Principles of Major Manufacturing Processes and Bulk Forming

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FUNDAMENTALS OF METAL FORMING

1. Overview of Metal Forming
2. Material Behavior in Metal Forming
3. Temperature in Metal Forming
4. Strain Rate Sensitivity
5. Friction and Lubrication in Metal Forming

Metal Forming

Large group of manufacturing processes in which plastic deformation is used to change the shape of metal workpieces

- The tool, usually called a ***die***, applies stresses that exceed the yield strength of the metal
- The metal takes a shape determined by the geometry of the die

Stresses in Metal Forming

- Stresses to plastically deform the metal are usually compressive
  - Examples: rolling, forging, extrusion
- However, some forming processes
  - Stretch the metal (tensile stresses)
  - Others bend the metal (tensile and compressive)
  - Still others apply shear stresses (shear spinning)

Material Properties in Metal Forming

- Desirable material properties:
  - **Low yield strength**
  - **High ductility**
- These properties are affected by **temperature**:
  - Ductility increases and yield strength decreases when work temperature is raised
- Other factors:
  - Strain rate and friction

Basic Types of Deformation Processes

1. Bulk deformation
   - Rolling
   - Forging
   - Extrusion
   - Wire and bar drawing

   (stock has high V/A)

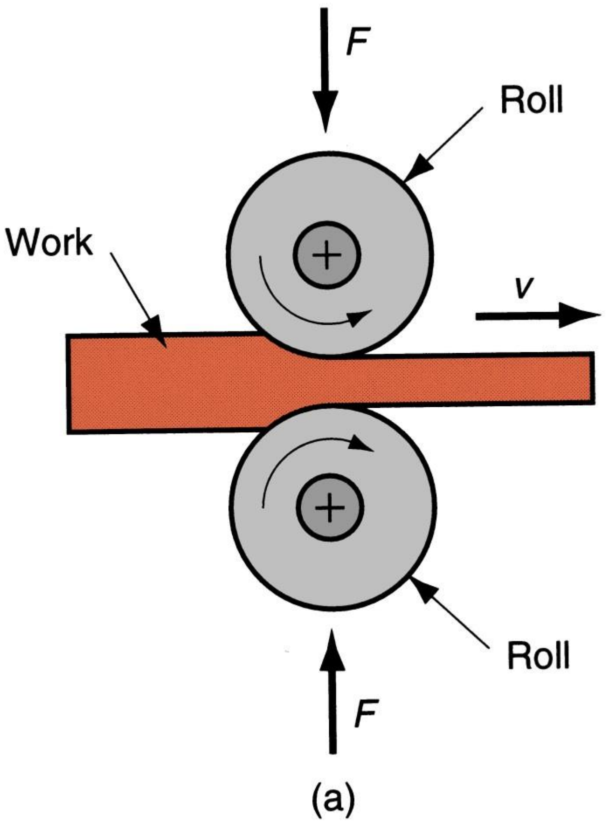
2. Sheet metalworking
   - Bending
   - Deep drawing
   - Cutting
   - Miscellaneous processes

   (stock has low V/A)

Bulk Deformation Processes

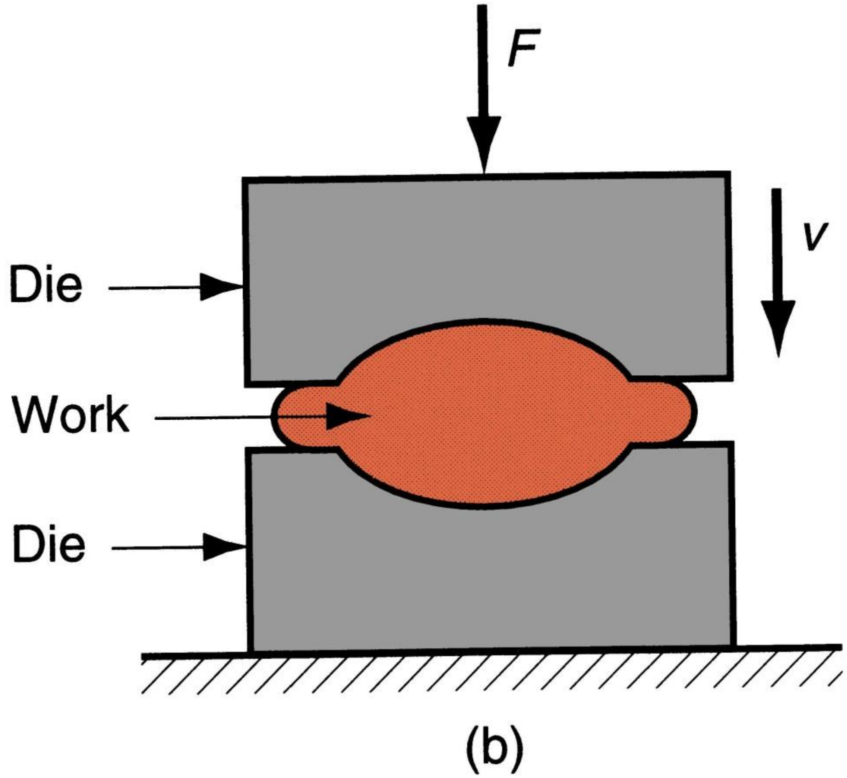
- Characterized by significant deformations and massive shape changes
- "Bulk" refers to workparts with relatively low surface area-to-volume ratios
- Starting work shapes include cylindrical billets and rectangular bars

Rolling



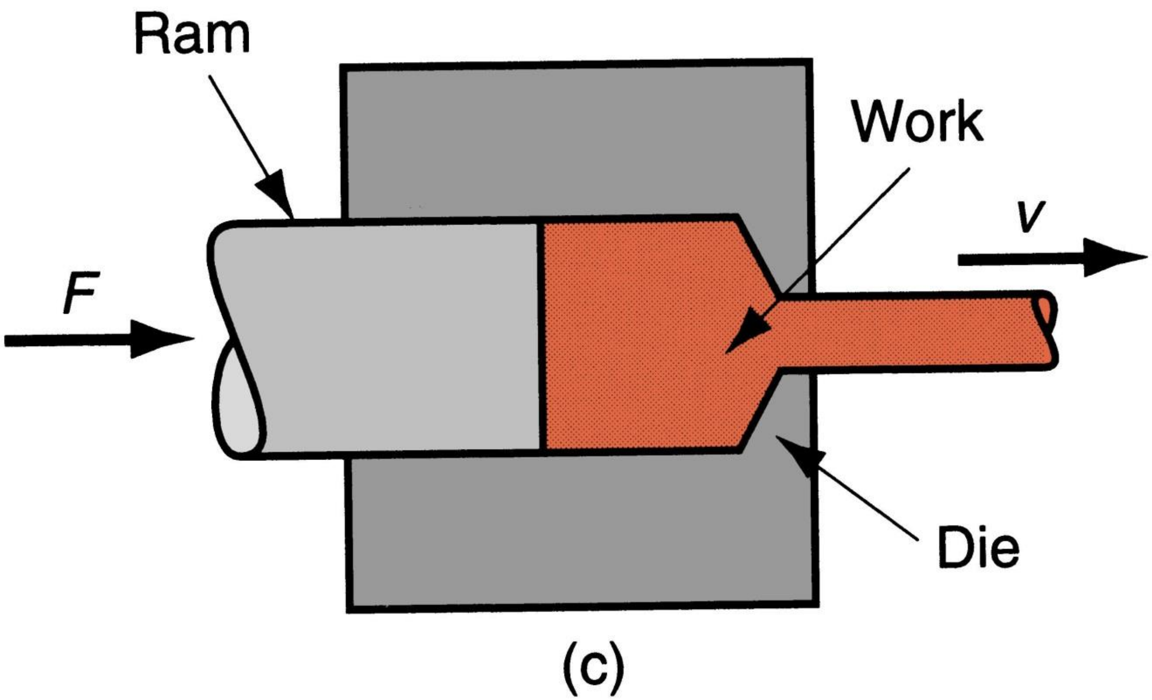
Basic bulk deformation processes: rolling

