# *Outline*

- Flat Rolling
- Other Deformation Processes Related to Rolling
  – *Shape rolling, thread rolling, ring rolling*
- Rolling Mills Configurations
- Rolling Analysis – *Friction is insignificant*
- Design Exercise
- Force Approximation - *Friction is significant*



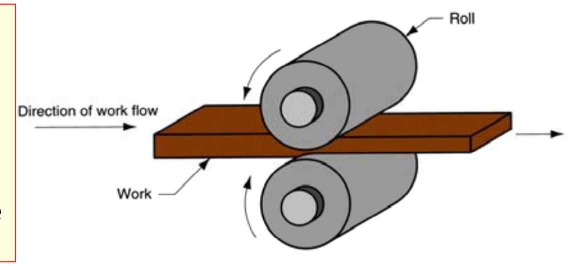
# Rolling

Deformation process in which work piece (slab or plate) thickness is reduced by compressive forces exerted by two opposing rolls

The rotating rolls perform two main functions:

• Pull the work into the gap between them by friction between workpart and rolls

• Simultaneously squeeze the work to reduce cross section




*The rolling process (specifically, flat rolling)*



# Types of Rolling

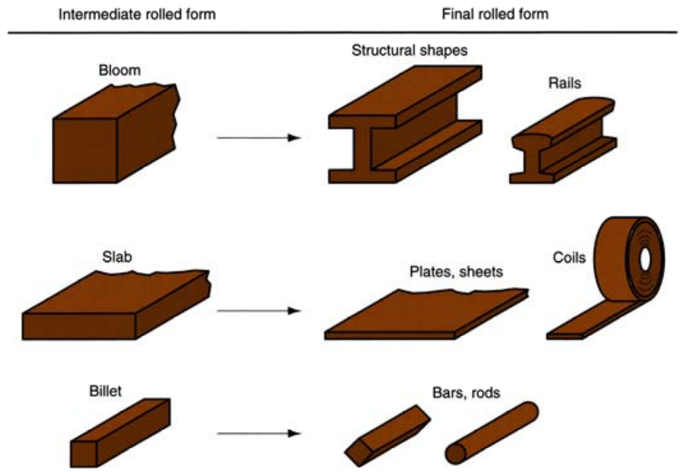
- By ........... of work:
  – *Flat rolling* - used to reduce thickness of a rectangular cross-section
  – *Shape rolling* - a square cross-section is formed into a shape such as an I-beam
- By .............. of work:
  – *Hot Rolling* – most common due to the large amount of deformation required
  – *Cold rolling* – produces finished sheet and plate stock



# Rolling Mills

A rolling mill for hot flat rolling; (*photo courtesy of Bethlehem Steel Company*)

Equipment is massive and expensive




*Some of the steel products made in a rolling mill*



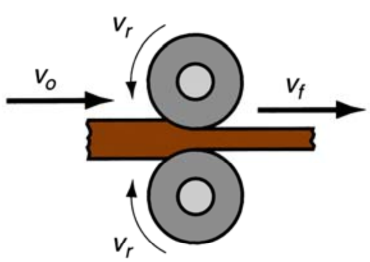
# Shape Rolling

Work is deformed into a contoured cross-section rather than flat (rectangular)

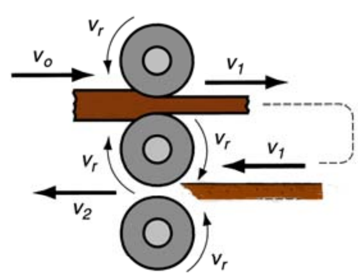
- Accomplished by passing work through rolls that have the reverse of desired shape
- Products include:
  - Construction shapes such as I-beams, L-beams, and U-channels
  - Rails for railroad tracks
  - Round and square bars and rods



