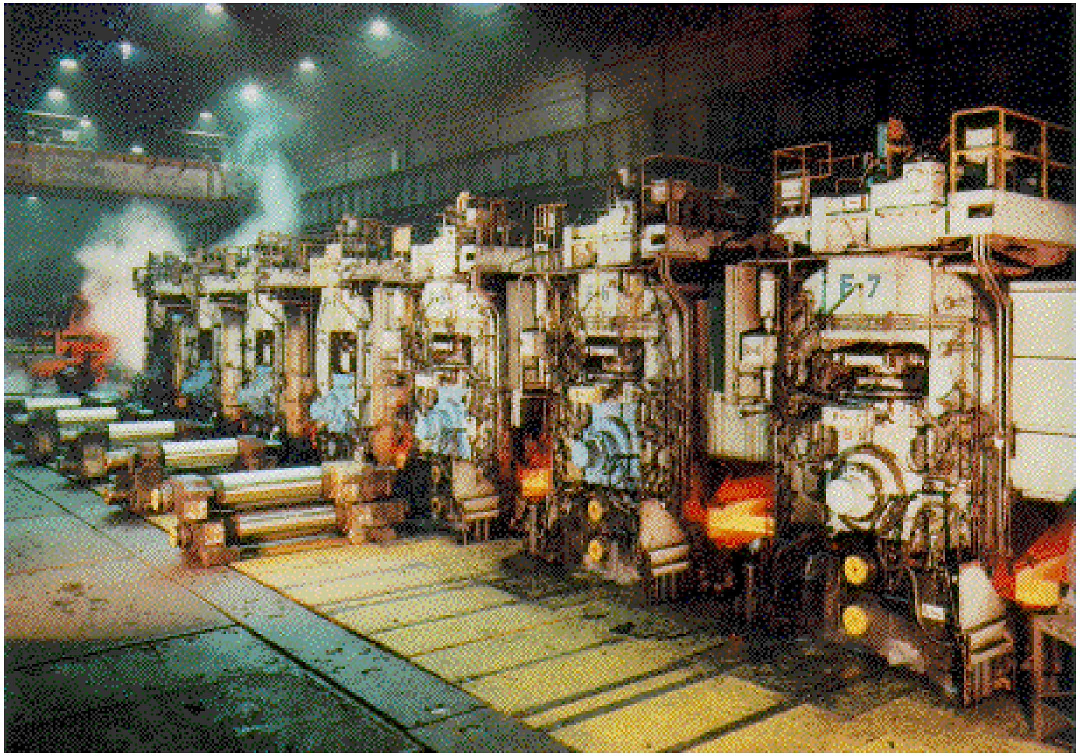
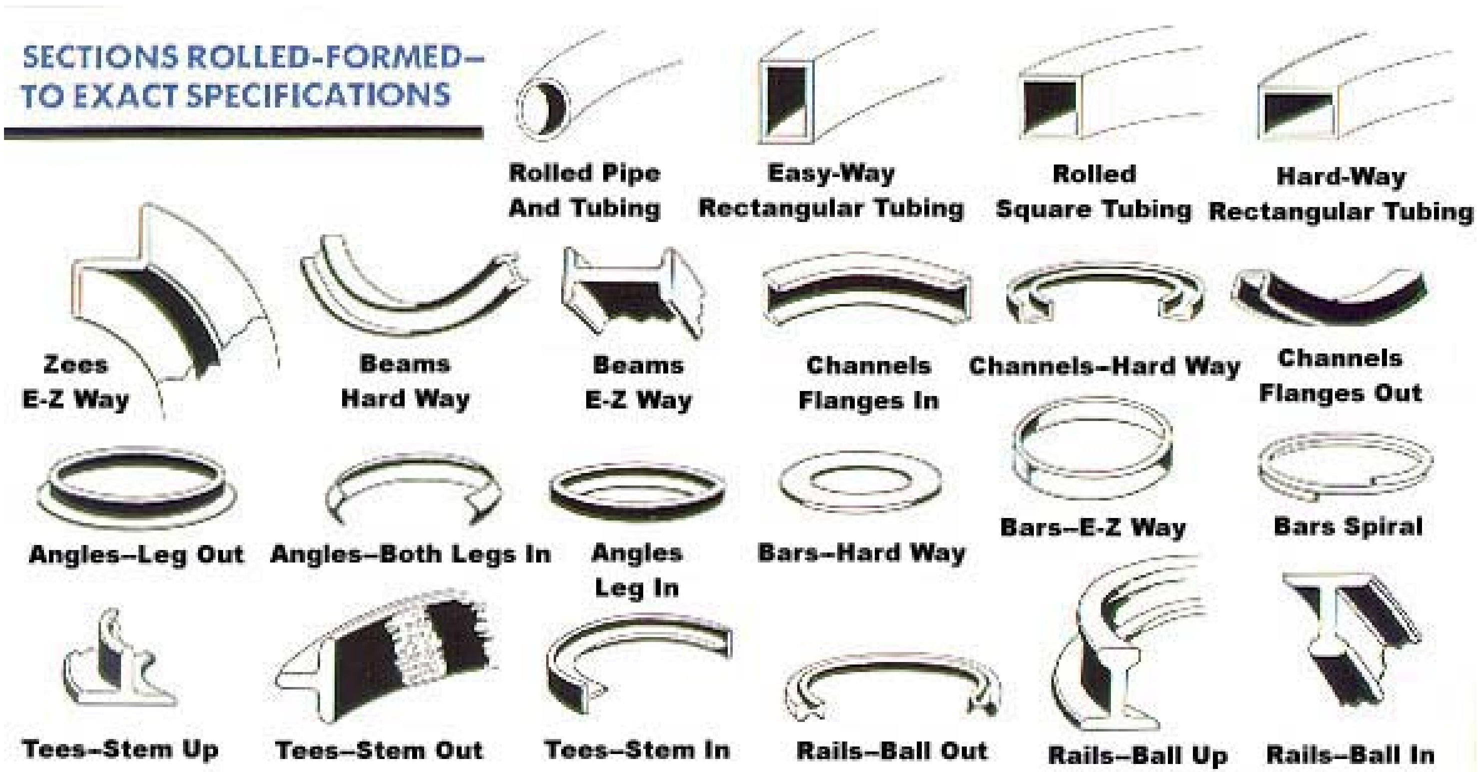
Equipment

Equipment



Products


SECTIONS ROLLED-FORMED–
TO EXACT SPECIFICATIONS
Rolled Pipe
And Tubing
Easy-Way
Rectangular Tubing
Rolled
Square Tubing
Hard-Way
Rectangular Tubing
Zees
E-Z Way
Beams
Hard Way
Beams
E-Z Way
Channels
Flanges In
Channels–Hard Way
Channels
Flanges Out
Angles–Leg Out
Angles–Both Legs In
Angles
Leg In
Bars–Hard Way
Bars–E-Z Way
Bars Spiral
Tees–Stem Up
Tees–Stem Out
Tees–Stem In
Rails–Ball Out
Rails–Ball Up
Rails–Ball In

Products

- Shapes
  - I-beams, railroad tracks
- Sections
  - door frames, gutters
- Flat plates
- Rings
- Screws

Products

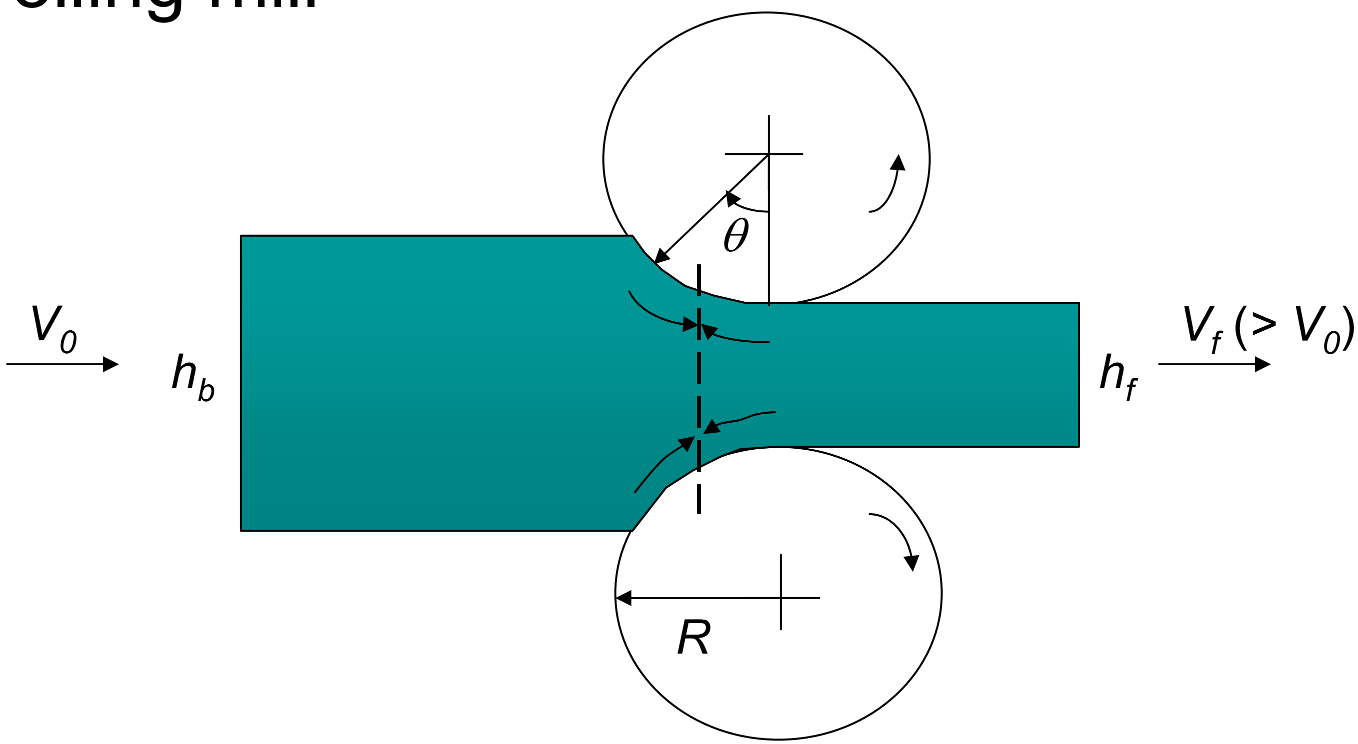
- A greater volume of metal is rolled than processed by any other means.