Forging



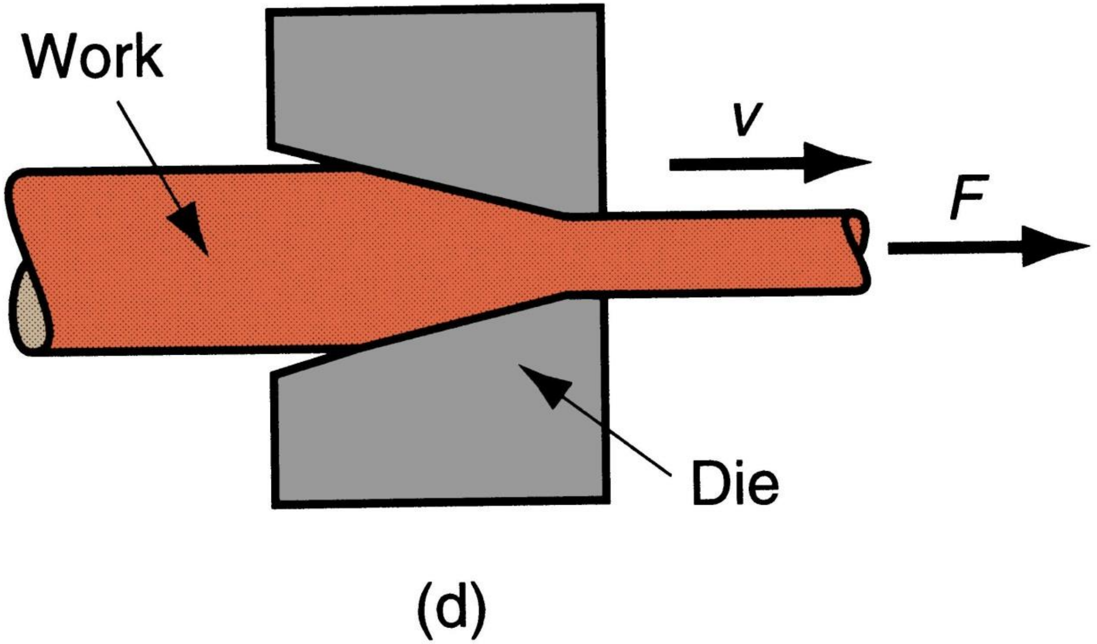
Basic bulk deformation processes: forging

Extrusion



Basic bulk deformation processes: (c) extrusion

Wire and Bar Drawing

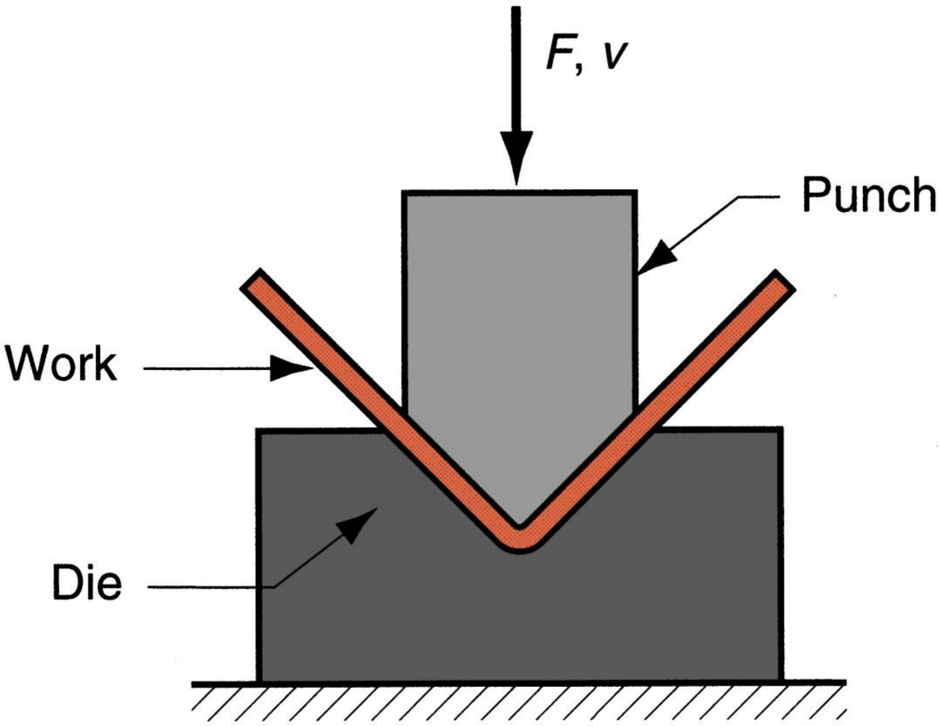


Basic bulk deformation processes: (d) drawing

Sheet Metalworking

- Forming and related operations performed on metal sheets, strips, and coils
- High surface area-to-volume ratio of starting metal, which distinguishes these from bulk deformation
- Often called *pressworking* because presses perform these operations
  - Parts are called *stampings*
  - Usual tooling: *punch* and *die*

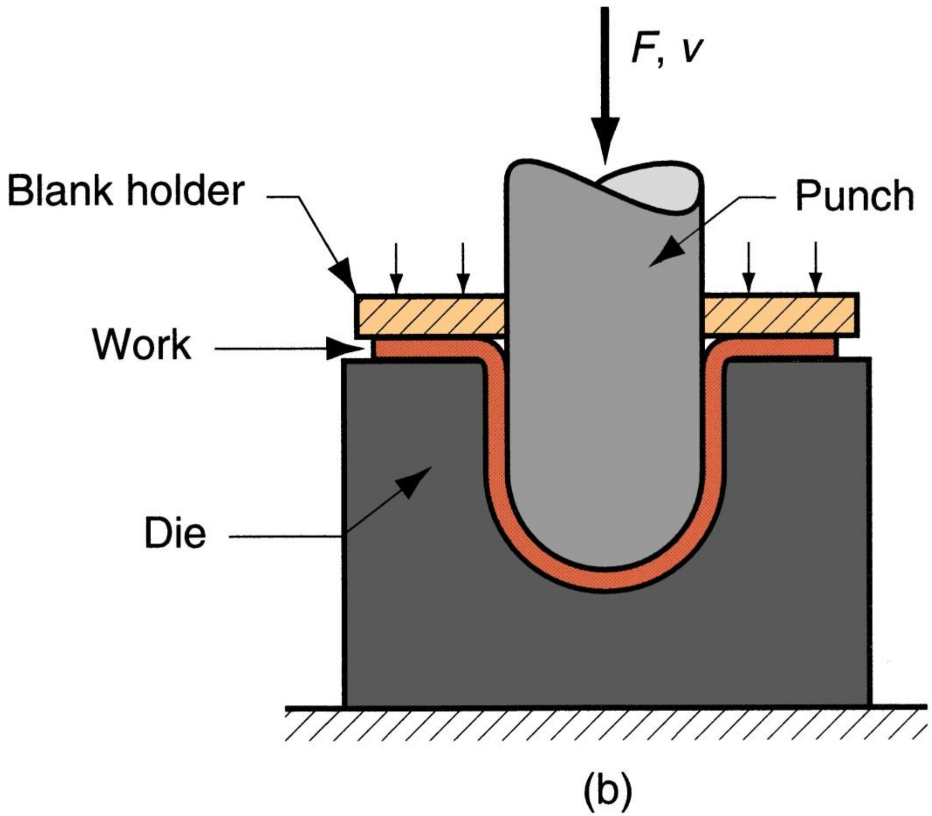
Sheet Metal Bending



(a)

