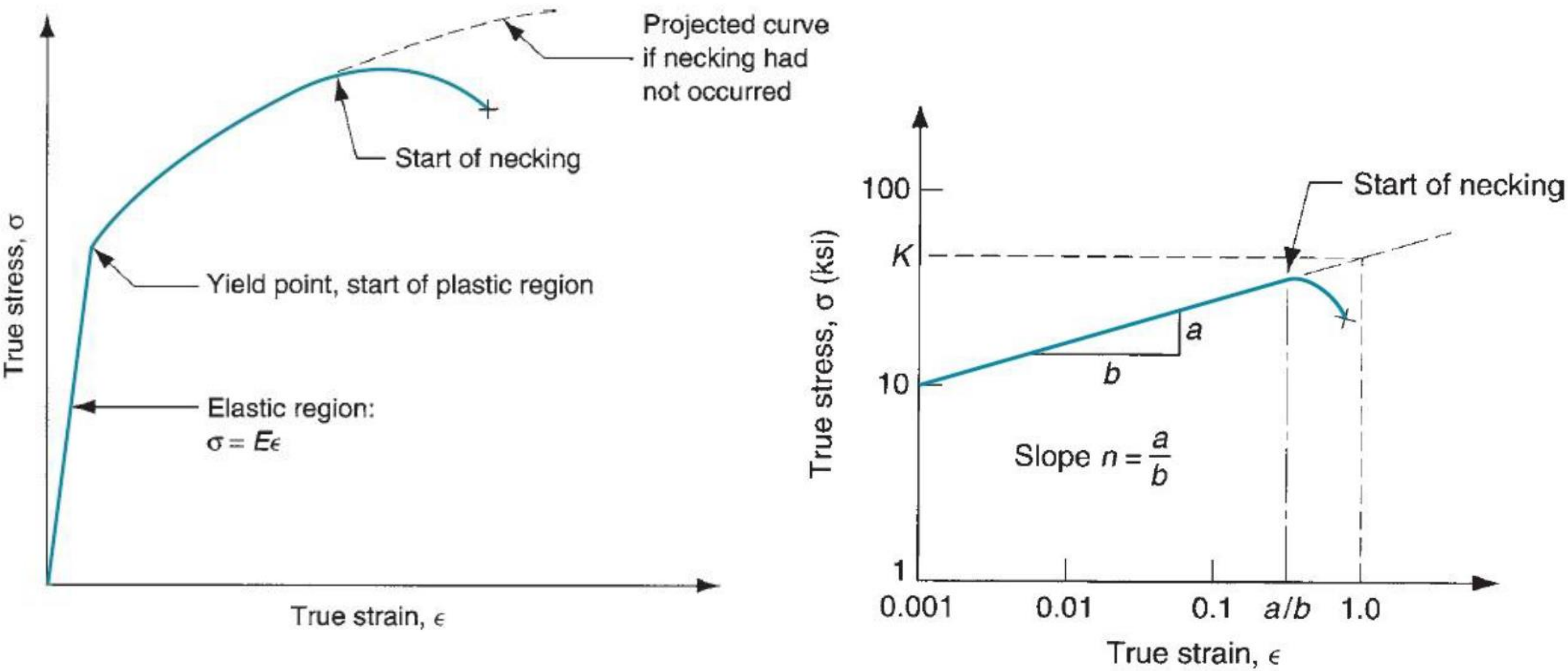
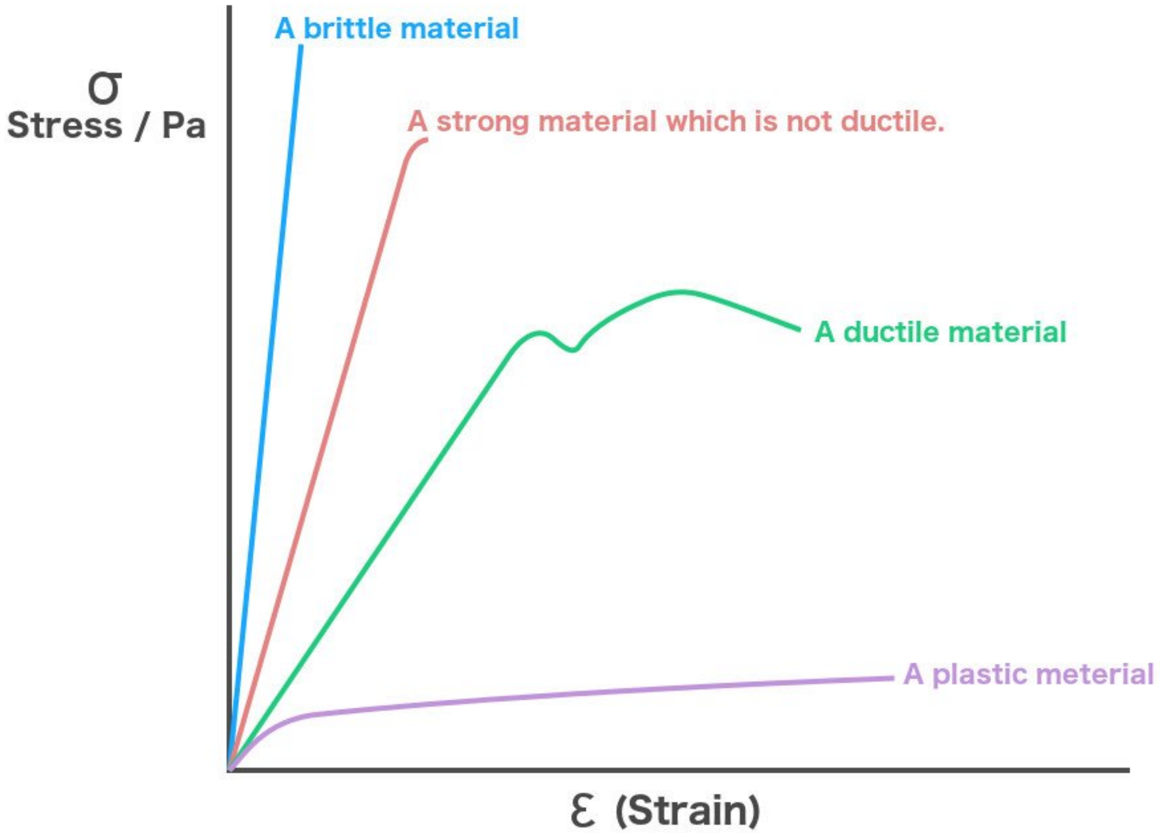
BMEE304L
Metal Forming and Machining

Stress-Strain Curve

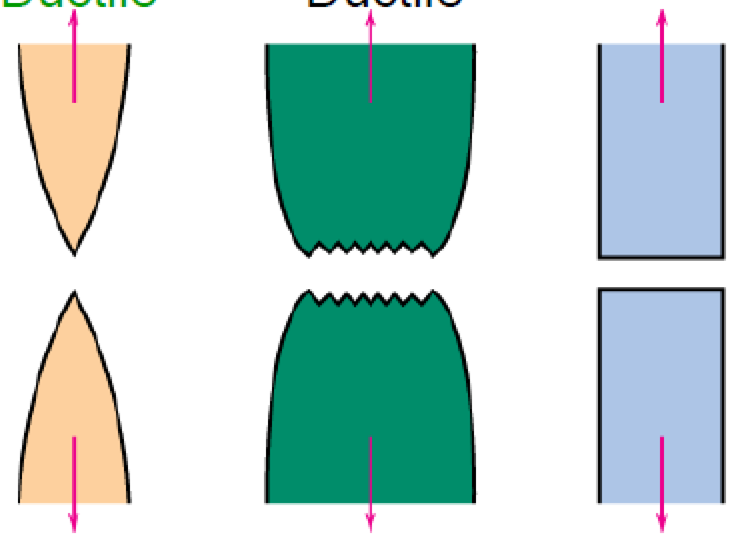



σ
Stress / Pa
A brittle material
A strong material which is not ductile.
A ductile material
A plastic meterial
Ɛ (Strain)

Ductile vs Brittle Failure

- Classification:

Fracture behavior:	Very Ductile	Moderately Ductile	Brittle



Adapted from Fig. 8.1, *Callister 7e.*

%*AR* or %*EL*	Large	Moderate	Small

- Ductile fracture is usually desirable!