Rolling Analysis

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

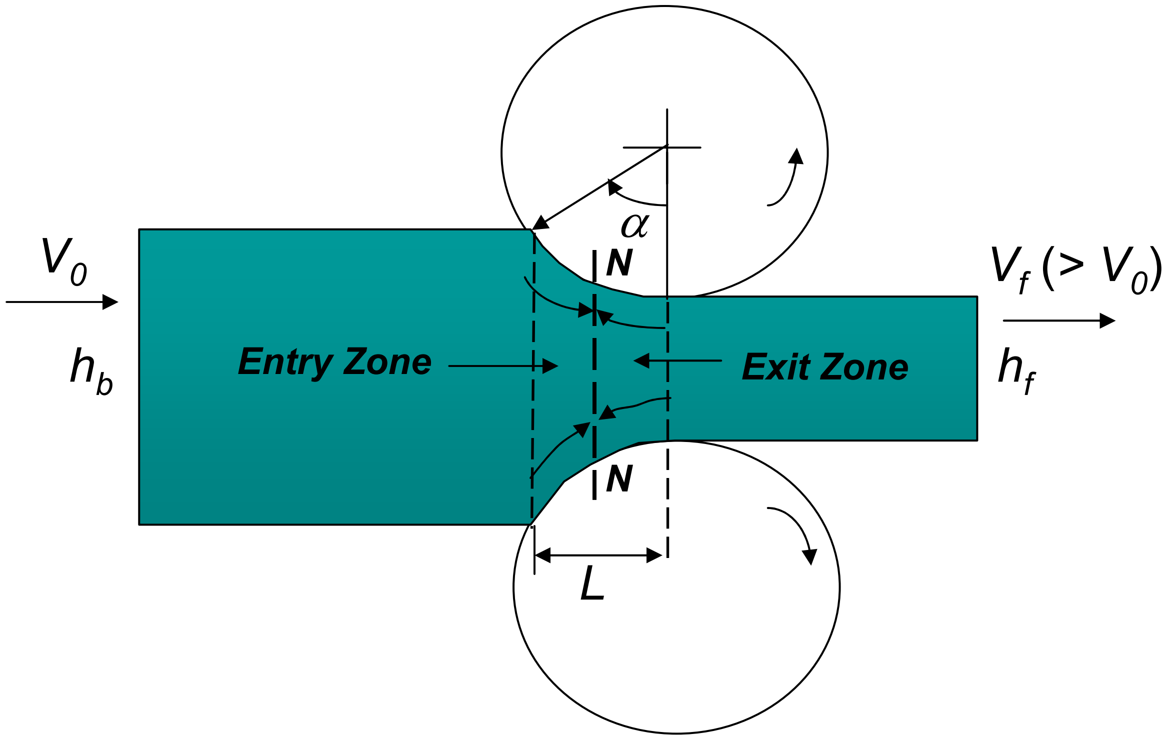
Flat Rolling Analysis

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



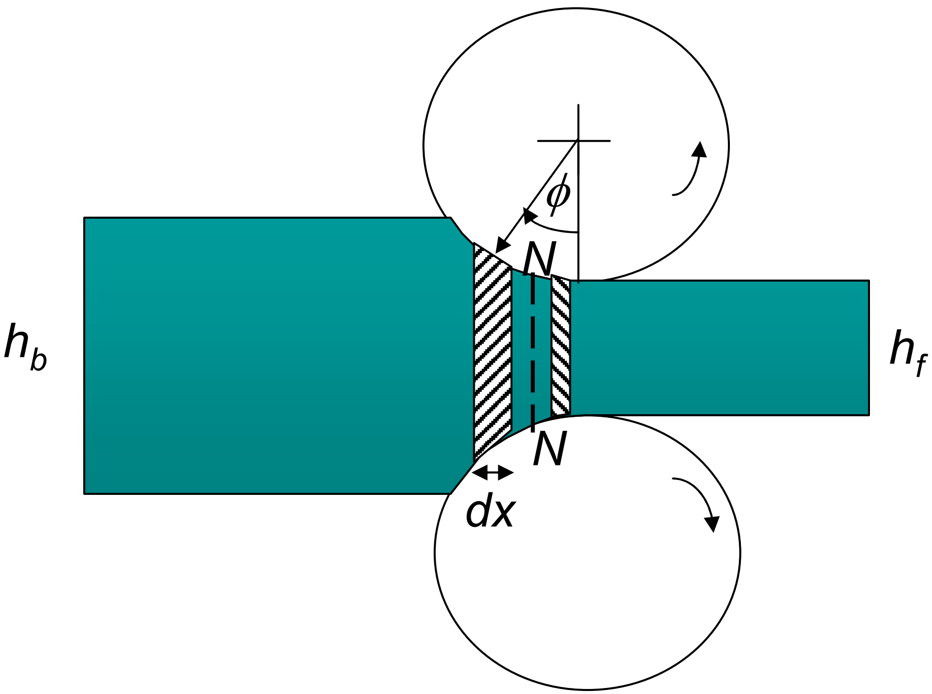
Width of plate w is large → plane strain

Flat Rolling Analysis

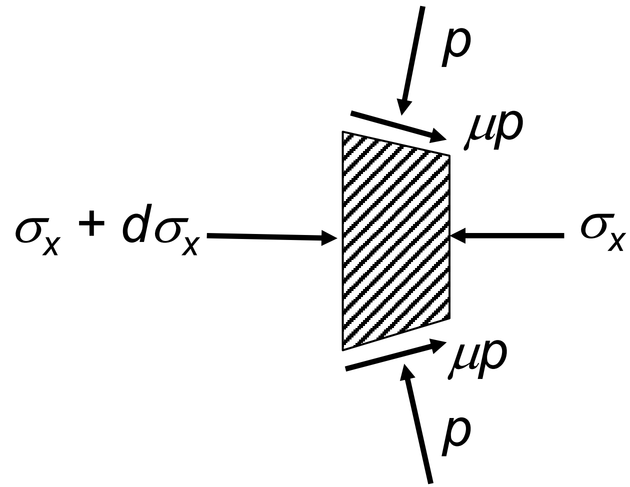


- Friction plays a critical role in enabling rolling → cannot roll without friction; for rolling to occur $\mu \geq \tan \alpha$
- Reversal of frictional forces at neutral plane (*NN*)

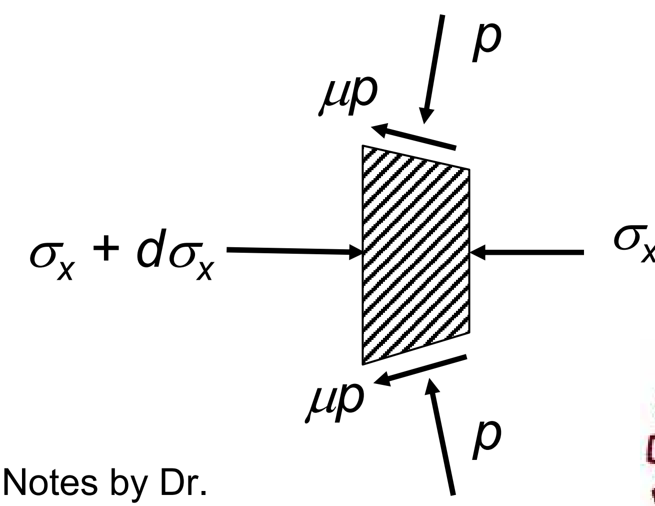
Flat Rolling Analysis



Stresses on Slab in Entry Zone



Stresses on Slab in Exit Zone



Equilibrium

- Appling equilibrium in x (top entry, bottom exit)

$$(\sigma_x + d\sigma_x)\cdot(h+dh) - 2pR\cdot d\phi\cdot\sin\phi \pm 2\mu pR\cdot d\phi\cdot\cos\phi - \sigma_x h = 0$$