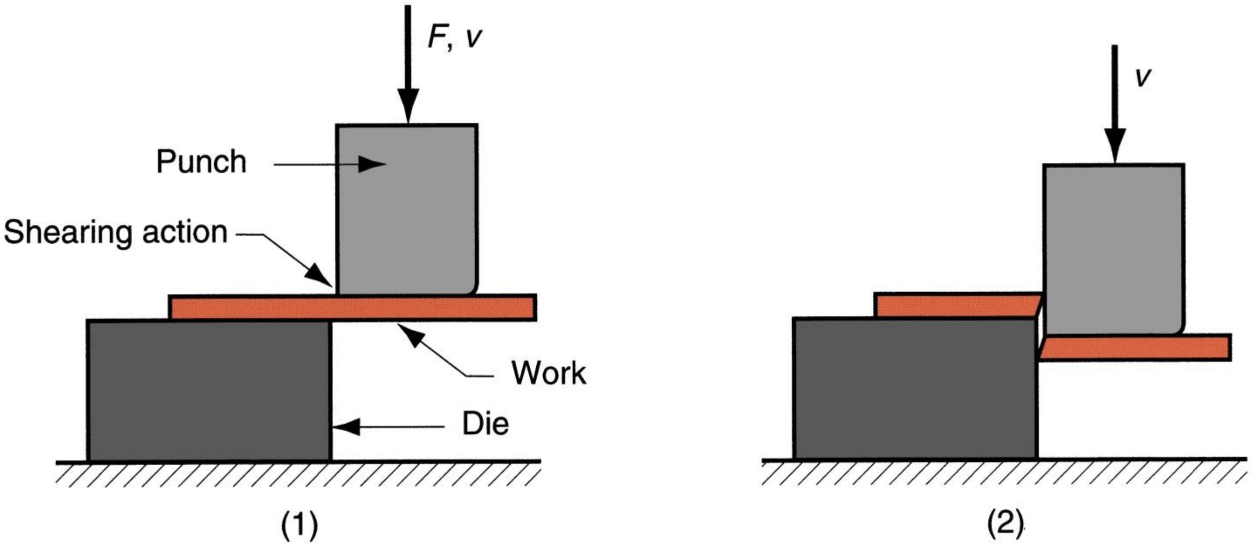
Basic sheet metalworking operations: bending

Deep Drawing



Basic sheet metalworking operations: drawing

Shearing of Sheet Metal



(c)

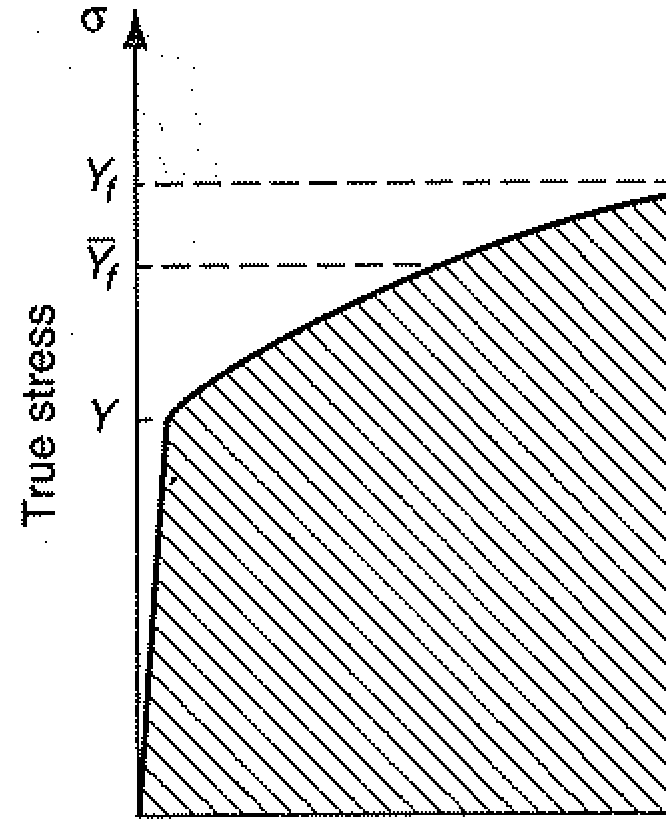
Basic sheet metalworking operations: shearing

Material Behavior in Metal Forming

- Plastic region of stress-strain curve is primary interest because material is plastically deformed
- In plastic region, metal's behavior is expressed by the flow curve:

where *K* = strength coefficient; and *n* = strain hardening exponent

- Flow curve based on true stress and true strain



Flow Stress

- For most metals at room temperature, strength increases when deformed due to strain hardening
- ***Flow stress*** = instantaneous value of stress required to continue deforming the material

$$Y_f = K\varepsilon^n$$

where Y_f = flow stress, i.e., the yield strength as a function of strain

Average Flow Stress

- Determined by integrating the flow curve equation between zero and the final strain value defining the range of interest

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

where $\bar{Y}_f$ = average flow stress; and $\boldsymbol{\varepsilon}$ = maximum strain during deformation process. *n* = strain hardening exponent

Temperature in Metal Forming

- For any metal, ***K*** and ***n*** in the flow curve depend on temperature
  - Both strength (***K***) and strain hardening (***n***) are reduced at higher temperatures
  - In addition, ductility is increased at higher temperatures

Temperature in Metal Forming

- Any deformation operation can be accomplished with lower forces and power at elevated temperature
- Three temperature ranges in metal forming:
  - Cold working
  - Warm working
  - Hot working

1. Cold Working

- Performed at room temperature or slightly above
- Many cold forming processes are important mass production operations
- Minimum or no machining usually required
  - These operations are *near net shape* or *net shape* processes

Advantages of Cold Forming

- Better accuracy, closer tolerances
- Better surface finish
- Strain hardening increases strength and hardness
- Grain flow during deformation can cause desirable directional properties in product
- No heating of work required

Disadvantages of Cold Forming

- Higher forces and power required in the deformation operation
- Ductility and strain hardening limit the amount of forming that can be done
  - In some cases, metal must be annealed to allow further deformation
  - In other cases, metal is simply not ductile enough to be cold worked

2. Warm Working

- Performed at temperatures above room temperature but below recrystallization temperature
- Dividing line between cold working and warm working often expressed in terms of melting point:
  - $0.3T_m$, where T_m = melting point (absolute temperature) for metal

Advantages of Warm Working

- Lower forces and power than in cold working
- More intricate work geometries possible
- Need for annealing may be reduced or eliminated
- Low spring back

Disadvantage:

1. Scaling of part surface

3. Hot Working

- Deformation at temperatures above the *recrystallization temperature*
- Recrystallization temperature = about one-half of melting point on absolute scale
  - In practice, hot working usually performed somewhat above $0.5T_m$
  - Metal continues to soften as temperature increases above $0.5T_m$, enhancing advantage of hot working above this level

Why Hot Working?

Capability for substantial plastic deformation of the metal - far more than possible with cold working or warm working

- Why?
  - Strength coefficient (***K***) is substantially less than at room temperature
  - Strain hardening exponent (*n*) is zero (theoretically)
  - Ductility is significantly increased

Advantages of Hot Working

- Workpart shape can be significantly altered
- Lower forces and power required
- Metals that usually fracture in cold working can be hot formed
- Strength properties of product are generally isotropic
- No work hardening occurs during forming
  - Advantageous in cases when part is to be subsequently processed by cold forming

Disadvantages of Hot Working

- Lower dimensional accuracy in case of bulk forming
- Higher total energy required (due to the thermal energy to heat the workpiece)
- Work surface oxidation (scale), poorer surface finish
- Shorter tool life

Isothermal Forming- A Type of Hot Forming

When highly alloyed metals such as Ti and Nickel alloys are heated to hot temp and bring in contact with cold tooling, the heat radiates from the metal to tooling. This result in high residual stresses and temp variation over metal and hence irregular material flow occurs during forming, causing cracks.

In order to avoid this problem, both metal and tooling are heated to same temp. However, this causes reduction in tooling life.

** **Mostly**, Forging is performed through this process

Strain Rate Sensitivity

- Theoretically, a metal in hot working behaves like a perfectly plastic material, with strain hardening exponent ***n* = 0**
  - The metal should continue to flow at the same flow stress, once that stress is reached
  - However, an additional phenomenon occurs during deformation, especially at elevated temperatures: **Strain rate sensitivity**

What is Strain Rate?