Ductile: warning before fracture

Brittle: No warning

Ductile vs. Brittle Failure

cup-and-cone fracture

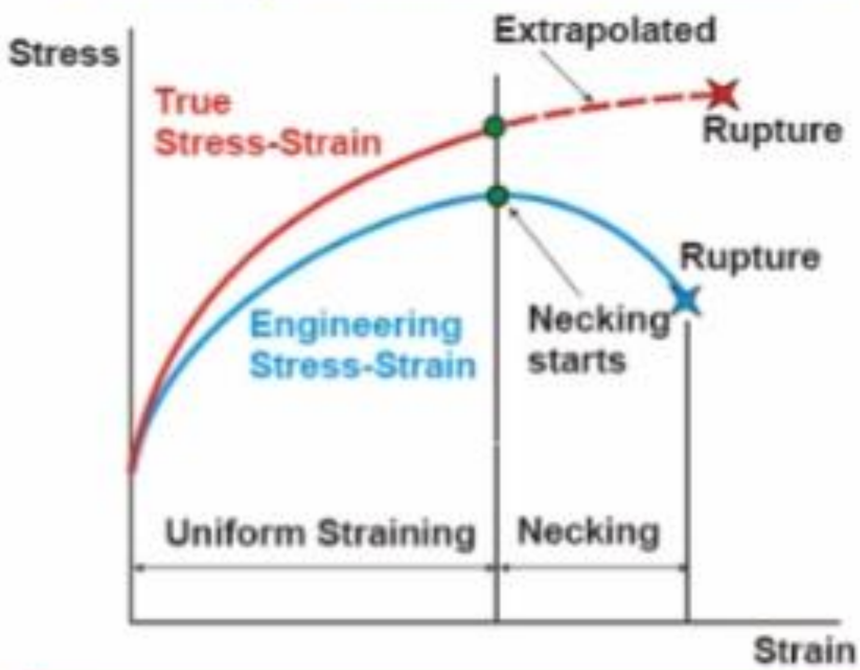
brittle fracture

Behavior described	Terms used	
Crystallographic mode	Shear	Cleavage
Appearance of fracture	Fibrous	Granular
Strain to fracture	Ductile	Brittle

Material Behavior in Metal Forming

- **The typical stress strain curve for most metals is divided into an elastic region and a plastic region**

- **Plastic region of stress-strain curve is primary interest because material is plastically deformed**

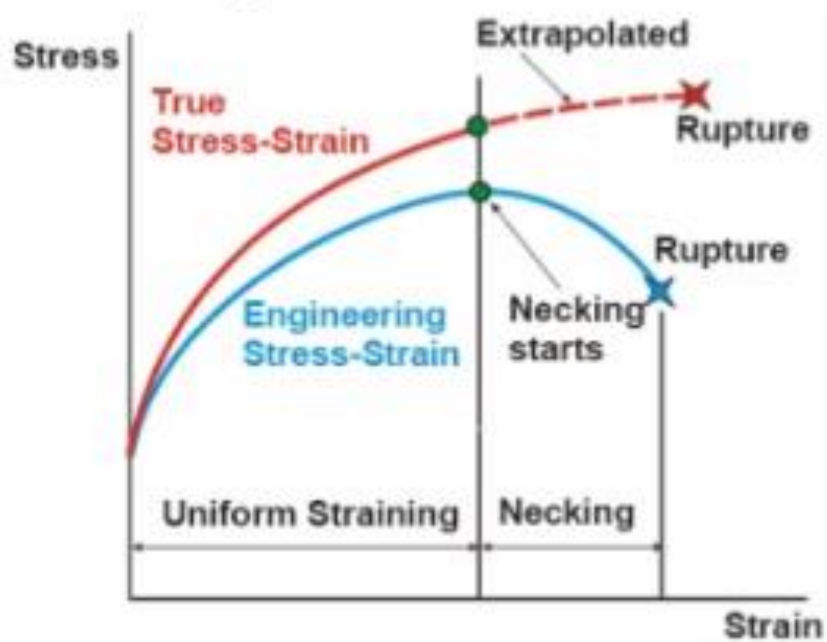


Necking starts at maximum engineering stress or, equivalently, at maximum tensile load.

Material Behavior in Metal Forming

- In plastic region, metal's behavior is expressed by the flow curve:

$$\boxed{\sigma = K\varepsilon^n}$$



K = strength coefficient (MPa); and *n* = strain hardening exponent. Stress and strain in flow curve are true stress and true strain.

Flow stress

Flow stress is the true stress acting inside the material.

It differs from engineering stress as it takes into account the changes in the dimensions of the work piece.

To accurately predict the forming loads, we need accurate values of stresses i.e. flow stress.

Flow curve is desirable to be drawn for actual working conditions as the operations involve large plastic strains.

Flow Stress

- **For most metals** at room temperature, strength increases when deformed due to strain hardening. The stress required to continue deformation must be increased to match this increase in strength.

- **Flow stress** is defined as the instantaneous value of stress required to continue deforming the material – to keep the metal "flowing".

$$\boxed{Y_f = K\varepsilon^n}$$

Where: Y_f = flow stress, that is, the yield strength as a function of strain

Typical Values of K and n

Typical Values of Strength Coefficient *K* and Strain Hardening Exponent *n* for Selected Metals.

Material	Strength coefficient, *K* lb/in.^{2}	(MPa)	Strain hardening exponent, *n*
Aluminum, pure, annealed	25,000	(175)	0.20
Aluminum alloy, annealed[a]	35,000	(240)	0.15
Aluminum alloy, hardened by heat treatment[a]	60,000	(400)	0.10
Copper, pure, annealed	45,000	(300)	0.50
Copper alloy: brass[a]	100,000	(700)	0.35
Steel, low C, annealed[a]	75,000	(500)	0.25
Steel, high C, annealed[a]	125,000	(850)	0.15
Steel, alloy, annealed[a]	100,000	(700)	0.15
Steel, stainless, austenitic, annealed[a]	175,000	(1200)	0.40

[a]Values of *K* and *n* will vary according to composition, heat treatment, and work hardening.

Metal Working

- Metalworking is the process of working with metals to create individual parts, assemblies, or large-scale structures.

- The term covers a wide range of work from **large ships and bridges to precise engine parts and delicate jewelry**.

- It therefore includes a correspondingly wide range of skills, processes, and tools.

Metal Working

- Useful shapes in metal can be generated in two basic ways:

- By plastic deformation process i.e. Metal Forming Process (Example- Forging, Rolling, Extrusion, etc.)

- By metal removal or machining process (Example- Shaping, milling, etc.)

1. By *plastic deformation processes* in which the volume and mass of metal are conserved and the metal is displaced from one location to another.
2. By *metal removal* or *machining processes* in which material is removed in order to give it the required shape.