Simplifying and ignoring HOTs

$$\frac{d(\sigma_x h)}{d\phi} = 2pR\cdot(\sin\phi \mp \mu\cos\phi)$$

Simplifying

- Since $\alpha << 1$, then $\sin\phi = \phi$, $\cos\phi = 1$

$$\frac{d(\sigma_x h)}{d\phi} = 2pR \cdot (\phi \mp \mu)$$

- Plane strain, von Mises

$$p - \sigma_x = 1.15 \cdot Y_{flow} \equiv Y'_{flow}$$

Differentiating

- Substituting

$$\frac{d\left[\left(p - Y'_{flow}\right)\cdot h\right]}{d\phi} = 2pR\cdot\left(\phi \mp \mu\right)$$

- or

$$\frac{d}{d\phi}\left[Y'_{flow}\cdot\left(\frac{p}{Y'_{flow}} - 1\right)\cdot h\right] = 2pR\cdot\left(\phi \mp \mu\right)$$

Differentiating

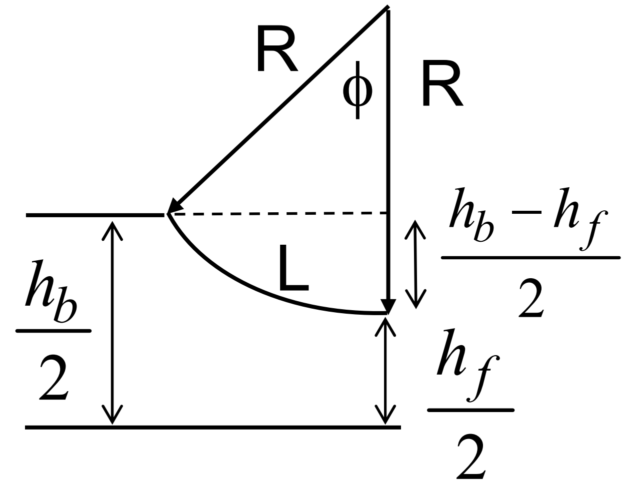
$$Y'_{flow} \cdot h \cdot \frac{d}{d\phi}\left(\frac{p}{Y'_{flow}}\right) + \left(\frac{p}{Y'_{flow}} - 1\right) \cdot \frac{d}{d\phi}\left(Y'_{flow} \cdot h\right) = 2pR \cdot (\phi \mp \mu)$$

Rearranging, the variation $Y'_{flow}.h$ with respect to ϕ is small compared to the variation p/ Y'_{flow} with respect to ϕ so the second term is ignored

$$\frac{\dfrac{d}{d\phi}\left(\dfrac{p}{Y'_{flow}}\right)}{\dfrac{p}{Y'_{flow}}} = \frac{2R}{h}(\phi \mp \mu)$$

Thickness

$$h = h_f + 2R \cdot (1 - \cos\phi)$$



from the definition
of a circular segment

or, after using a Taylor's series expansion, for small ϕ

$$\cos\phi = 1 - \frac{\phi^2}{2!} + \cancelto{0}{\frac{\phi^4}{4!}} \cdots$$

$$h = h_f + R \cdot \phi^2$$

Substituting and integrating

$$\int \frac{d\left(\dfrac{p}{Y'_{flow}}\right)}{\dfrac{p}{Y'_{flow}}} = \int \frac{2R}{h_f + R\cdot\phi^2}(\phi \mp \mu)\cdot d\phi$$

In[1]:= $\int \frac{2\,R\,(\phi - \mu)}{hf + R\,\phi^2}\,d\phi$

Out[1]= $2\,R\left(-\frac{\mu\,\mathrm{ArcTan}\left[\frac{\sqrt{R}\,\phi}{\sqrt{hf}}\right]}{\sqrt{hf}\,\sqrt{R}} + \frac{\mathrm{Log}\left[hf + R\,\phi^2\right]}{2\,R}\right)$

$$\ln\frac{p}{Y'_f} = \ln\frac{h}{R} \mp 2\mu\sqrt{\frac{R}{h_f}}\tan^{-1}\left(\phi\sqrt{\frac{R}{h_f}}\right) + \ln C$$

Eliminating *ln()*

$$p = C \cdot Y'_{flow} \cdot \frac{h}{R} \exp\left(\mp \mu H\right)$$

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

Entry region

- at $\phi = \alpha$, $H = H_b$,

$$p = C \cdot Y'_{flow} \cdot \frac{h}{R} \exp(-\mu H)$$

$$C = \frac{R}{h_b} \exp(\mu H_b)$$

$$p = Y'_{flow} \frac{h}{h_b} \exp(\mu [H_b - H])$$

$$p = (Y'_{flow} - \sigma_{xb}) \frac{h}{h_b} \exp(\mu [H_b - H])$$

With back tension=(Y'flow – σ_{xb})

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

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

Exit region

at $\phi = 0$, $H = H_f = 0$,

$$C = \frac{R}{h_f}$$

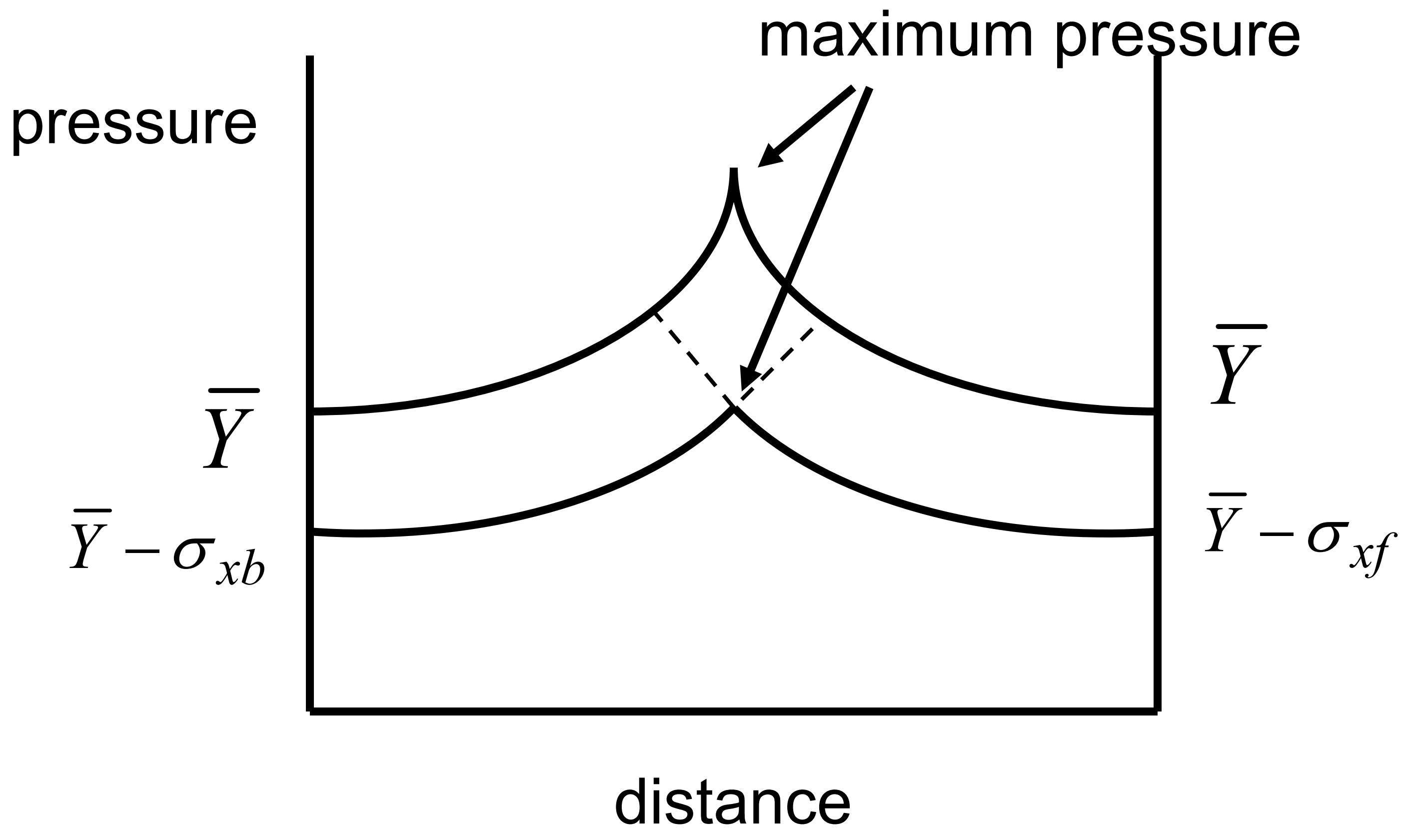
$$p = \left(Y'_{flow}\right)\frac{h}{h_f}\exp\left(\mu H\right)$$