- Strain rate in forming is directly related to speed of deformation ***v***
- Deformation speed ***v*** = velocity of the ram or other movement of the equipment
- *Strain rate* is defined:

where = true strain rate; and *h* = instantaneous height of workpiece being deformed

Evaluation of Strain Rate

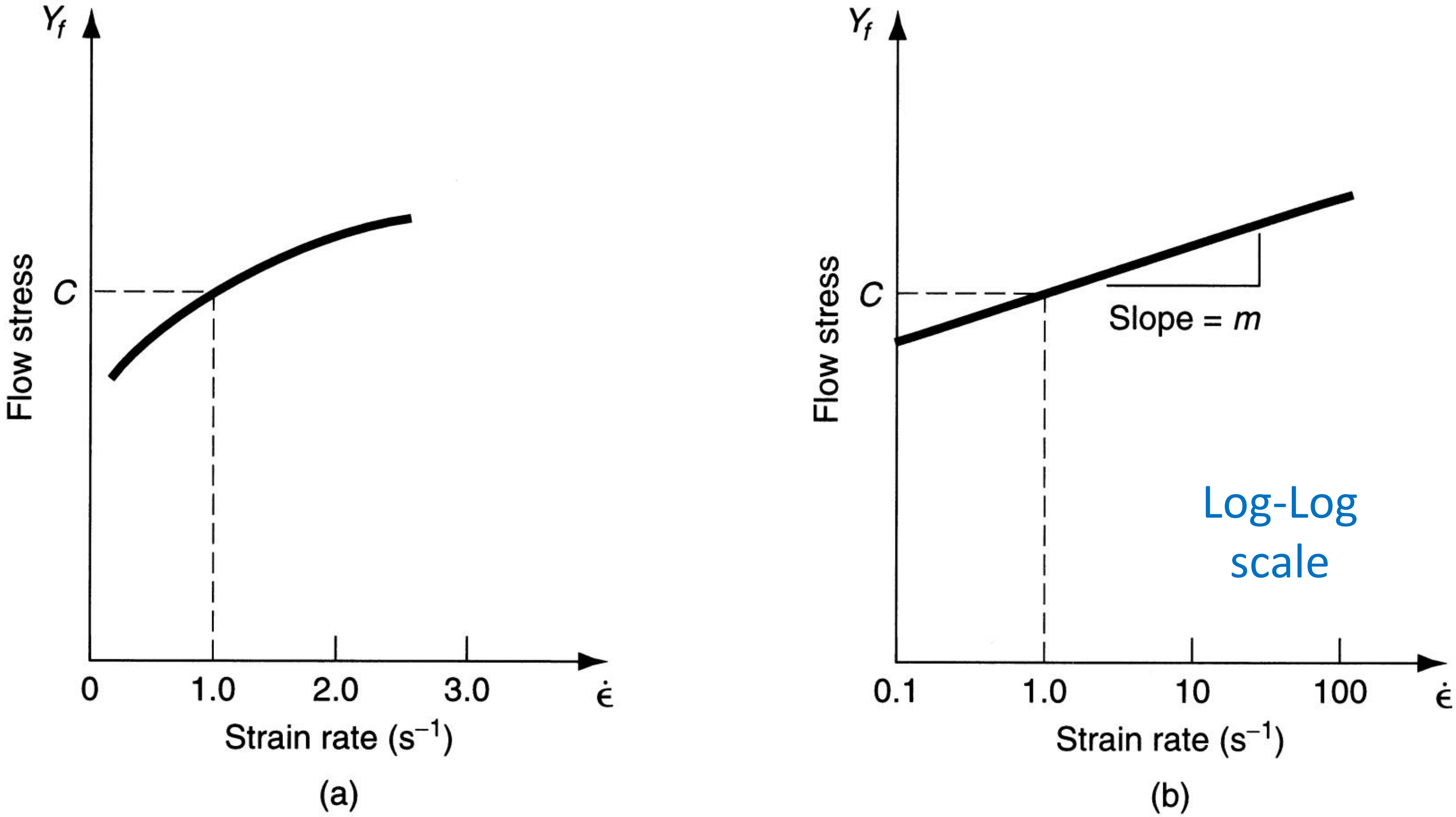
- In most practical operations, evaluation of strain rate is complicated by
  - Workpart geometry
  - Variations in strain rate in different regions of the part
- Strain rate can reach 1000 s^{-1} or more for some metal forming operations

Effect of Strain Rate on Flow Stress

- Flow stress is a function of temperature
- At hot working temperatures, flow stress also depends on strain rate
  - As strain rate increases, resistance to deformation increases
  - This effect is known as strain-rate sensitivity

Strain Rate Sensitivity

Effect of strain rate on strength properties/ flow stress is called strain rate sensitivity

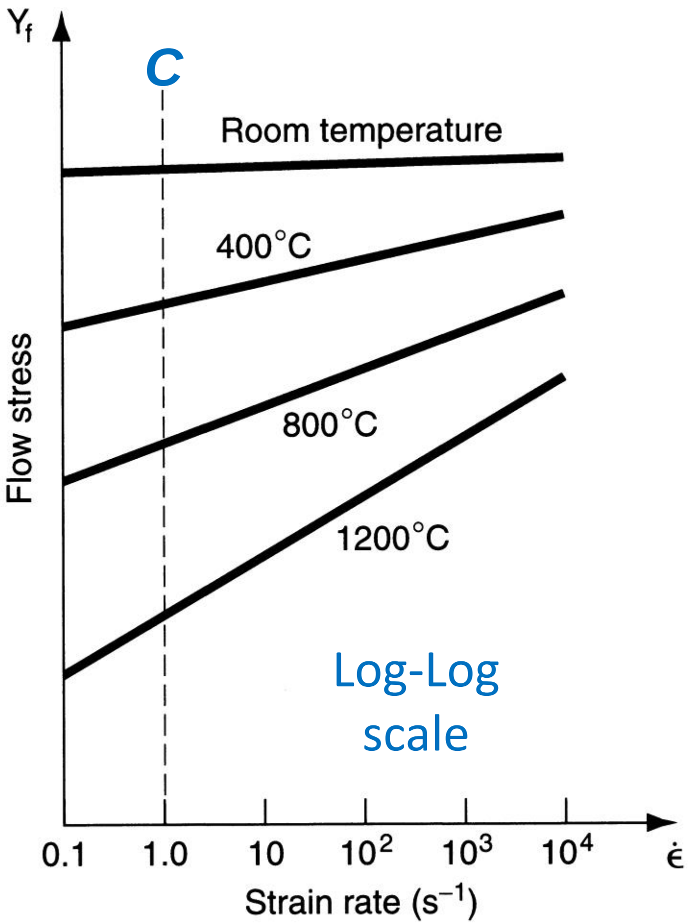


(a) Effect of strain rate on flow stress at an elevated work temperature.
(b) Same relationship plotted on log-log coordinates.

Strain Rate Sensitivity Equation

where C = strength constant (similar but not equal to strength coefficient in flow curve equation), and *m* = strain-rate sensitivity/ exponent

Effect of Temperature on Flow Stress



Effect of temperature on flow stress for a typical metal. The constant ***C***, as indicated by the intersection of each plot with the vertical dashed line at strain rate = 1.0, decreases, and ***m*** (slope of each plot) increases with increasing temperature.

Observations about Strain Rate Sensitivity

- Increasing temperature decreases **C** and increases ***m***
  - At room temperature, effect of strain rate is almost negligible
  - As temperature increases, strain rate becomes increasingly important in determining flow stress

Friction in Metal Forming

Sticking: If the coefficient of friction becomes too large, a condition known as ***STICKING*** occurs.

Definition: Sticking in metal working is the tendency for the two surfaces in relative motion to *adhere* to each other rather than slide.

When Sticking Occurs??

The friction stress between the surfaces becomes higher than the shear flow stress of the metal thus causing the material to deform by a shear process beneath the surface rather than slip at the surface.