# Rolling Mills Configurations



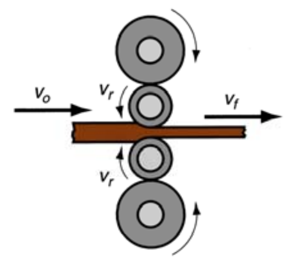

Two-high:
two opposing large diameter rolls




Three-high:
work passes through both directions

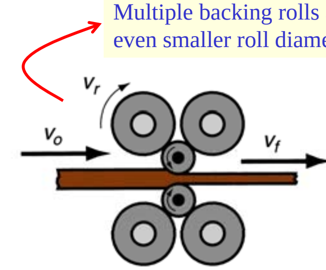


# Rolling Mills Configurations

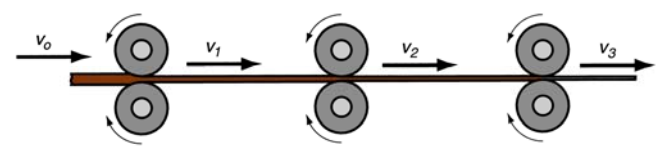



Four-high:
backing rolls support smaller work rolls

Multiple backing rolls allow even smaller roll diameters



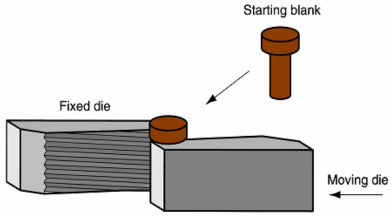

Cluster mill:
multiple backing rolls on smaller rolls



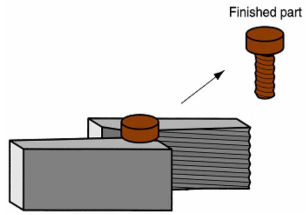

Tandem rolling mill: sequence of two-high mills

# Thread Rolling

- Bulk deformation process used to form *threads on cylindrical* parts by rolling them between two dies
- Most important commercial process for **mass producing** bolts and screws
- Performed by cold working in thread rolling machines
- Advantages over thread cutting (machining):
  - Higher production rates
  - Better material utilization
  - Stronger threads due to *work hardening*
  - Better fatigue resistance due to compressive stresses introduced by rolling




(1) start of cycle

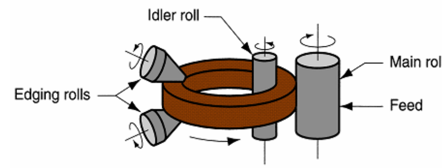



(2) end of cycle

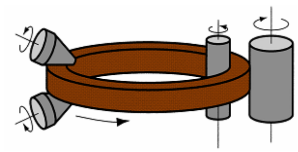


# Ring Rolling

- Deformation process in which a **thick**-walled ring of smaller diameter is rolled into a **thin**-walled ring of larger diameter
- As thick-walled ring is compressed, deformed metal elongates, causing diameter of ring to be enlarged
- Hot working process for large rings and cold working process for smaller rings
- Applications: ball and roller bearing races, steel tires for railroad wheels, and rings for pipes, pressure vessels, and rotating machinery
- Advantages: material savings, ideal grain orientation, strengthening through cold working




(1) start of cycle



(2) end of cycle



# Flat Rolling – Terminology

*Draft* = amount of thickness reduction:

$$d = t_o - t_f$$

Where:

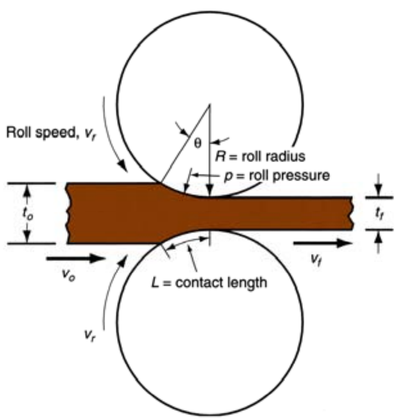
$d$ = draft

$t_o$ = starting thickness

$t_f$ = final thickness

*Reduction* = draft expressed as a fraction of starting stock thickness:

$$r = \frac{d}{t_o}$$




*Side view of flat rolling, indicating before and after thicknesses, work velocities, angle of contact with rolls, and other features*



# Flat Rolling – Terminology

- Friction at the entrance controls the maximum possible draft.

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

$d_{max}$ = Maximum draft (mm)

$\mu$ = coefficient of friction

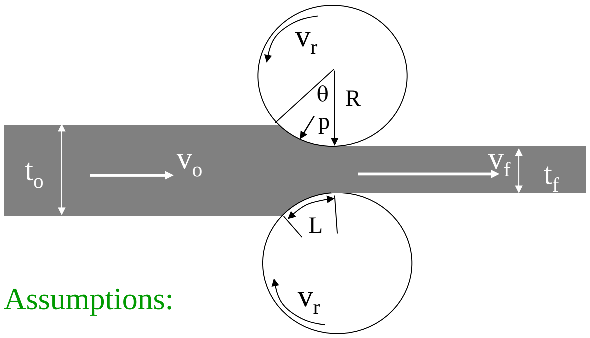
$R$ = *Roll Radius (mm)*

- However, it depends on lubrication, work-piece and roller materials and temperature.

$$\mu = \begin{bmatrix} 0.1 \\ 0.2 \\ 0.3 \end{bmatrix} \begin{matrix} \text{for cold working} \\ \text{for warm working} \\ \text{for hot working} \end{matrix}$$

- When sticking occurs, μ can be as high as 0.7

# Rolling Analysis




R = **roller radius**
p = **roll pressure**
L = **contact length**
**θ = contact angle**
$V_r$ **= roll speed**
$t_o$ **= initial plate thickness**
$t_f$ **= final plate thickness**
$V_o$ **= plate entry speed**
$V_f$ **= plate exit speed**

Assumptions:

- Infinite sheet
- Uniform, perfectly rigid rollers
- Constant material volume:
  $t_o\, w_o\, L_o = t_f\, w_f\, L_f$

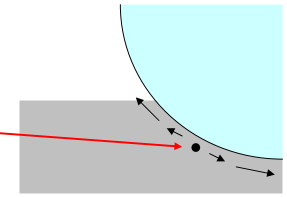
where
$L_o$ = initial plate length
$L_f$ = final plate length