$$p = \left(Y'_{flow} - \sigma_{xf}\right)\frac{h}{h_f}\exp\left(\mu H\right)$$

With forward tension

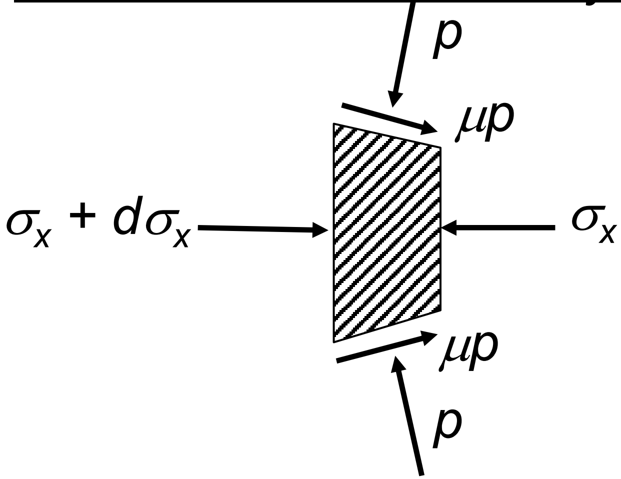
$$H = 2\sqrt{\frac{R}{h_f}}\tan^{-1}\left(\phi\sqrt{\frac{R}{h_f}}\right)$$

Effect of back and front tension

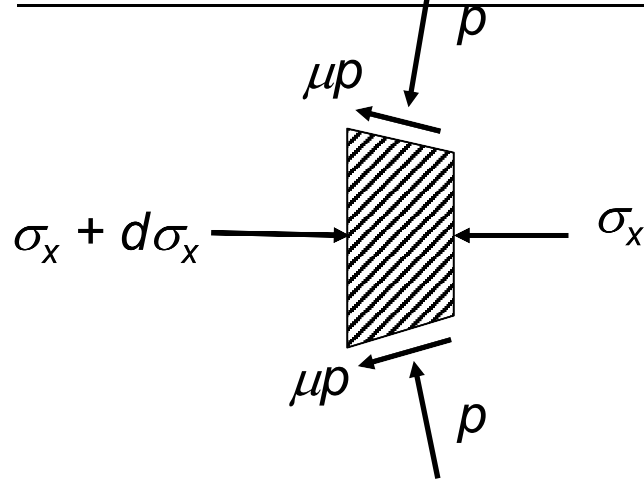


Flat Rolling Analysis Results – without front and back tension

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: h_0 and h_b are the same thing

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

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

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

Entry Zone

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

Exit Zone

Average rolling pressure – per unit width

$$p_{ave,entry} = -\frac{1}{R(\alpha-\phi_n)}\int_{\alpha}^{\phi_n} p_{entry} R d\phi; \quad p_{ave,exit} = \frac{1}{R\phi_n}\int_{0}^{\phi_n} p_{exit} R d\phi$$

Rolling force

- $F = p_{ave,entry} \times Area_{entry} + p_{ave,exit} \times Area_{exit}$

Force

- An alternative method

$$F = \int_{\phi_n}^{\alpha} w \cdot p_{entry} \cdot R \cdot d\phi + \int_{0}^{\phi_n} w \cdot p_{exit} \cdot R \cdot d\phi$$

- again, very difficult to do.

Force - approximation

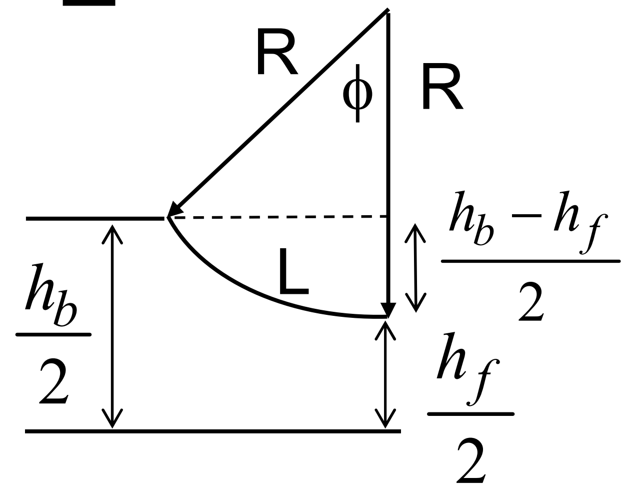
F / roller = L w p_{ave}

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

$\Delta h = h_b - h_f$

$$p_{ave} = f\left(\frac{h_{ave}}{L}\right)$$

Derivation of “L”



circular segment

$$h = h_f + 2R \cdot (1 - \cos\phi)$$

Taylor’s expansion

$$\cos\phi = 1 - \frac{\phi^2}{2!} + \cancelto{0}{\frac{\phi^4}{4!}} \cdots$$

$$h = h_f + R \cdot \phi^2$$

$$R \cdot \phi = L$$

Derivation of “L”

setting h = h_b at $\phi = \alpha$, substituting, and rearranging

$$h_b - h_f = \Delta h = R \cdot \left(\frac{L}{R} \right)^2$$

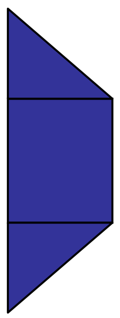
or

$$L = \sqrt{R \cdot \Delta h}$$

Approximation based on forging plane strain – von Mises

$$p_{ave} = 1.15 \cdot \overline{Y}_{flow} \left(1 + \frac{\mu L}{2 h_{ave}} \right)$$

average flow stress:
due to shape of element



Small rolls or small reductions

$$\Delta = \frac{h_{ave}}{L} >> 1$$

- friction is not significant (μ -> 0)

$$p_{ave} = 1.15 \cdot \overline{Y}_{flow} \left(1 + \cancelto{0}{\frac{\mu L}{2h_{ave}}} \right)$$

$$p_{ave} = 1.15 \cdot \overline{Y}_{flow}$$

Large rolls or large reductions

$$\Delta \equiv \frac{h_{ave}}{L} << 1$$

- Friction is significant (forging approximation)

$$p_{ave} = 1.15 \cdot \overline{Y}_{flow} \left(1 + \frac{\mu L}{2h_{ave}} \right)$$

Force approximation: low friction

$$\Delta \equiv \frac{h_{ave}}{L} >> 1$$

$$F/_{roller} = 1.15 \cdot Lw\overline{Y}_{flow}$$

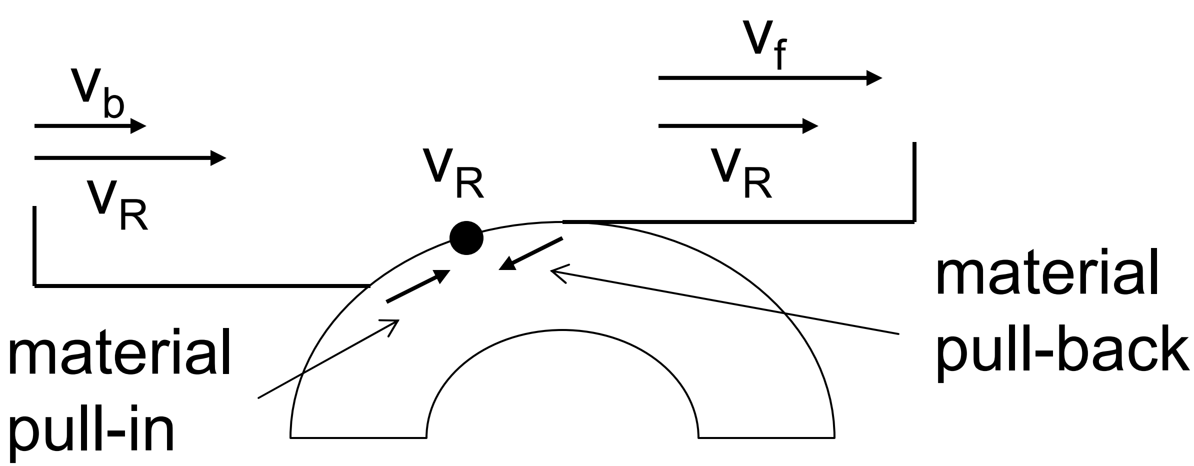
Force approximation: high friction

$$\Delta \equiv \frac{h_{ave}}{L} << 1$$

$$F/_{roller} = 1.15 \cdot Lw\bar{Y}_{flow}\left(1 + \frac{\mu L}{2h_{ave}}\right)$$

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.