Sticking is a prominent problem in forming operations, especially rolling.

Lubrication in Metal Forming

- Metalworking lubricants are applied to tool-work interface to reduce magnitude of friction co-efficient in order to reduce harmful effects of friction
- **Benefits:**
  - Reduced sticking, forces, power, tool wear
  - Better surface finish
  - Removes heat from the tooling

Lubricants: Mineral oils, Fats, Fatty oils, water based emulsions, Soaps and Coatings

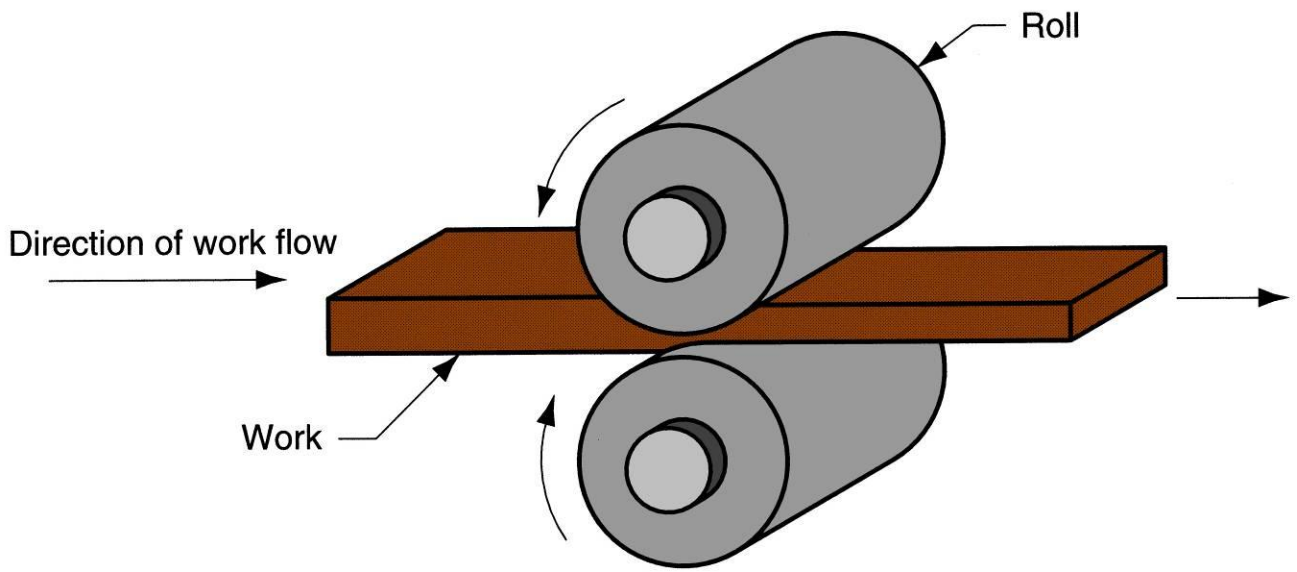
For hot working: Graphite, Molten glass. Graphite can be used in solid as well as in water suspension form. Glass is useful in hot extrusion of steel alloys.

Four Basic Bulk Deformation Processes

1. **Rolling** – slab or plate is squeezed between opposing rolls
2. **Forging** – work is squeezed and shaped between opposing dies
3. **Extrusion** – work is squeezed through a die opening, thereby taking the shape of the opening
4. **Wire and bar drawing** – diameter of wire or bar is reduced by pulling it through a die opening

1. Rolling

Deformation process in which work thickness is reduced by compressive forces exerted by two opposing rolls



The rolling process (specifically, flat rolling).