Manufacturing Processes

- Casting
- Forming
- Machining
- Joining

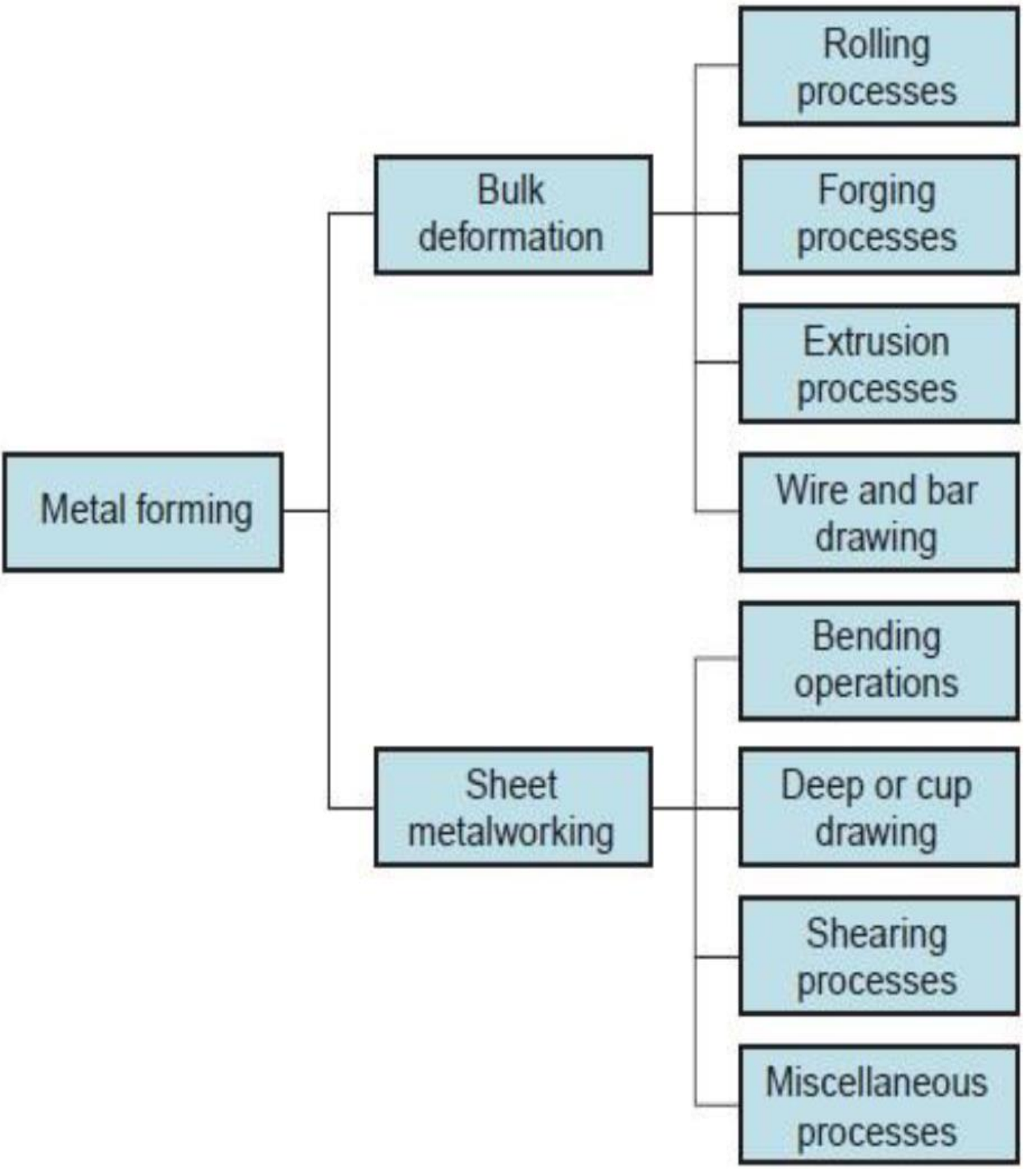
Forming Processes

- Bulk Forming - Sheet Forming	- Hot Forming (>0.5 T_M) - Cold Forming (<0.3 T_M) - Warm Forming (0.3-0.5 T_M)	- Primary Process - Secondary & - Tertiary Process	- Continuous - Incremental Etc...

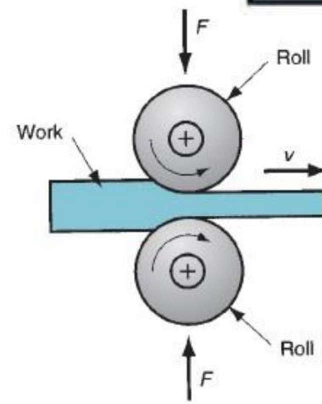
Plasticity

Process Selection Criteria

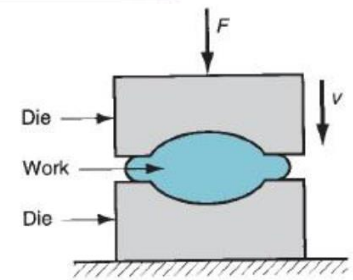
- Material Type
- Available Technology
- Post Processing
- Accuracy
- Product Quality, etc...



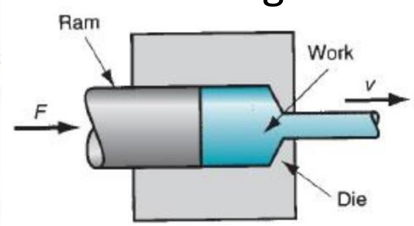
Bulk deformation



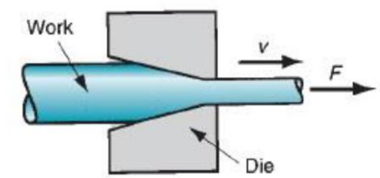
Rolling



Forging

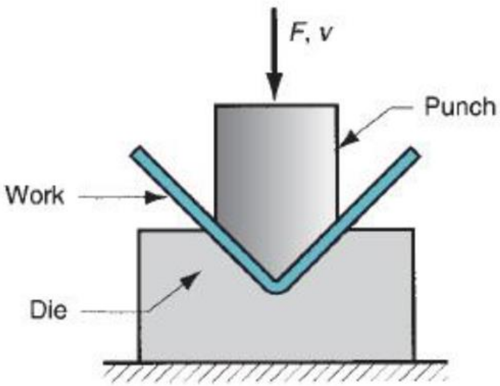


Extrusion

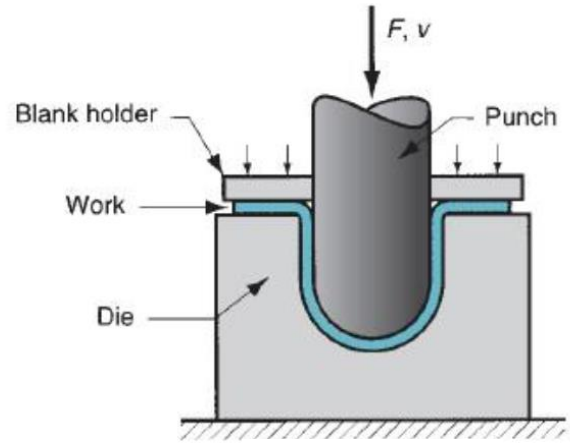


Wire and Bar Drawing

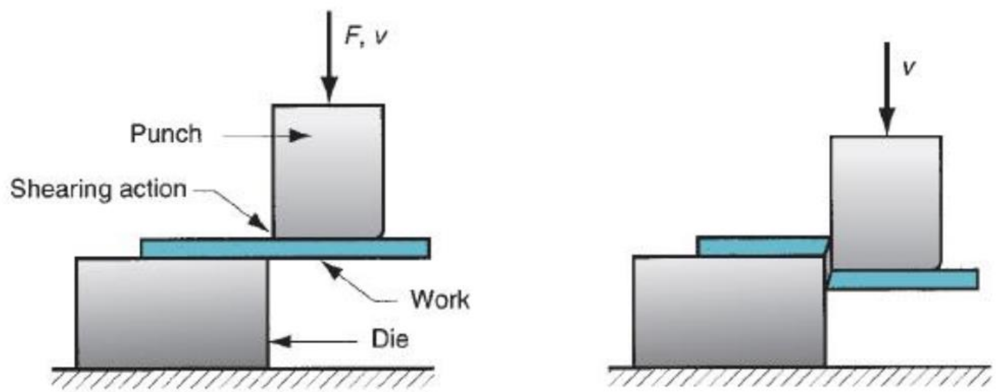
Sheet metalworking



Bending



Drawing



(1) Shearing (2)

Bulk Deformation

- Metal forming operations which cause significant shape change by deforming metal parts whose initial form is bulk rather than sheet
- Starting forms:
  - Cylindrical bars and billets,
  - Rectangular billets and slabs, and similar shapes
- These processes stress metal sufficiently to cause plastic flow into desired shape
- Performed as cold, warm, and hot working operations