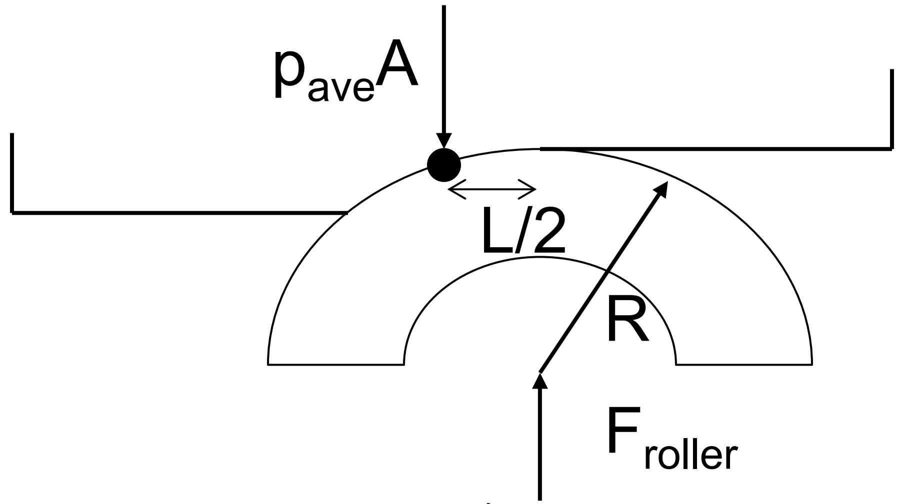
$$\frac{h_b}{h_f} = \frac{\exp(\mu H_b)}{\exp(2\mu H_n)} = \exp(\mu(H_b - 2H_n))$$

Neutral point

$$H_n = \frac{1}{2}\left(H_b - \frac{1}{\mu} \ln \frac{h_b}{h_f} \right)$$

$$\phi_n = \sqrt{\frac{h_f}{R}} \tan\left(\frac{H_n}{2} \sqrt{\frac{h_f}{R}} \right)$$

Torque



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

$\Delta h = h_b - h_f$

$$\sum F_y = 0$$

$$\therefore F_{roller} = p_{ave}A$$

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

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

Power

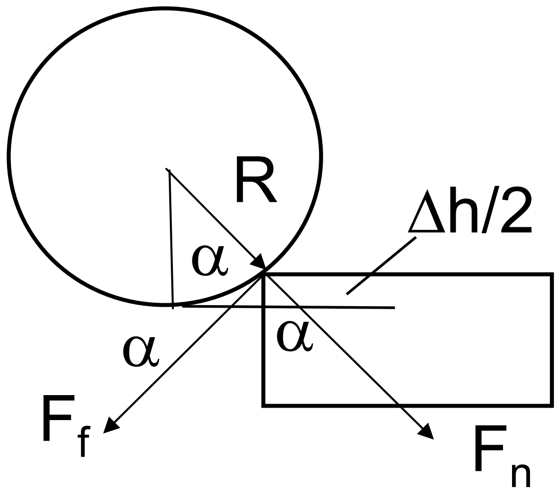
Power / roller = $T\omega$ = $F_{roller}L\omega / 2$

$\omega = 2\pi N$

N = [rev/min]

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 $\Delta h << R$

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

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

$$\sin\alpha \approx \sqrt{\frac{\Delta h}{R}}$$

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

Processing limits

So, approximately

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

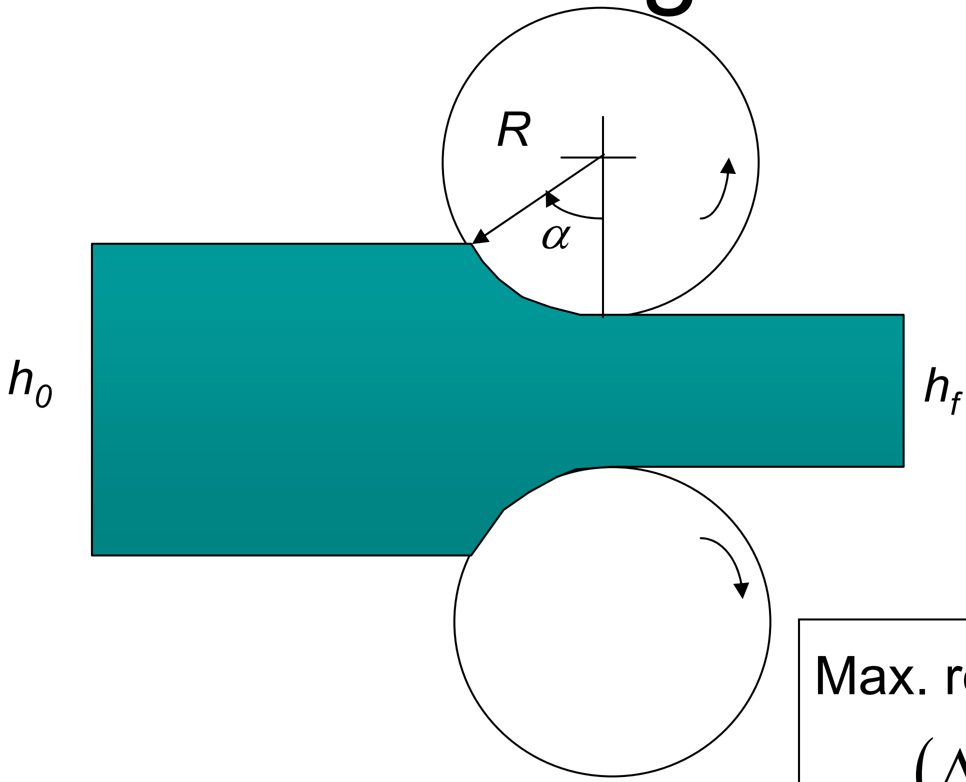
Hence, maximum draft

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

Maximum angle of acceptance

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

Processing Limits



Max. reduction in thickness

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

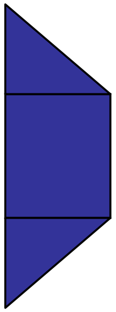
Max. angle of acceptance

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

Cold rolling
(below recrystallization point) strain hardening, plane strain – von Mises

$$2\tau_{flow} = 1.15 \cdot \overline{Y}_{flow} = 1.15 \cdot \frac{K\varepsilon^{n}}{n+1}$$

average flow stress:
due to shape of element

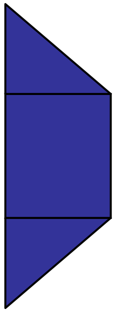


Hot rolling – (above recrystallization point) strain rate effect, plane strain - von Mises

- Average strain rate

$$\dot{\varepsilon} = \frac{\bar{\varepsilon}}{t} = \frac{V_R}{L} \ln\left(\frac{h_b}{h_f}\right)$$

$$2\tau_{flow} = 1.15 \cdot \bar{Y}_{flow} = 1.15 \cdot C \cdot \dot{\bar{\varepsilon}}^{m}$$



average flow stress:
due to shape of element

Example 1.1

- Cold roll a 5% Sn-bronze

- Calculate force on roller
- Calculate power
- Plot pressure in nip (no back or forward tension)

Example 1.2

- $w = 10$ mm
- $h_b = 2$ mm
- height reduction = 30% ($h_f = 0.7\ h_b$)
  - $h_f = 1.4$ mm
- $R = 75$ mm
- $v_R = 0.8$ m/s
- mineral oil lubricant ($\mu = 0.1$)
- $K = 720$ MPa, $n = 0.46$

Example 1.3

- Maximum draft:

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

$$= (0.1)^2 \cdot 75 = 0.75 \text{ mm}$$

$$\Delta h_{actual} = h_b - h_f = 2 - 1.4$$

$$= 0.6 \text{ mm}$$

Example 1.4

- Maximum angle of acceptance

ϕ_{max} = tan^{-1} μ = tan^{-1}(0.1) = 0.1 radian

$$\alpha = \sqrt{(h_b - h_f)/R} = \sqrt{(2-1.4)/75}$$

$$= 0.089 \; rad = 5.12^{\circ}$$

Example 1.5

- Roller force: $F = L\ w\ p_{ave}$
- $L = (R\Delta h)^{0.5} = [75 \times (2-1.4)]^{0.5}$

  $= 6.7$ mm
- w = 10 mm
- $h_{ave} = (h_b+h_f) / 2 = 1.7$ mm

  $h_{ave} / L = 1.7 / 6.7 = 0.25 < 1$

  $\therefore$ friction is important

$$F/_{roller} = 1.15 \cdot Lw\overline{Y}_{flow}\left(1+\frac{\mu L}{2h_{ave}}\right)$$

Example 1.6

$$\varepsilon_f = \left|\ln\left(\frac{h_f}{h_b}\right)\right| = \left|\ln\left(\frac{1.4}{2}\right)\right| = 0.36$$

$$2\tau_{flow} = 1.15 \cdot \overline{Y} = 1.15 \cdot \frac{K\varepsilon_f^n}{n+1}$$

$$= 1.15 \cdot \frac{720 \cdot (0.36)^{0.46}}{1.46} = 354\ MPa$$

Example 1.7

$$F/_{roller} = 1.15 \cdot Lw\overline{Y}_{flow}\left(1 + \frac{\mu L}{2h_{ave}}\right)$$

$$= 6.7\times10^{-3} \cdot 10\times10^{-3} \cdot 354\times10^{6}$$

$$\times\left(1 + \frac{0.1\times6.7}{2\times1.7}\right)$$

$$= 28{,}392\ N = 3.2\ \ tons$$

Example 1.8

$$Power\ (kW)\Big/_{roller} = T \times \omega = \frac{F \cdot L \cdot V_R}{2 \cdot R}$$

$$Power\ (kW)/\ roll = \frac{28{,}392 \cdot 6.7 \times 10^{-3} \cdot 0.8}{2 \cdot 0.075}$$

$$= 1.01\, kW\ /\ roll = 1.35\, hp$$

Example 1.9

- Entrance

$$p = \left(Y'_{flow} - \sigma_{xb}\right)\frac{h}{h_b}\exp\left(\mu\left(H_b - H\right)\right)$$