The Rolls

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 its cross section

Types of Rolling

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

Rolled Products Made of Steel

150*150mm

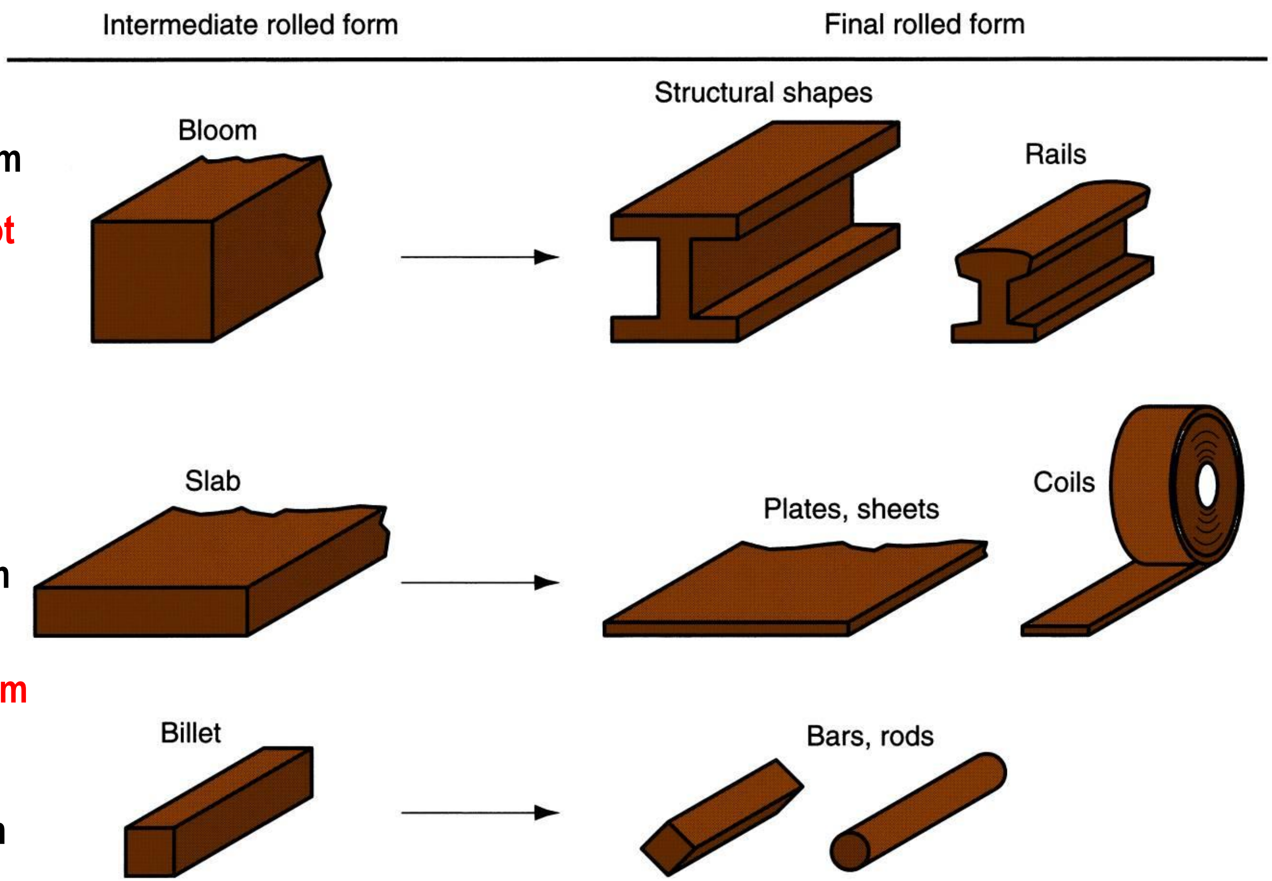
From Ingot

250*40mm

From Ingot/Bloom

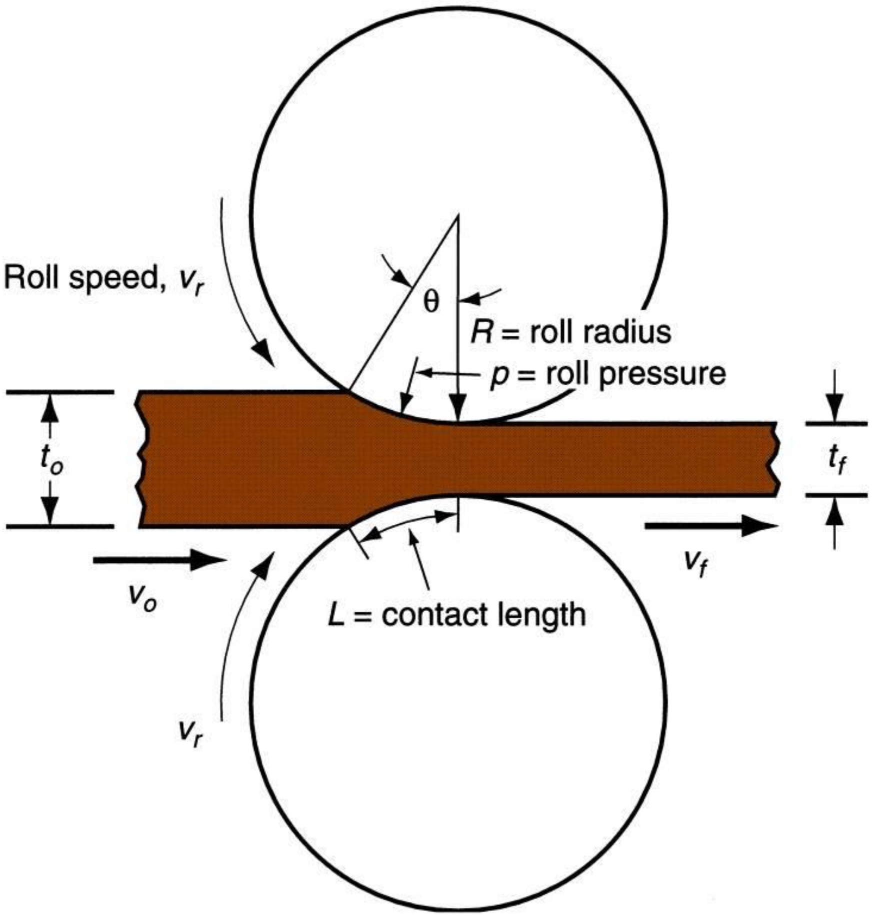
40*40mm

From Bloom



Some of the steel products made in a rolling mill.

Diagram of Flat Rolling



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

Flat Rolling Terminology

Draft = amount of thickness reduction

$$d = t_o - t_f$$

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

where d = draft; t_o = starting thickness; and t_f = final thickness; d_{max}= max possible draft; μ: Friction Coefficient;

R: Roll radius

Flat Rolling Terminology

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

$$r = \frac{d}{t_o} \qquad d = t_o - t_f$$

where ***r*** = reduction

* ***Volume entrance = Volume at exit***

$$t_o w_o L_o = t_f w_f L_f$$

* ***Volume flow rate at entrance = Volume flow rate at exit***

$$t_o w_o v_o = t_f w_f v_f$$

* **Forward slip:** $s = \dfrac{v_f - v_r}{v_r}$

* **Strain:** $\epsilon = \ln \dfrac{t_o}{t_f}$

* **Average flow stress:** $\overline{Y}_f = \dfrac{K\epsilon^n}{1+n}$

Flat Rolling Terminology

* **Rolling force by one roll:** $F = w\int_0^L p\,dL$ = $F = \bar{Y}_f w L$

Length of contact: $L = \sqrt{R(t_o - t_f)}$

Torque required by one roll: $T = 0.5FL$ $T = F*L/2$

Power required for rolling (based on 2 rolls): $P = 2\pi NFL$

Example 19.1

A 300-mm-wide strip 25 mm thick is fed through a rolling mill with two powered rolls each of radius = 250 mm. The work thickness is to be reduced to 22 mm in one pass at a roll speed of 50 rev/min. The work material has a flow curve defined by $K = 275$ MPa and $n = 0.15$, and the coefficient of friction between the rolls and the work 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: The draft attempted in this rolling operation is

$$d = 25 - 22 = 3 \text{ mm}$$

$$d = t_o - t_f$$

From Eq. (19.8), the maximum possible draft for the given coefficient of friction is

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

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

Since the maximum allowable draft exceeds the attempted reduction, the rolling operation is feasible. To compute rolling force, we need the contact length L and the average flow stress $\overline{Y}_f$. The contact length is given by Eq. (19.11):

$$L = \sqrt{250(25 - 22)} = 27.4 \text{ mm}$$

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

$\overline{Y}_f$ is determined from the true strain:

$$\epsilon = \ln \frac{25}{22} = 0.128$$

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

$$\overline{Y}_f = \frac{275(0.128)^{0.15}}{1.15} = 175.7 \text{ MPa}$$

$$\overline{Y}_f = \frac{K\epsilon^n}{1 + n}$$

Example 19.1

Rolling force is determined from Eq. (19.10):

$$F = 175.7(300)(27.4) = 1{,}444{,}786 \text{ N}$$

$$F = \overline{Y}_f w L$$

Torque required to drive each roll is given by Eq. (19.12):

$$T = 0.5(1{,}444{,}786)(27{,}4)(10^{-3}) = 19{,}786 \text{ N-m}$$

$$T = 0.5FL$$

and the power is obtained from Eq. (19.13):

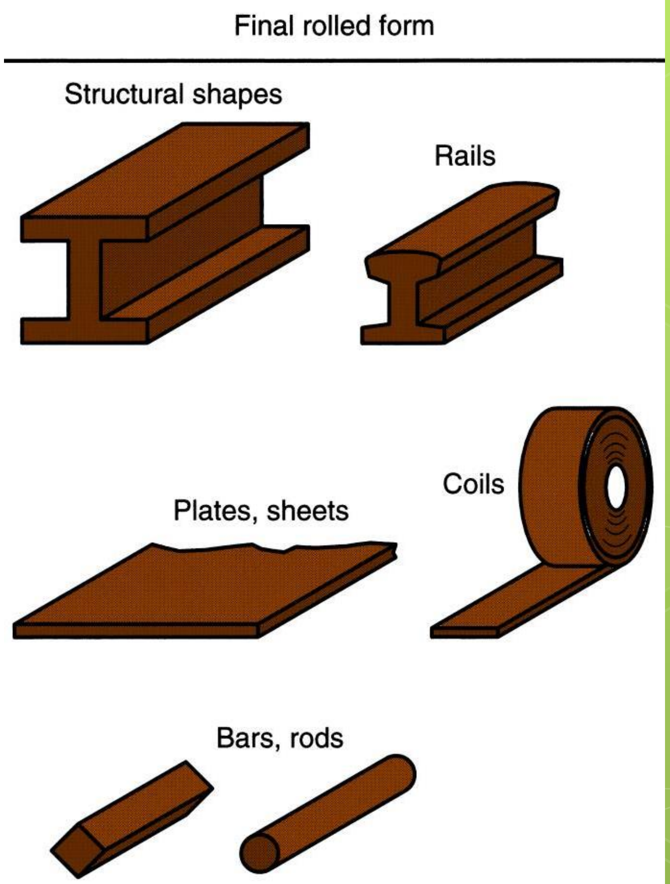
$$P = 2\pi(50)(1{,}444{,}786)(27.4)(10^{-3}) = 12{,}432{,}086 \text{ N-m/min} = 207{,}201 \text{ N-m/s(W)}$$