Importance of Bulk Deformation

- In hot working, significant shape change can be accomplished

- In cold working, strength is increased during shape change

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

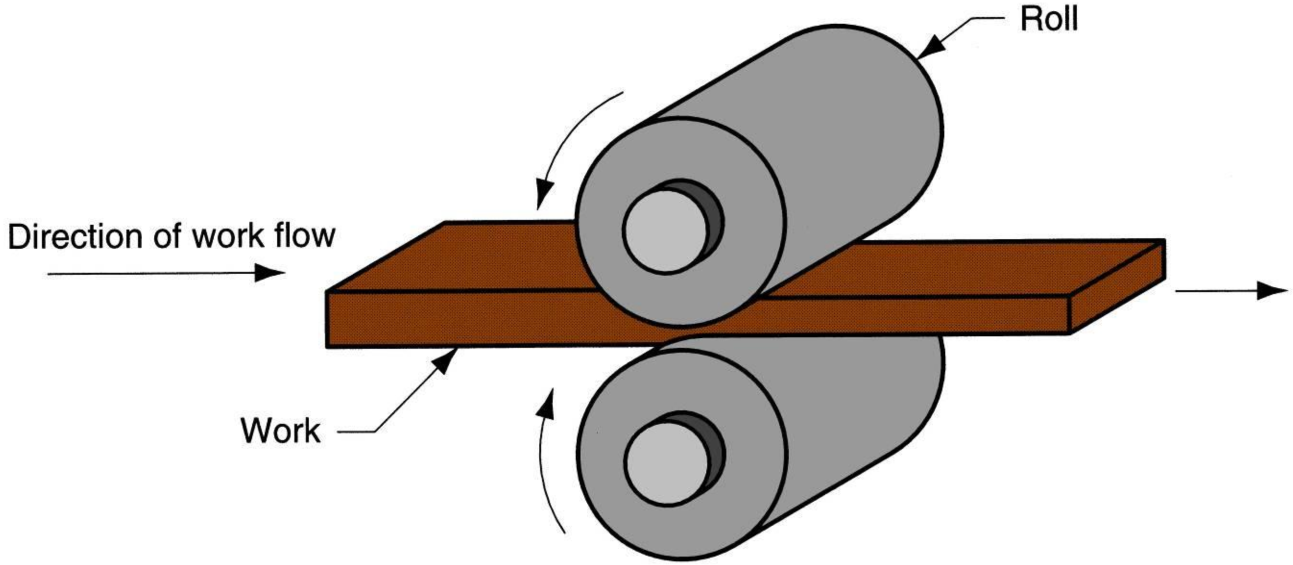
3. Extrusion – work is squeezed through a die opening, thereby taking the shape of the opening

4. Wire and bar drawing – diameter of wire or bar is reduced by pulling it through a die opening

Rolling

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

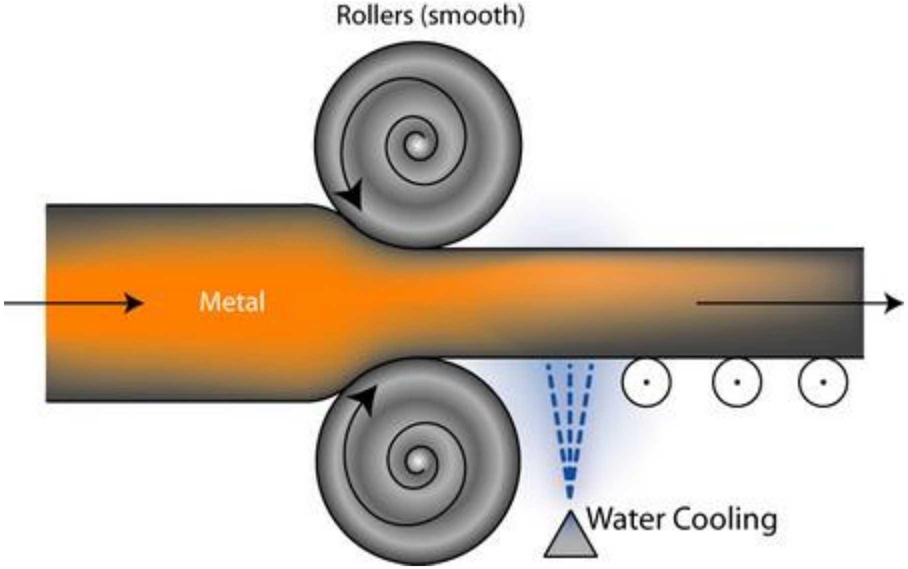
- Rotating rolls perform two main functions:

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

✓ Simultaneously squeeze the work to reduce its cross section

Rolling Processes

Working Principle



Rolling Processes

The process of plastically deforming metal by passing it between rolls is known as Rolling.

In deforming metal between rolls, the work is subjected to high compressive stress from the squeezing action of the rolls and to surface shear stresses as a result of the friction between rolls and metals.