$\Rightarrow t_o\, w_o\, v_o = t_f\, w_f\, v_f$ *(flow rate)*



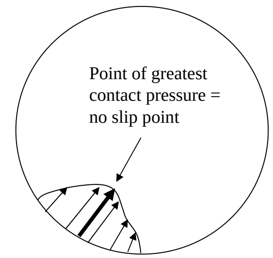
# Rolling Analysis

- Slipping and friction on the contact arc except on no-slip point (neutral point)
  - *One point along the arc where work velocity equals roll velocity.*
- Amount of slip between the work and the rolls: Forward slip



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

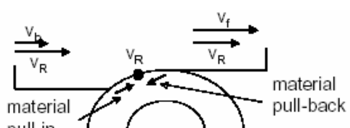
Does it make sense that $v_r < v_f$?





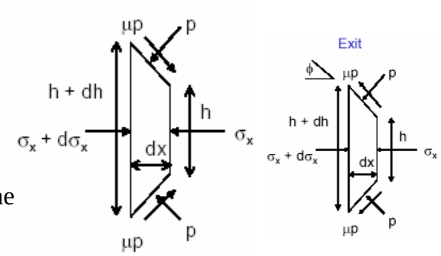

# Rolling Analysis

- 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*



*schematic*

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



*Entrance*



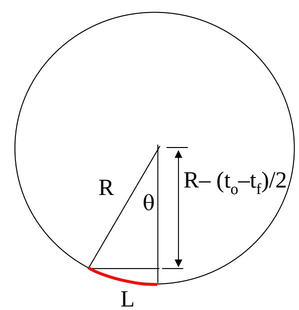
# Rolling Analysis

- Define true strain $\varepsilon = \ln\frac{t_o}{t_f}$ **(Note: use $t_o/t_f$ to keep > 0)**
- Apply average flow stress $\bar{Y}_f = \frac{K\varepsilon^n}{1+n}$
- Approximate roll force:

If friction is not significant, i.e. $\frac{h_{ave}}{L} >> 1$

$$F = w\int_0^L p\,dL = \bar{Y}_f\, wL$$

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




- Torque estimated by T/roller = 0.5 F L
- Power = P = Tω = 2π N F L (for two rollers)

# Example

Roll a 12 inch wide strip which is 1 inch thick, to 0.875 inch thickness in one pass with roll speed of 50 rpm and radius = 10 inches. Material has K = 40,000 psi, n = 0.15 and μ = 0.12.

Is this is a feasible process? If so calculate F, T, and power. *(Assume friction is not significant!)*



# Force Approximation: Large Rolls

*Large Reduction and Significant Friction*

$\frac{h_{ave}}{L} << 1$ Friction is significant

$$p_{ave} = \overline{Y}'_f\left(1+\frac{\mu L}{2h_{ave}}\right)$$

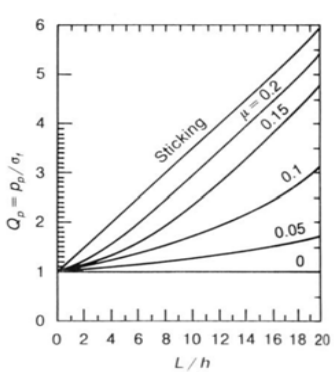
$$F/_{roller} = Lw\overline{Y}'_f\left(1+\frac{\mu L}{2h_{ave}}\right)$$

$$\overline{Y}' = 1.15\overline{Y} = 1.15\times\frac{K\varepsilon^n}{n+1}$$

- The last equation can be used in both cases, *i.e. when friction is significant or not.*
- It is an approximation using the distortion-energy criterion for plane strain (**von Mises**). *[see 6.2.2 Kalpakjian]*



# Interface Pressure: *h/L ratio*

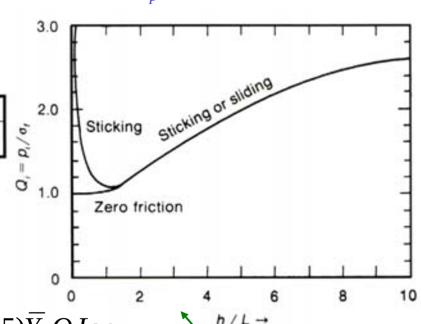



Average pressures in upsetting a rectangular slab increase with friction and $L/h$ ratio. (*After J. F. W. Bishop, Quart. J. Mech. Appl. Math.* **9**:*236–246 (1956). With permission of Pergamon Press.*)

When $h/L > 1.0$ ⟹ Inhomogeneous deformation and use $Q_i$

When $h/L < 1.0$ ⟹ Frictional effects are more severe use $Q_p$

$$Q_i = \frac{P_i}{\sigma_f}$$




*Pressure needed to indent a workpiece*

$$F = (1.15)\overline{Y}_f Q_i L w$$

$$F = (1.15)\overline{Y}_f Q_p L w$$



Next time

**Extrusion**