$$P = 2\pi NFL$$

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

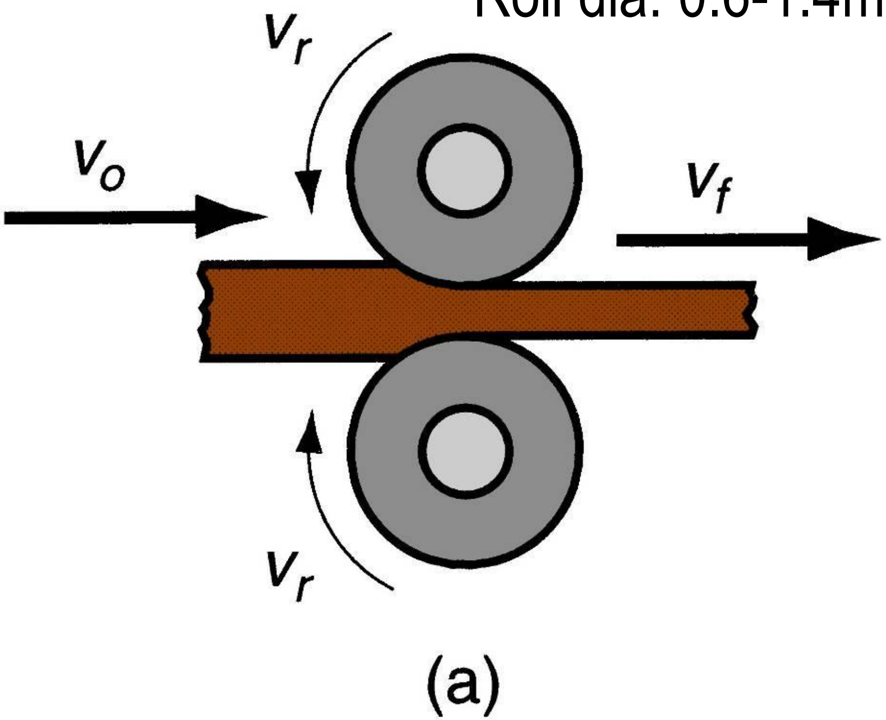
- Equipment is massive and expensive
- Rolling mill configurations:
  - **Two-high** – two opposing rolls
  - **Three-high** – work passes through rolls in both directions
  - **Four-high** – backing rolls support smaller work rolls
  - **Cluster mill** – multiple backing rolls on smaller rolls
  - **Tandem rolling mill** – sequence of two-high mills

Two-High Rolling Mill

A ***two-high non-reversing***, which means there are two rolls that turn only in one direction.

The ***two-high reversing*** mill has rolls that can rotate in both directions, but the disadvantage is that the rolls must be stopped, reversed, and then brought back up to rolling speed between each pass

Roll dia: 0.6-1.4m

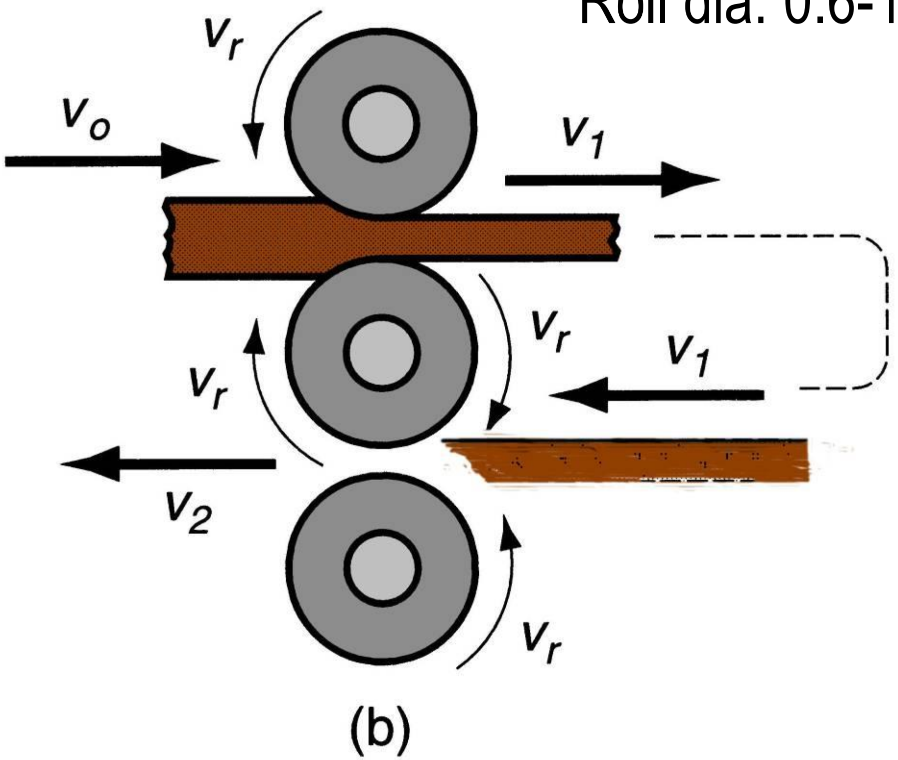


Various configurations of rolling mills: (a) **2-high rolling mill.**

Three-High Rolling Mill

Roll dia: 0.6-1.4m

The disadvantage to this system is the work-piece must be lifted and lowered using an elevator



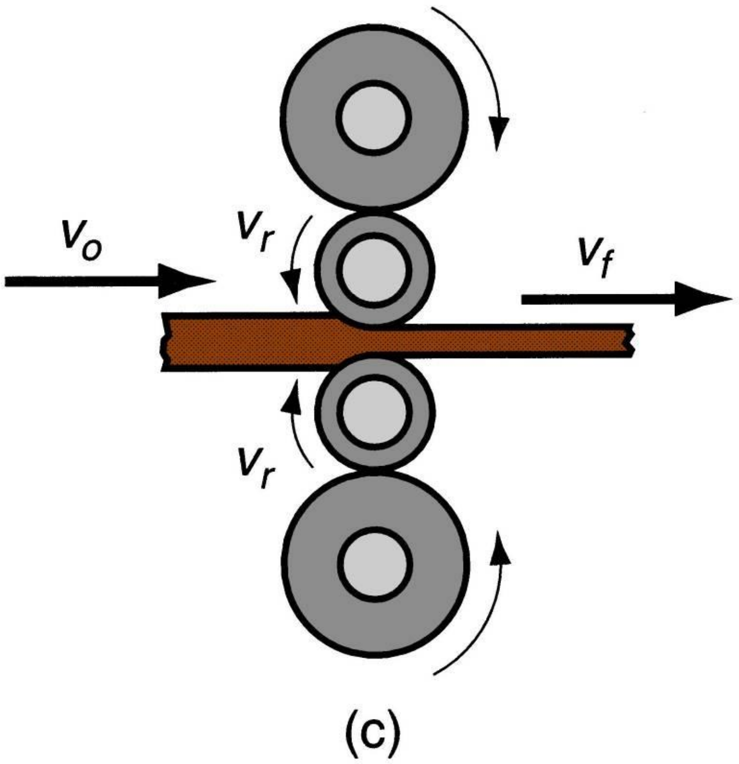
Various configurations of rolling mills: (b) **3-high rolling mill.**

Four-High Rolling Mill

$$F = \overline{Y}_f w L$$

A small roll diameter is advantageous because less roll is in contact with the material, which results in a lower force and energy requirement.

The stiffness of small roll is increased by back-up large roll

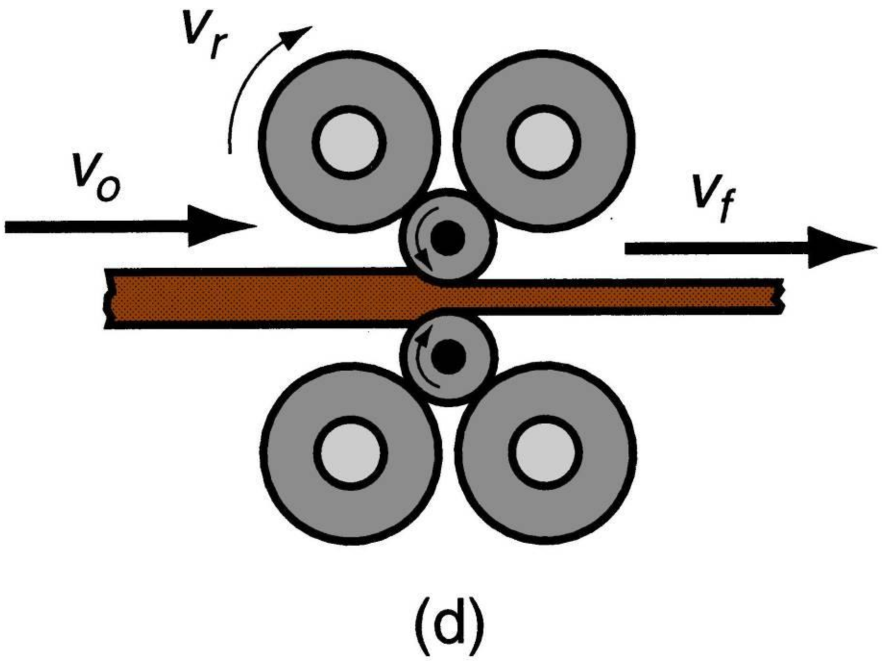


Various configurations of rolling mills: (c) **four-high rolling mill.**

Cluster Mill

Multiple backing rolls allow even smaller roll diameters

These types of mills are commonly used to hot roll wide plates, most cold rolling applications, and to roll foils