The frictional forces are also responsible for drawing the metal into the rolls

Types of Rolling

- Based on workpiece 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

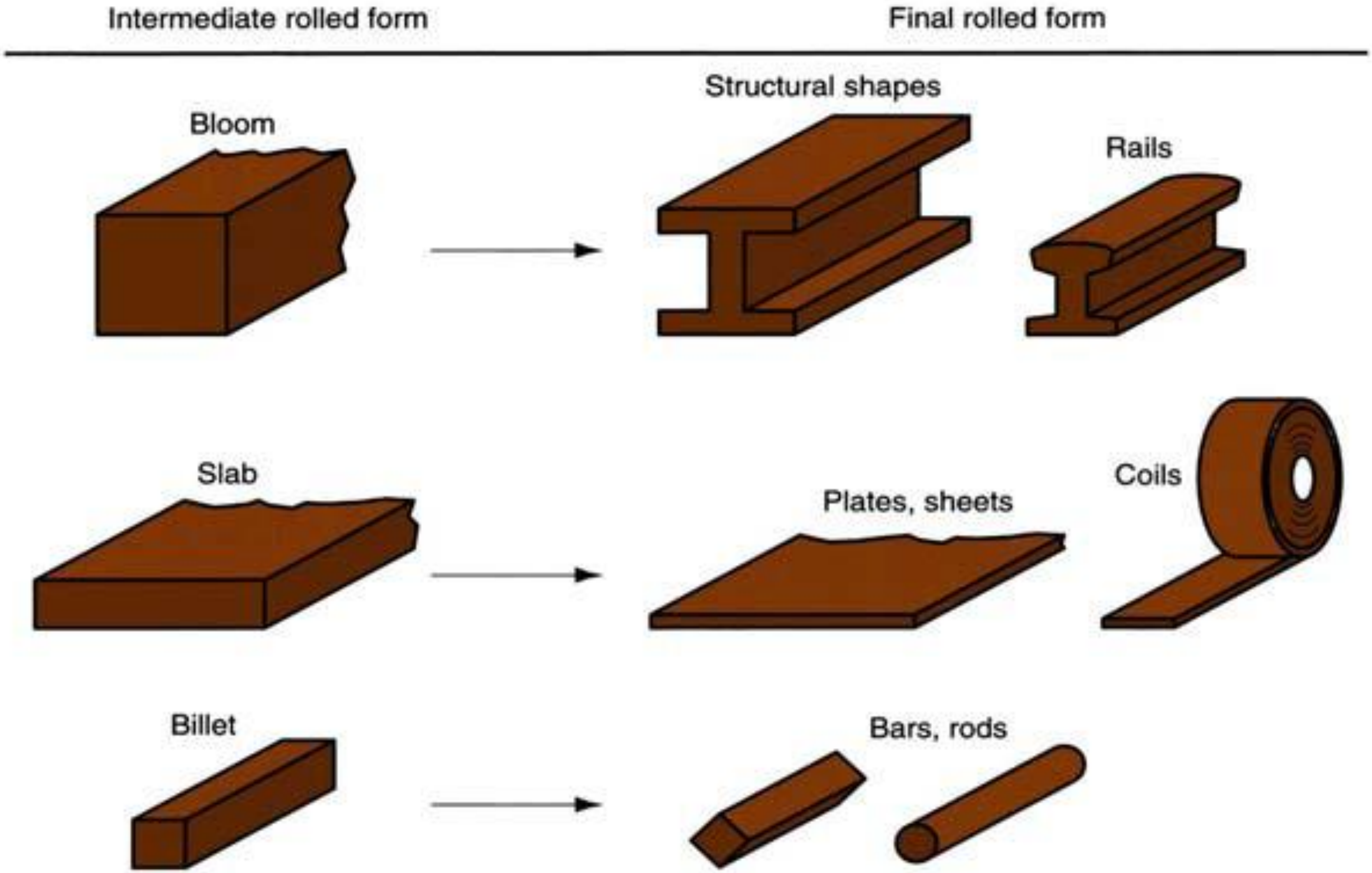
TERMINOLOGY

INGOT

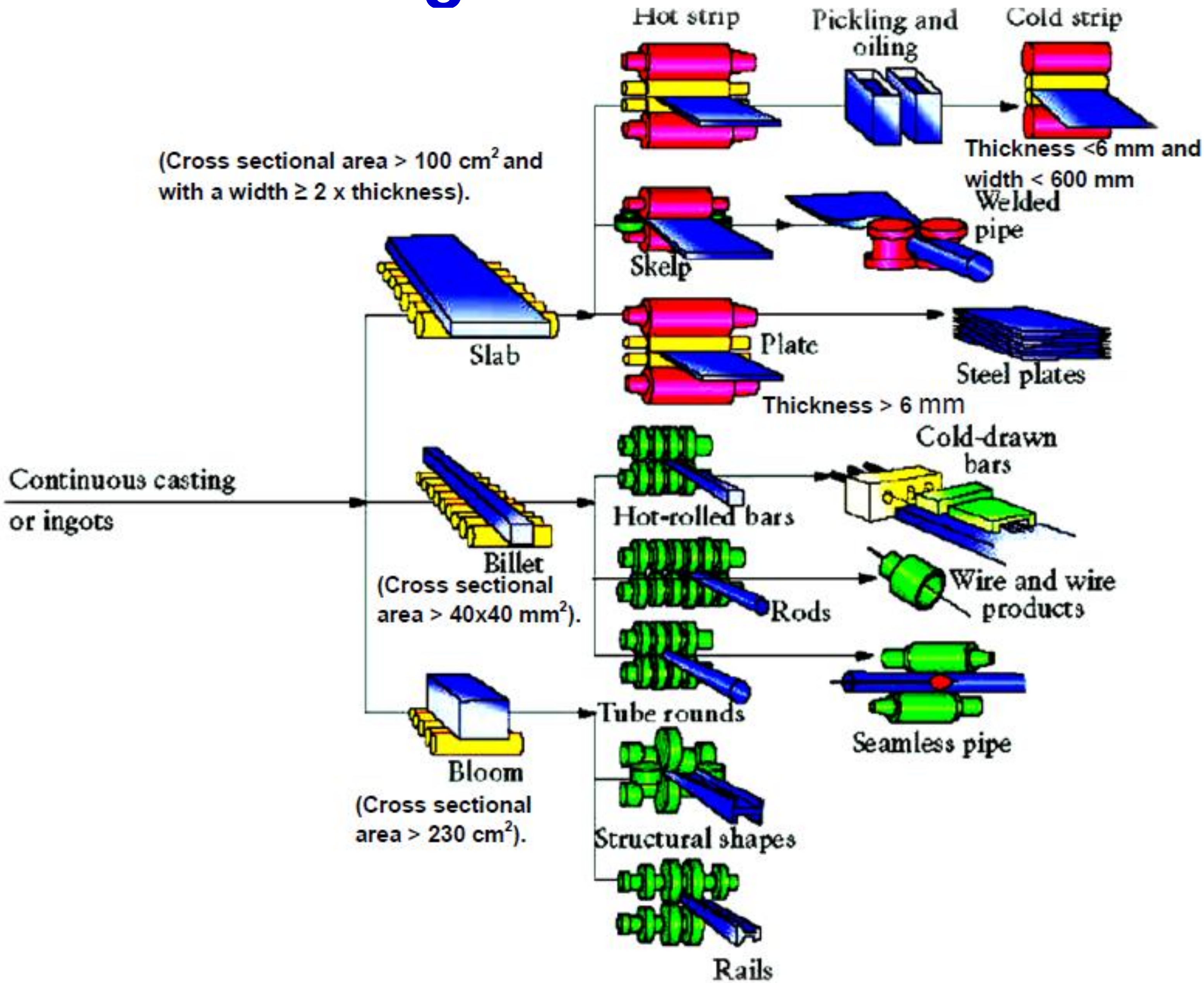
Bloom, Billet & Slab are Semi finished products

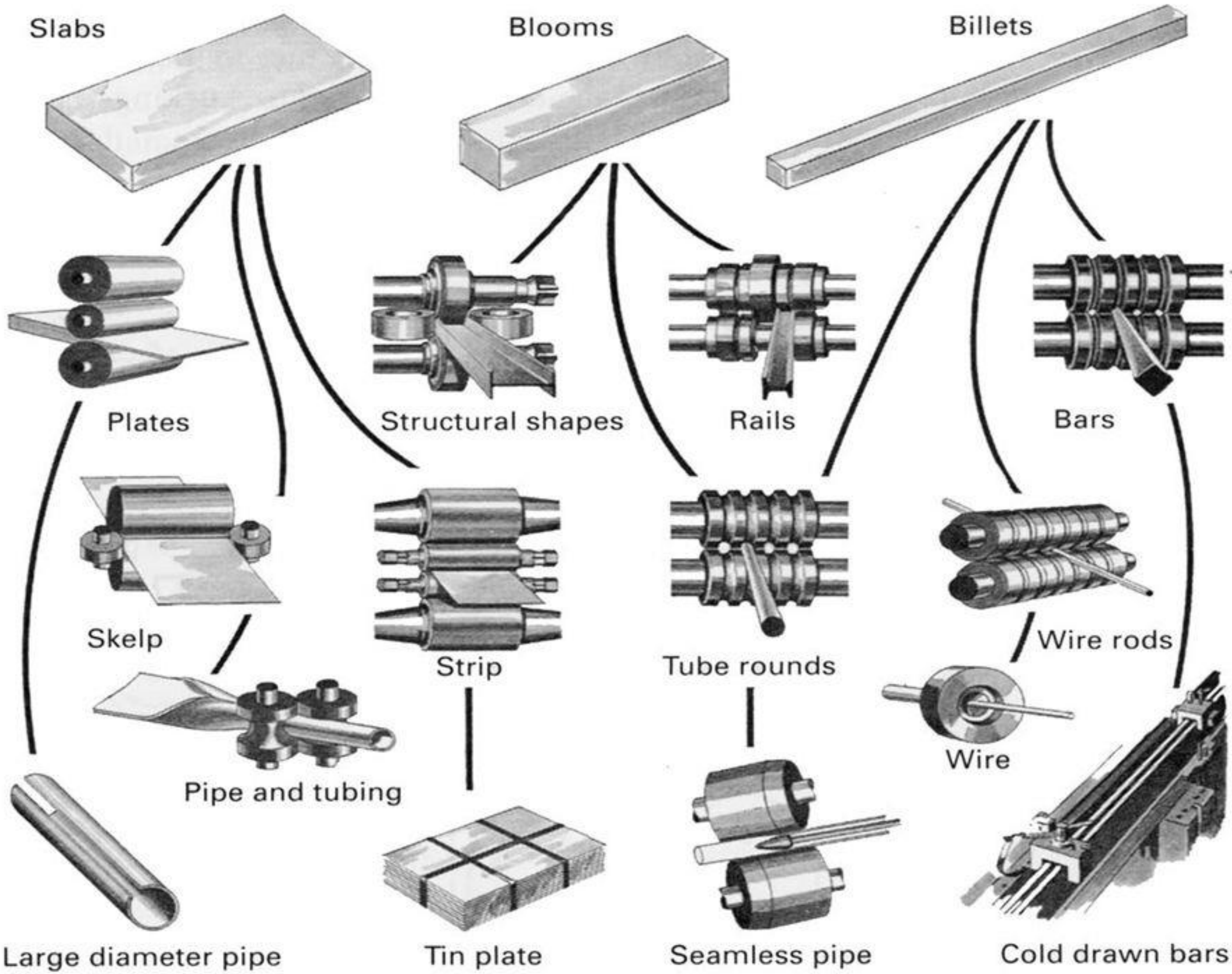
- **BLOOM** [150 x150 mm] or [250x300 mm]
  Width is equal to thickness & Cross section is more than 230 cm2
- **BILLET** : Minimum Cross Section is 40x40
  [50 x 50] or [125 x 125]
- **SLAB** : Cross sectional area is more than 100 cm2
  Width is twice of thickness
- **PLATE** [t > 6.35 mm]
- **SHEET** [t < 6.35]
- **STRIP** [t = 6.35 & b = 600 mm]
- **FOIL** [t < 1.5 mm & b= 300mm]