- Exit

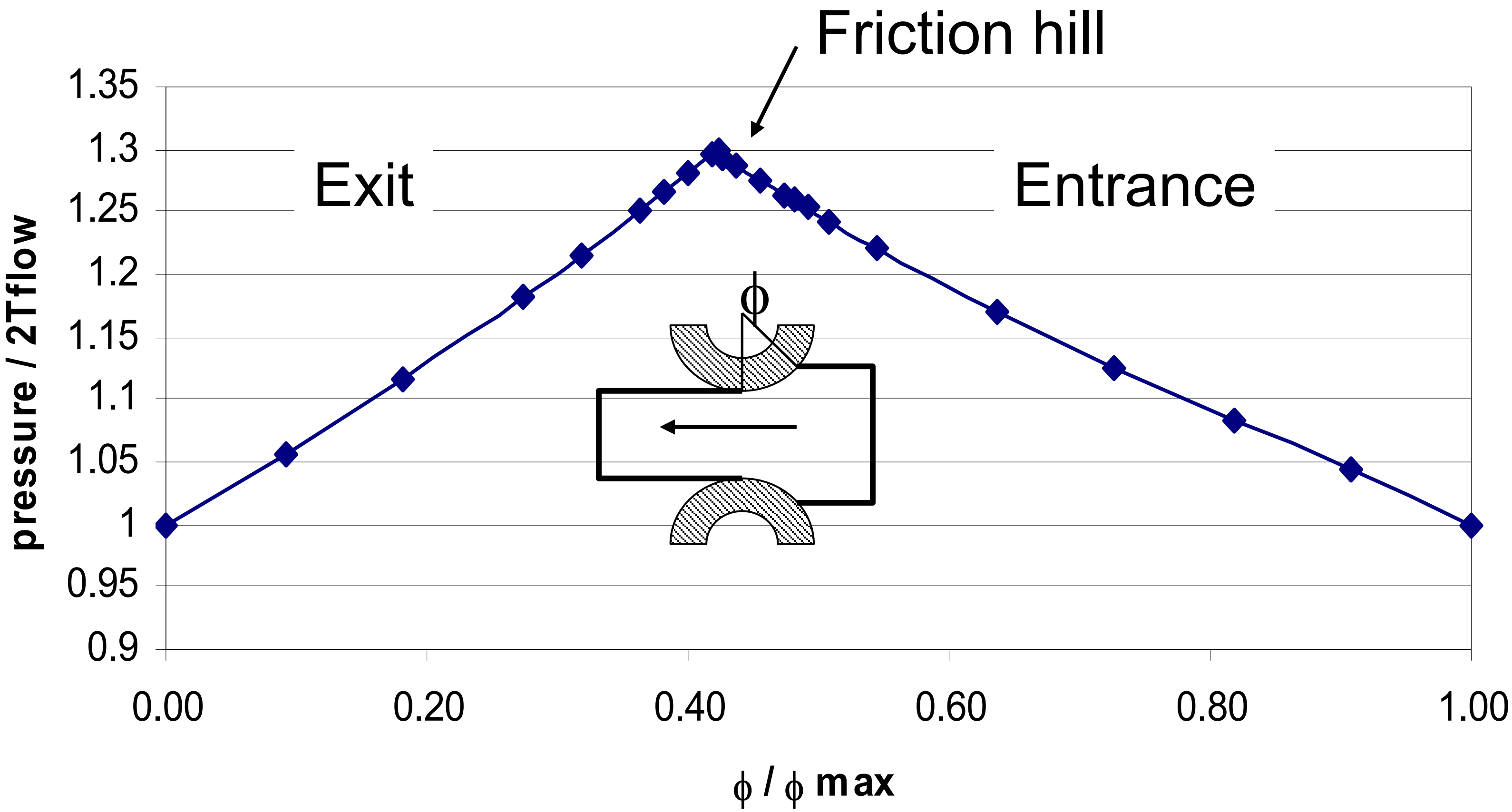
$$p = \left(Y'_{flow} - \sigma_{xf}\right)\frac{h}{h_f}\exp\left(\mu\left(H\right)\right)$$

Example 1.10

$$\phi = \sqrt{\left(h - h_f\right) / R}$$

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

Example 1.11



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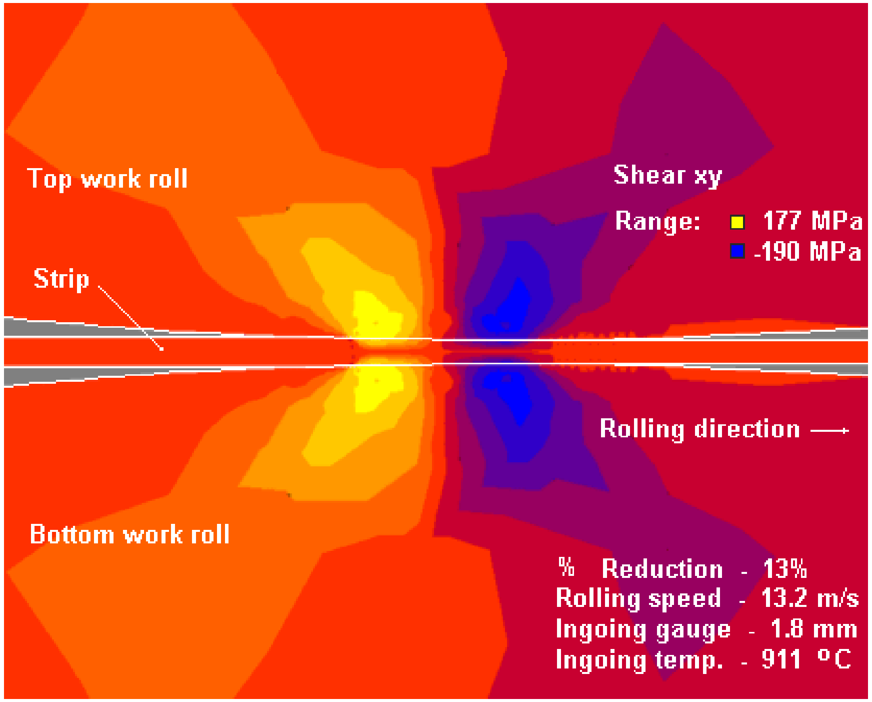
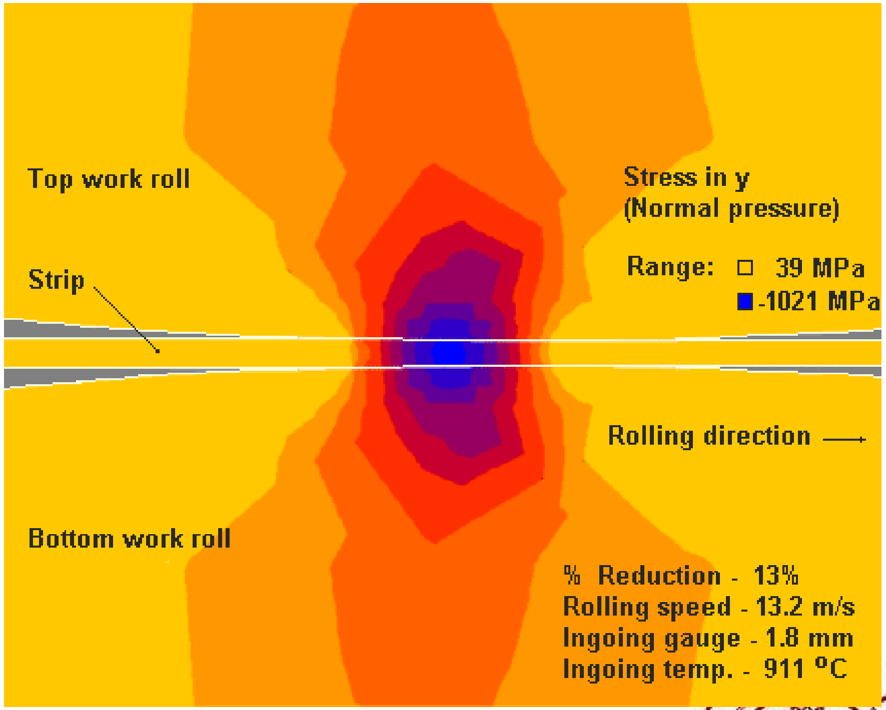
Rolling