Various configurations of rolling mills: (d) **cluster mill**

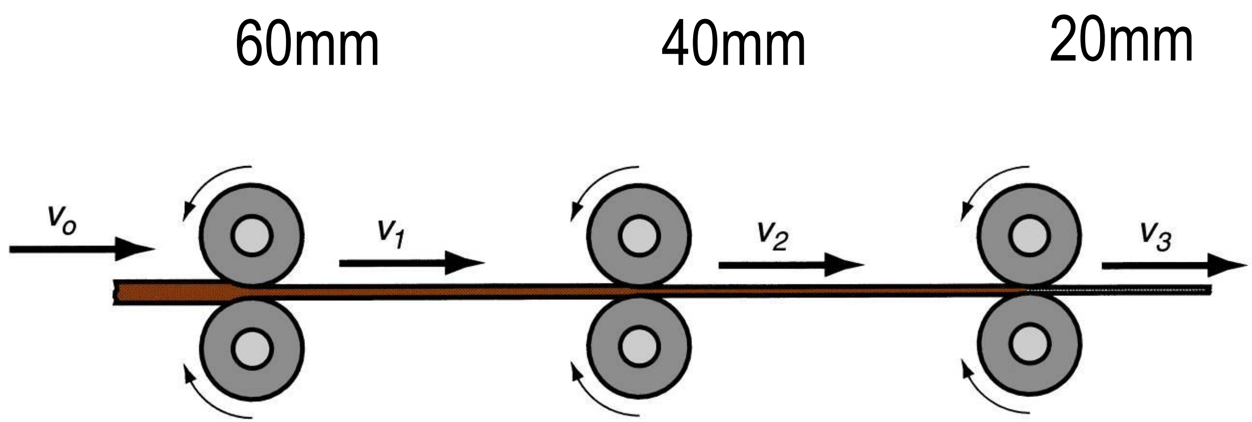
Tandem Rolling Mill

A **tandem mill** is a special type of modern rolling mill where rolling is done in one pass.

In a traditional rolling mill rolling is done in several passes, but in tandem mill there are several *stands* and reductions take place successively.

The number of stands ranges from 2 to 18. Tandem mill can be either hot or cold rolling mill type

A series of rolling stands in sequence



(e)

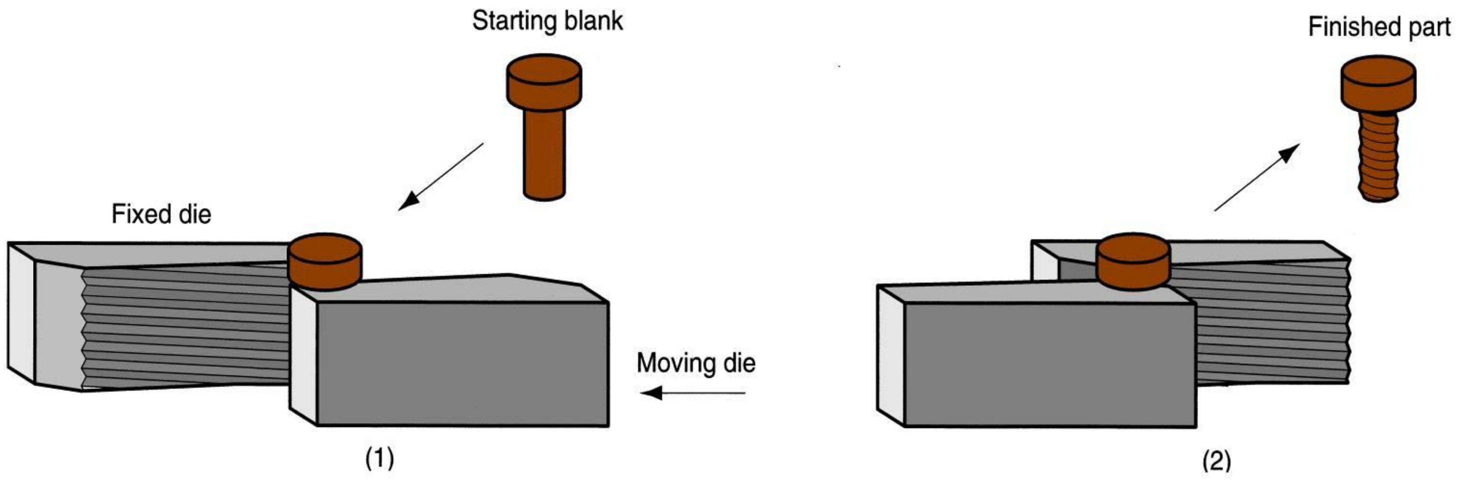
Various configurations of rolling mills: (e**) tandem rolling mill.**

Thread Rolling

Bulk deformation process used to form threads on cylindrical parts by rolling them between two dies

- 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 and better fatigue resistance due to work hardening

Thread Rolling

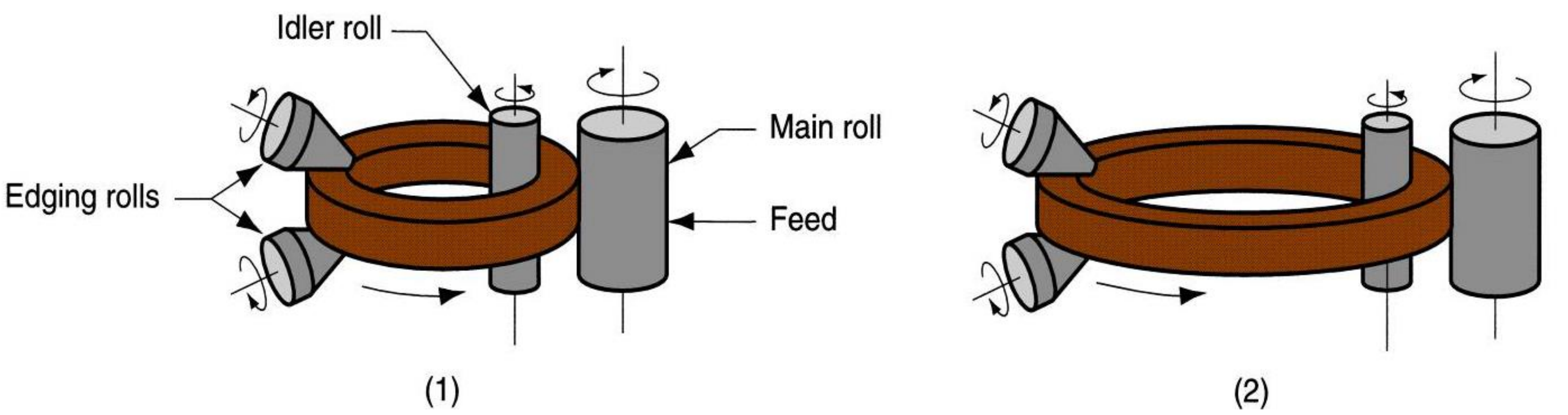


Thread rolling with flat dies: (1) start of cycle, and (2) end of cycle.

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



Ring rolling used to reduce the wall thickness and increase the diameter of a ring: (1) start, and (2) completion of process.

Ring Rolling

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