Rolling Processes



Rolling Processes



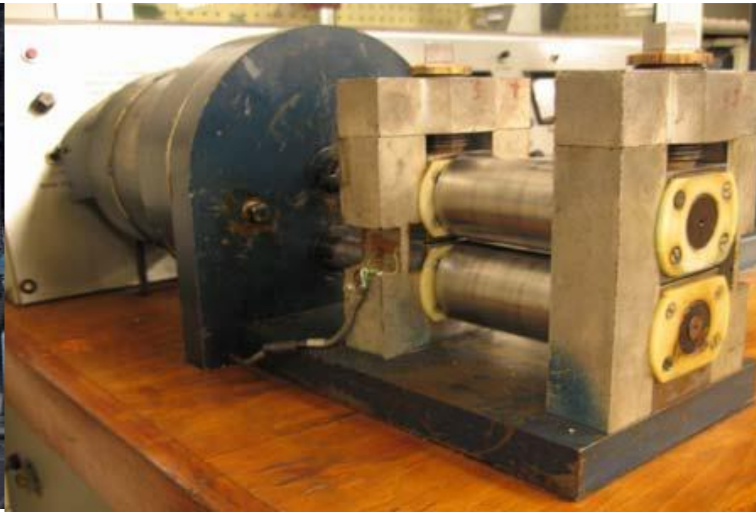

Slabs
Blooms
Billets
Plates
Structural shapes
Rails
Bars
Skelp
Strip
Tube rounds
Wire rods
Wire
Pipe and tubing
Large diameter pipe
Tin plate
Seamless pipe
Cold drawn bars

Rolling Mills

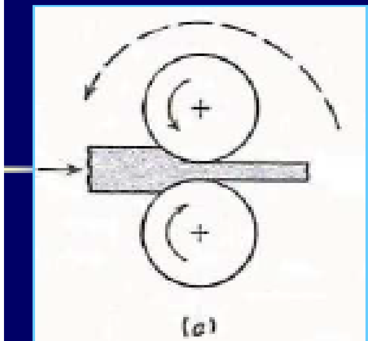
A rolling mill consist of basically of rolls, bearings, a housing for containing these parts and a drive for applying power to the rolls and controlling their speed.

The force involved during rolling are in MN range.

Very rigid construction is needed and very large motors are required to provide necessary powers.

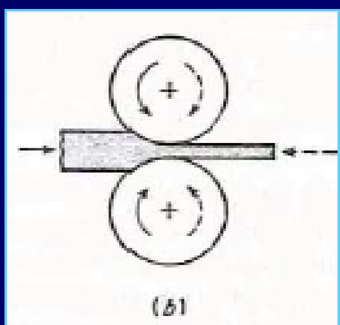


Typical arrangement of rollers for rolling mills



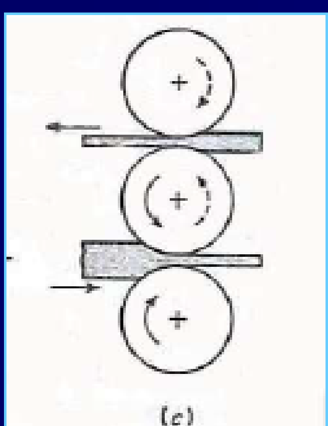
Two-high mill, pullover

The stock is returned to the entrance for further reduction.



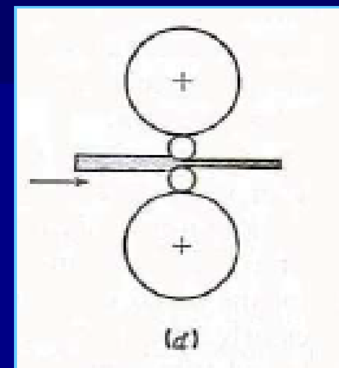
Two-high mill, reversing

The work can be passed back and forth through the rolls by reversing their direction of rotation.



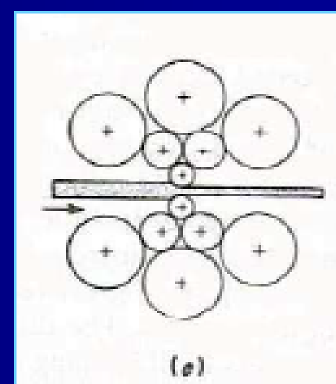
Three-high mill

Consist of upper and lower driven rolls and a middle roll, which rotates by friction.



Four-high mill

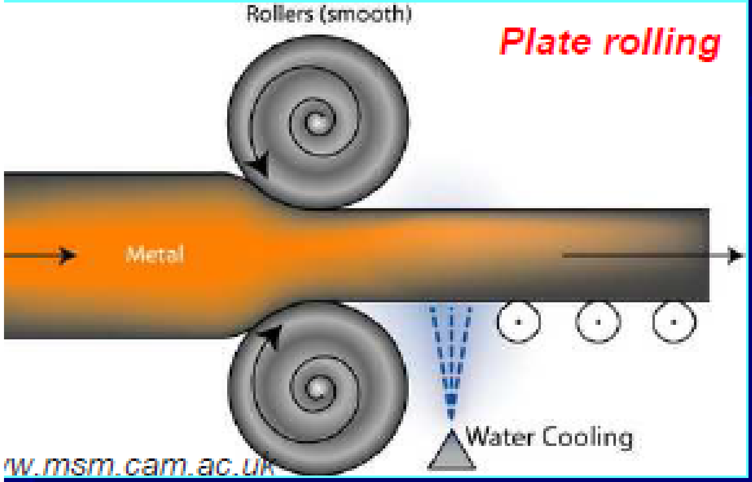
Small-diameter rolls (less strength & rigidity) are supported by larger-diameter backup rolls



Cluster mill or Sendzimir mill

Each of the work rolls is supported by two backing rolls.