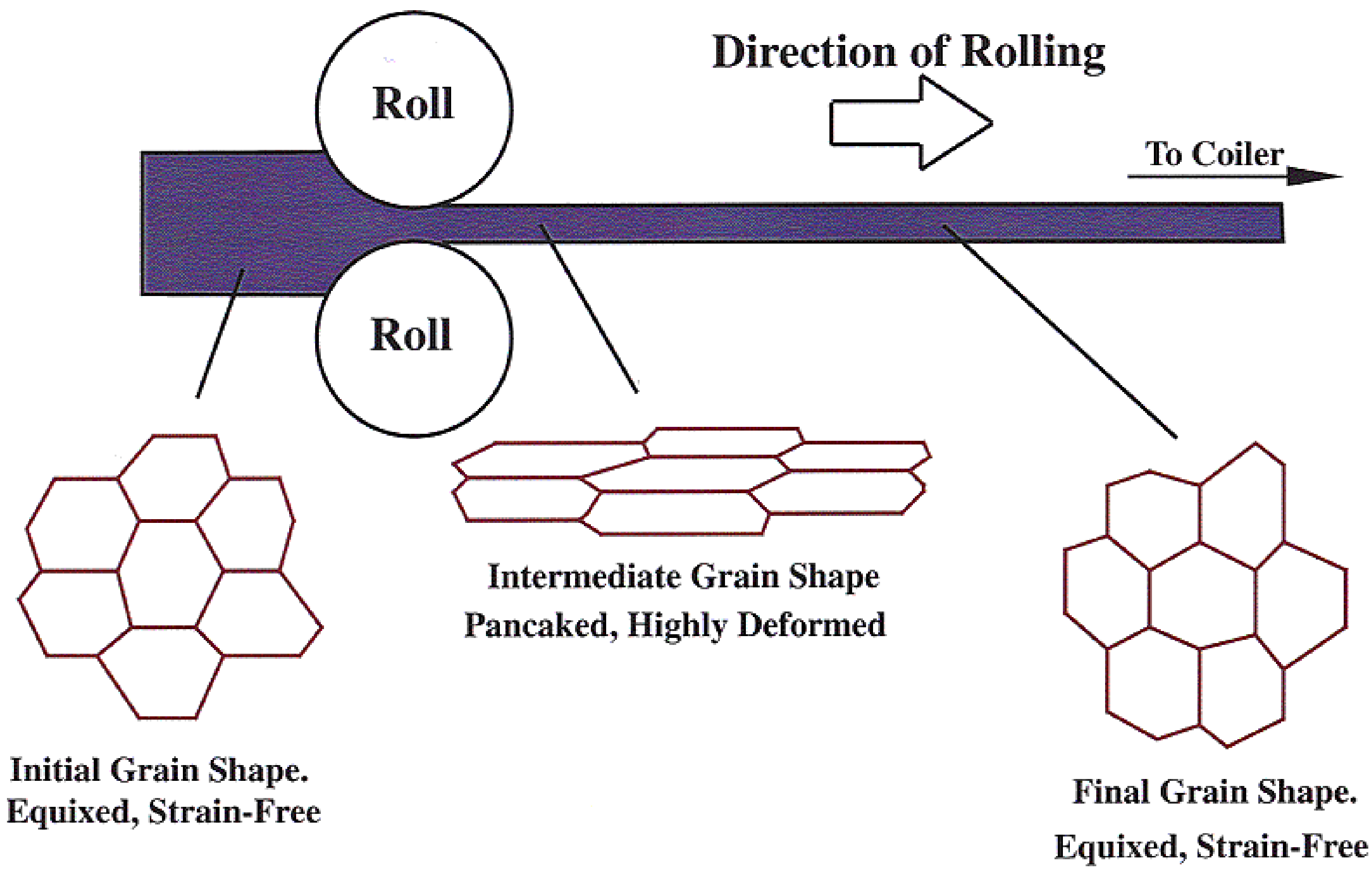


Shear stress

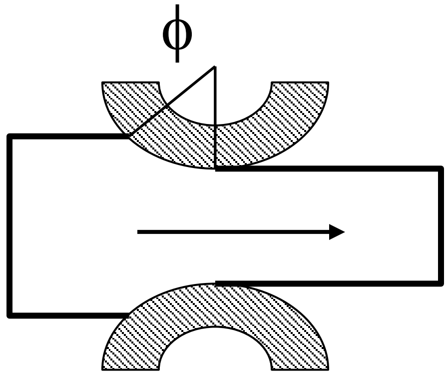
Normal Stress



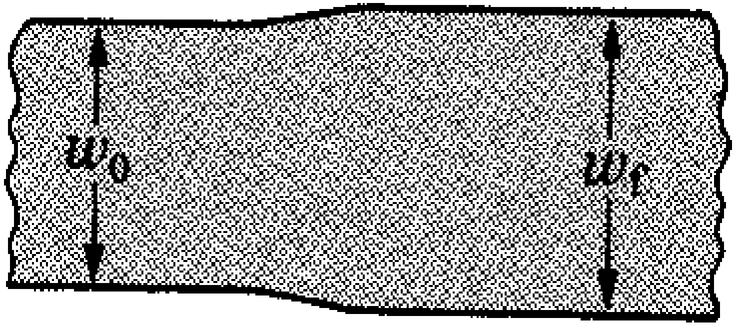
EFFECT OF FINISH HOT-ROLLING ON THE STRIP SHAPE AND THE AUSTENITE GRAIN STRUCTURE.



Widening of material



Side view

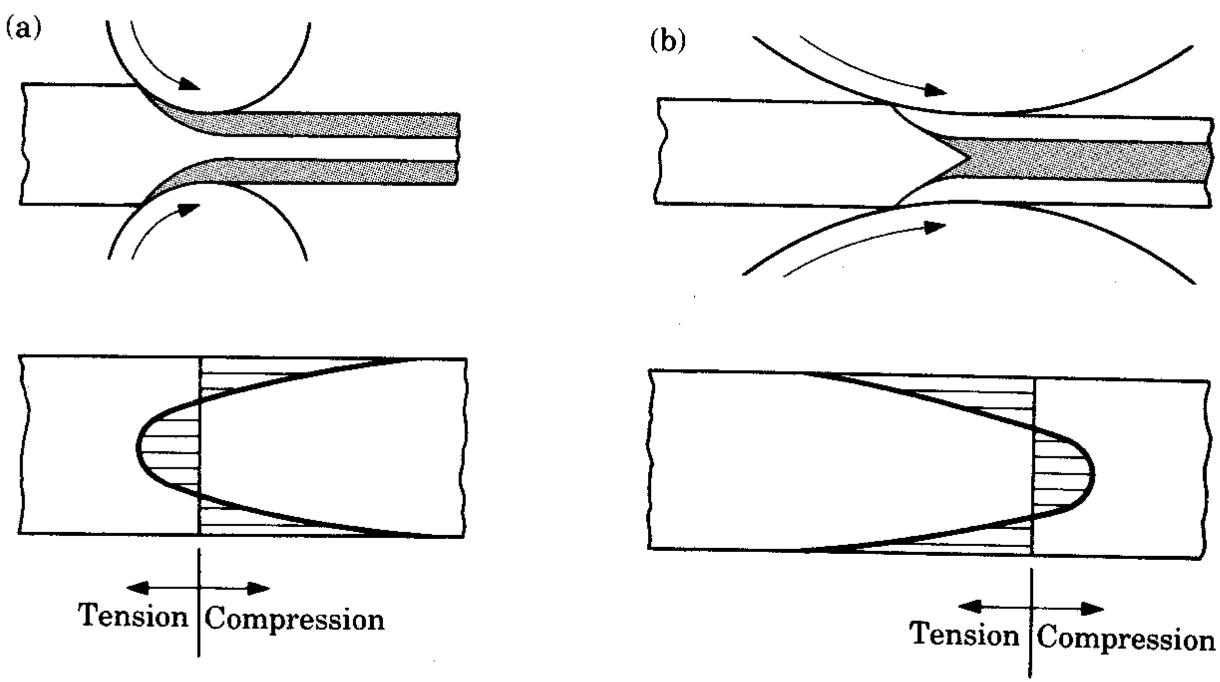


Top view

Residual stresses - due to frictional constraints

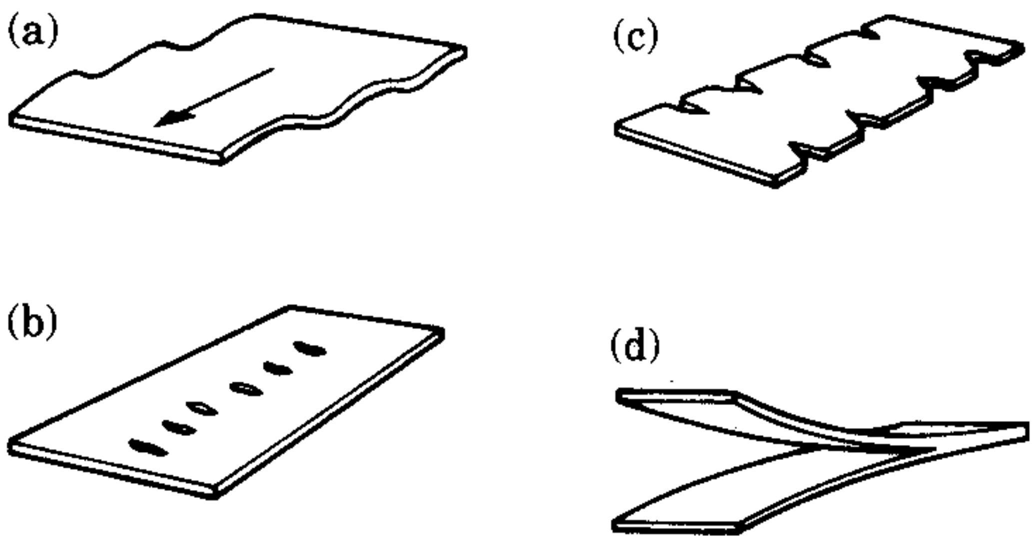
a) small rolls or small reduction (ignore friction)

b) large rolls or large reduction (include friction)