Hot-rolling



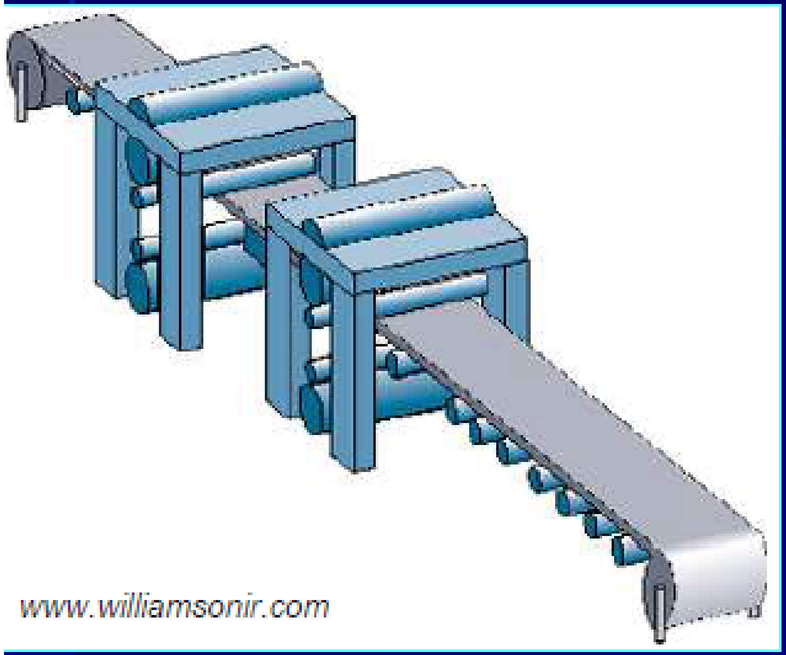
- The first hot-working operation for most steel products is done on the ***primary roughing mill*** (blooming, slabbing or cogging mills).

- These mills are normally two-high reversing mills with 0.6-1.4 m diameter rolls (designated by size).

- The objective is to breakdown the cast ingot into ***blooms*** or ***slabs*** for subsequent finishing into bars, plate or sheet.

- In ***hot-rolling steel***, the slabs are heated initially at 1100 -1300 ºC. The temperature in the last finishing stand varies from 700 - 900 ºC, but should be above the upper ***critical temperature*** to produce uniform equiaxed ferrite grains.

Cold-rolling



• Cold rolling is carried out under recrystallisation temperature and introduces work hardening.

• The starting material for cold-rolled steel sheet is pickled hot-rolled breakdown coil from the continuous hot-strip mill.

• The ***total reduction*** achieved by cold-rolling generally will vary from about 50 to 90%.

• The reduction in each stand should be distributed uniformly without falling much below the ***maximum reduction*** for each pass.

Cold-rolling

- Cold rolling provide products with ***superior surface finish*** (due to low temperature → no oxide scales)

- Better ***dimensional tolerances*** compared with hot-rolled products due to less thermal expansion.

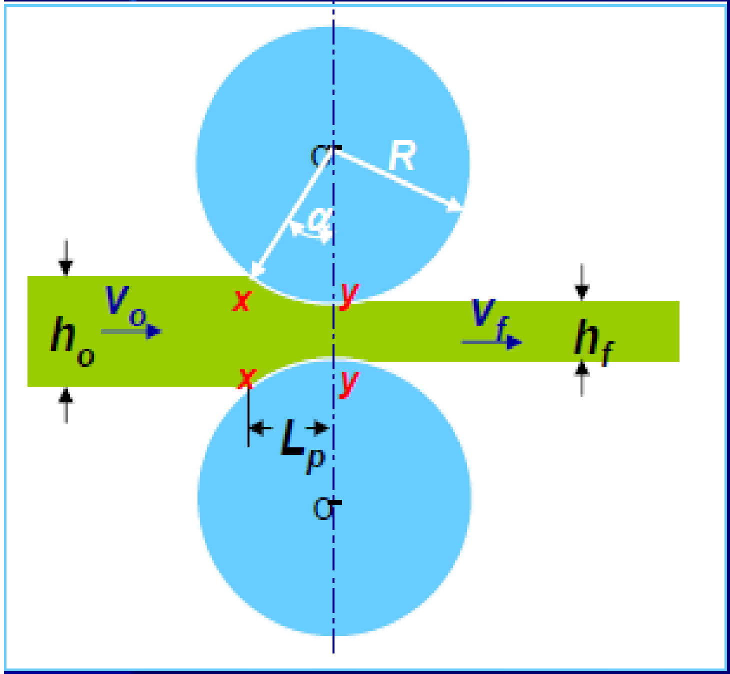
- Cold-rolled nonferrous sheet may be produced from hot-rolled strip, or in the case of certain copper alloys it is cold-rolled directly from the cast state.

Cold rolled strips

Cold rolled metals are rated as 'temper'

Fundamental concept of metal rolling

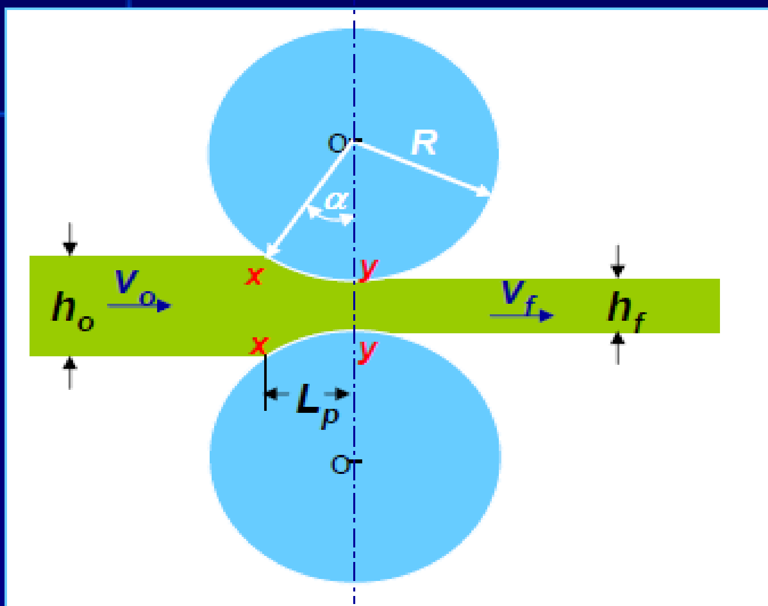
Assumptions



1) The ***arc of contact*** between the rolls and the metal is a part of a circle.
2) The ***coefficient of friction***, μ, is constant in theory, but in reality μ varies along the arc of contact.
3) The metal is considered to ***deform plastically*** during rolling.
4) The ***volume of metal*** is constant before and after rolling. In practical the volume might decrease a little bit due to close-up of pores.
5) The ***velocity of the rolls*** is assumed to be constant.
6) The metal only extends in the rolling direction and ***no extension in the width of the material***.

Forces and geometrical relationships in rolling

Forces and geometrical relationships in rolling

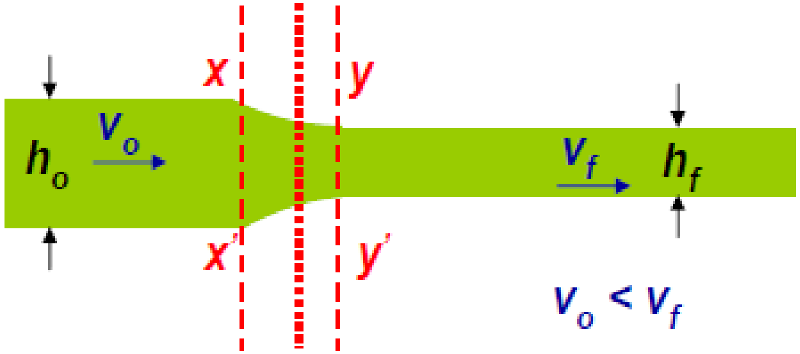


- A metal sheet with a thickness h_o enters the rolls at the entrance plane *xx* with a velocity v_o.
- It passes through the roll gap and leaves the exit plane *yy* with a reduced thickness h_f and at a velocity v_f.
- Given that there is ***no increase in width***, the vertical compression of the metal is translated into an elongation in the rolling direction.
- Since there is ***no change in metal volume*** at a given point per unit time throughout the process, therefore

$$bh_o v_o = bhv = bh_f v_f \quad \text{...Eq.1}$$

Where b is the width of the sheet

v is the velocity at any thickness h intermediate between h_o and h_f.