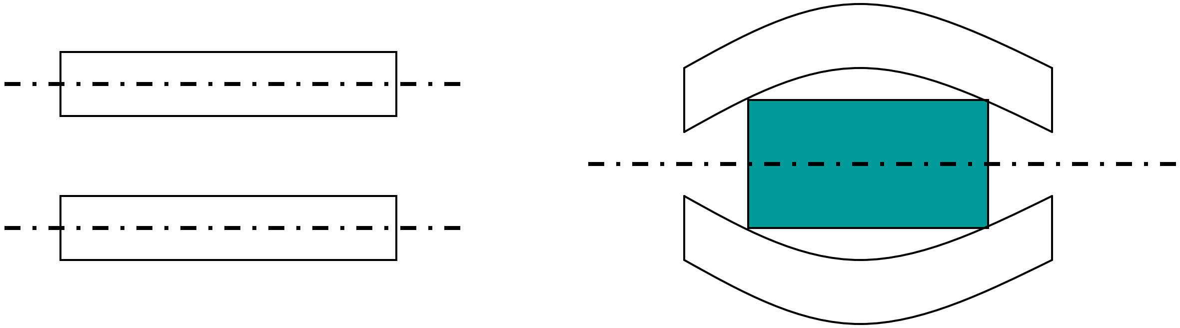
Defects

- a) wavy edges
  - roll deflection
- b) zipper cracks
  - low ductility
- c) edge cracks
  - barreling
- d) alligatoring
  - piping, inhomogeniety

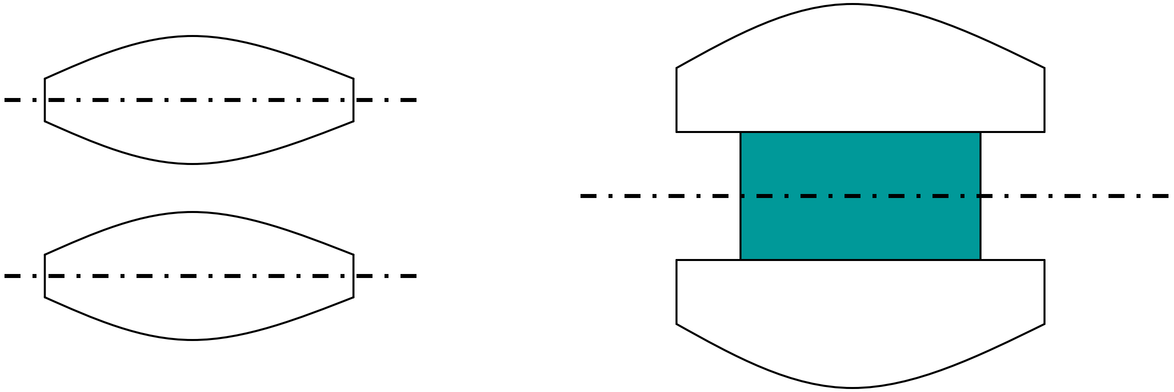


Roll deflection

Rolls can deflect under load

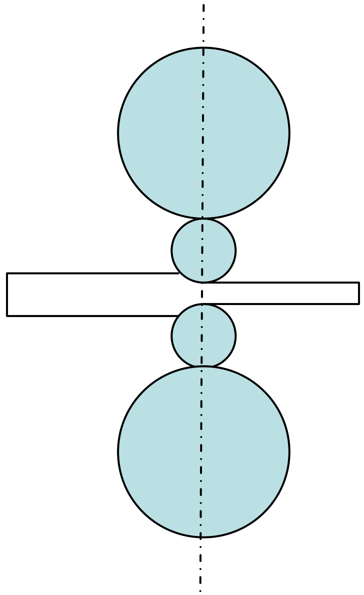


Rolls can be crowned

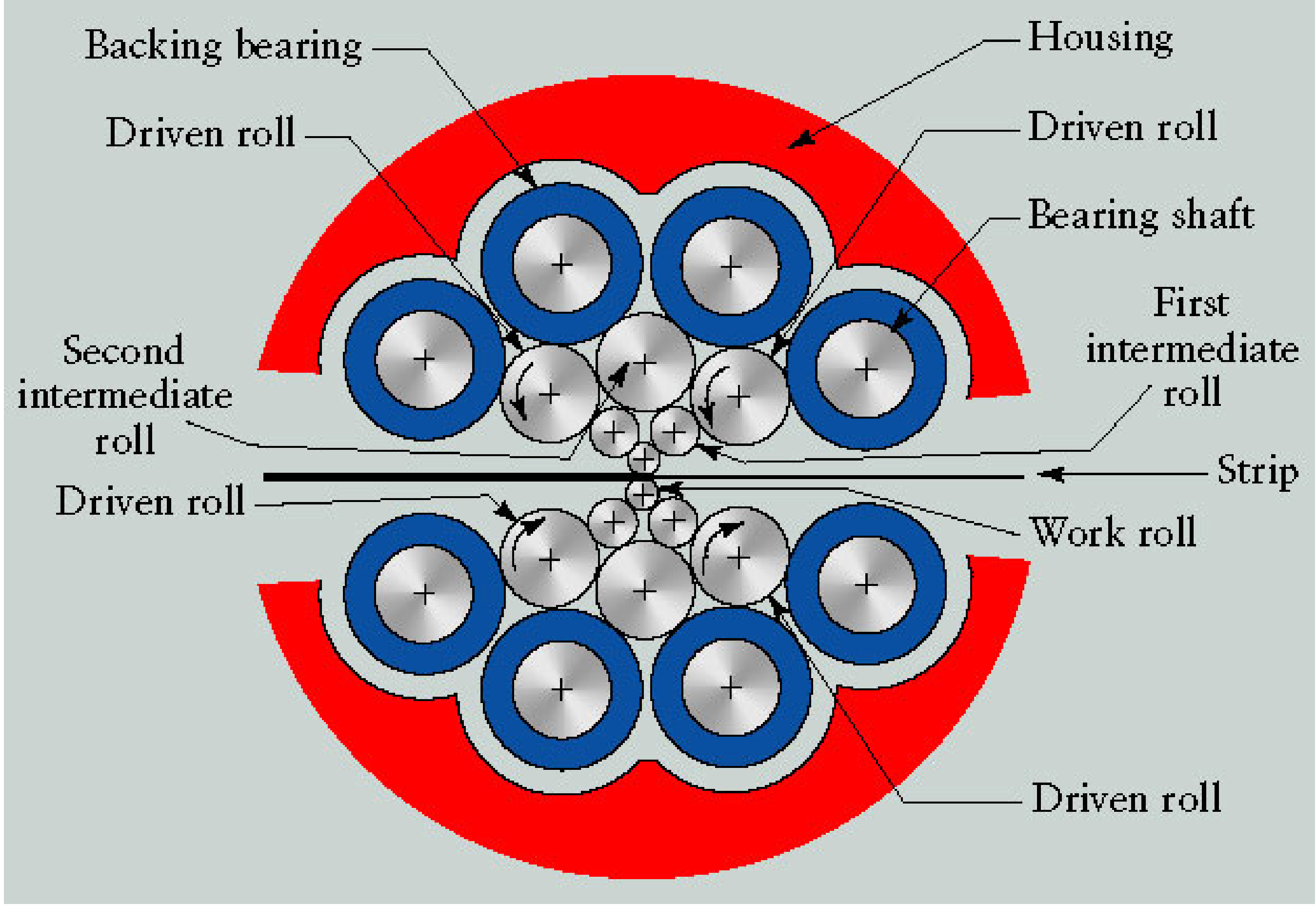


Roll deflection

Rolls can be stacked for stiffness



Method to reduce roll deflection



Summary

- Process
- Equipment
- Products
- Mechanical Analysis
- Defects