From *Eq.1*

$$bh_o v_o = bh_f v_f$$

Given that $b_o = b_f$

$$h_o \frac{L_o}{t} = h_f \frac{L_f}{t}$$

Then we have

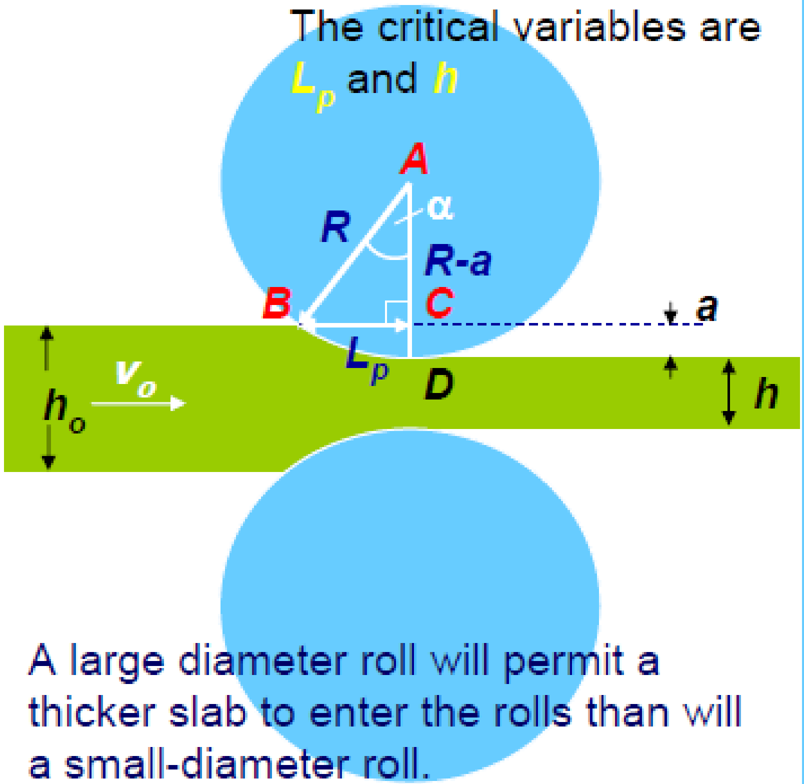
$$v_o h_o = v_f h_f$$

$$\frac{v_o}{v_f} = \frac{h_f}{h_o} \quad \text{...Eq.2}$$

When $h_o > h_f$, we then have $v_o < v_f$

The *velocity* of the sheet must steadily increase from entrance to exit such that a vertical element in the sheet remain *undistorted*.

The maximum reduction



A large diameter roll will permit a thicker slab to enter the rolls than will a small-diameter roll.

From triangle ***ABC***, we have

$$R^2 = L_p^2 + (R-a)^2$$

$$L_p^2 = R^2 - (R^2 - 2Ra + a^2)$$

$$L_p^2 = 2Ra - a^2$$

As ***a*** is much smaller than ***R***, we can then ignore ***a***^{2}.

$$L_p \approx \sqrt{2Ra} \approx \sqrt{R\Delta h} \quad \text{...Eq.6}$$

Where $\Delta h = h_o - h_f = 2a$

$$\mu = \tan\alpha = \frac{L_p}{R - \Delta h/2} \approx \frac{\sqrt{R\Delta h}}{R - \Delta h/2} \approx \sqrt{\frac{\Delta h}{R}}$$

$$\Rightarrow (\Delta h)_{max} = \mu^2 R \quad \text{...Eq.7}$$

Rolling Parameters

- Draught (or draft):
- Absolute: $$\delta_t = t_1 - t_2$$
- Maximum: $$\delta_{\max} = \mu^2 R$$

where t_1, t_2 – initial and final thickness
μ = coefficient of friction between roll and work and
R = Radius of roll

Absolute elongation: $$\delta_l = l_2 - l_1$$

where l_1 is the initial length of w/p

l_2 is the final length of w/p

Absolute spread: $$\delta_b = b_2 - b_1$$

where b_1 is initial breadth of w/p

b_2 is final breadth of w/p

Angle of contact:

$$\cos\alpha = 1 - \frac{\delta_t}{D}$$

where D is the diameter of the roll=$2R$

Coefficient of friction:

$$\mu = \tan\alpha$$

- Rolling Force F = $\bar{Y}_f \, wL$

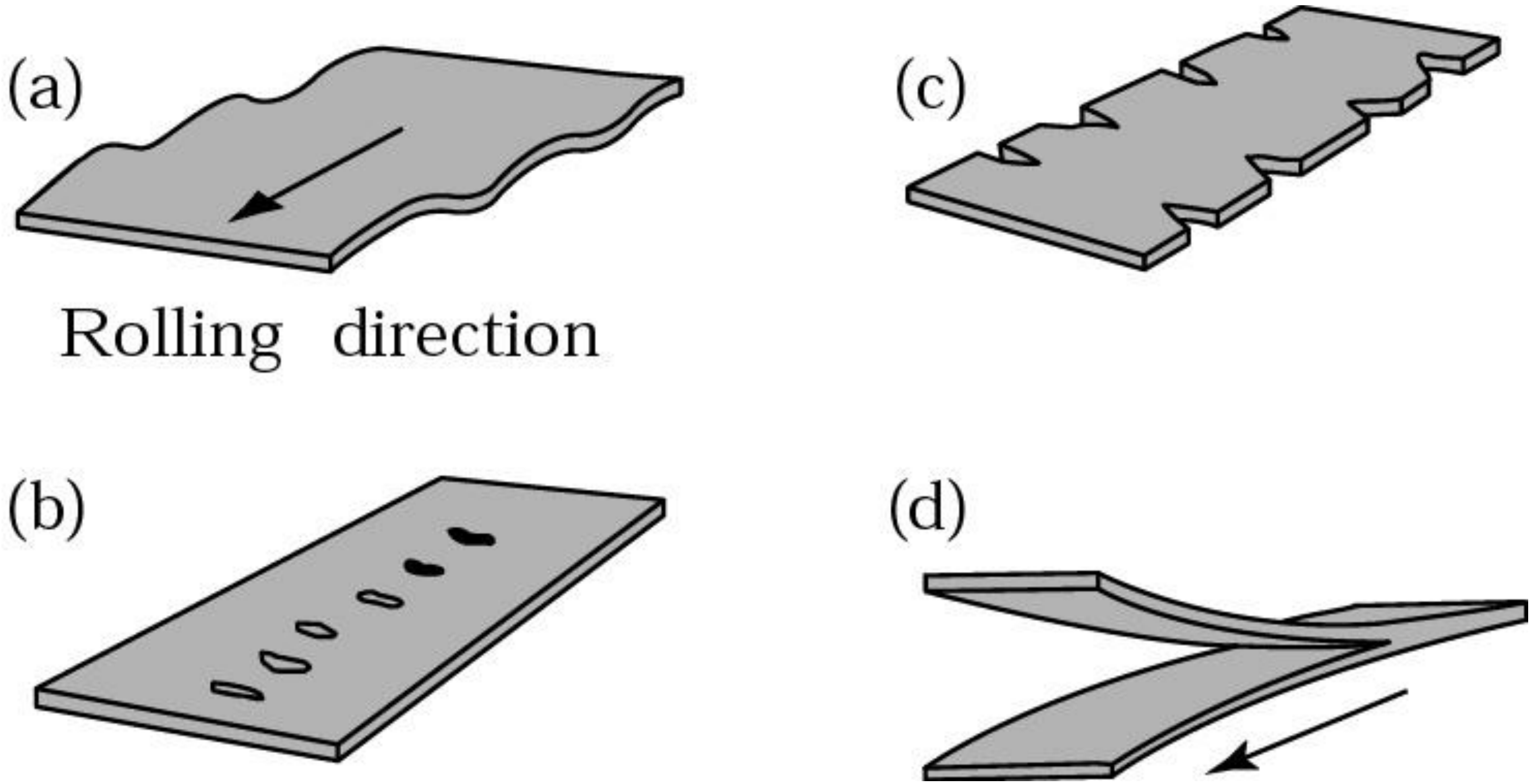
- Where w= width of workpiece
- L = length of contact

- Torque T = 0.5 FL

- Power P = 2πNFL

- N – rotational speed of roll (rev/min)

Rolling Defects



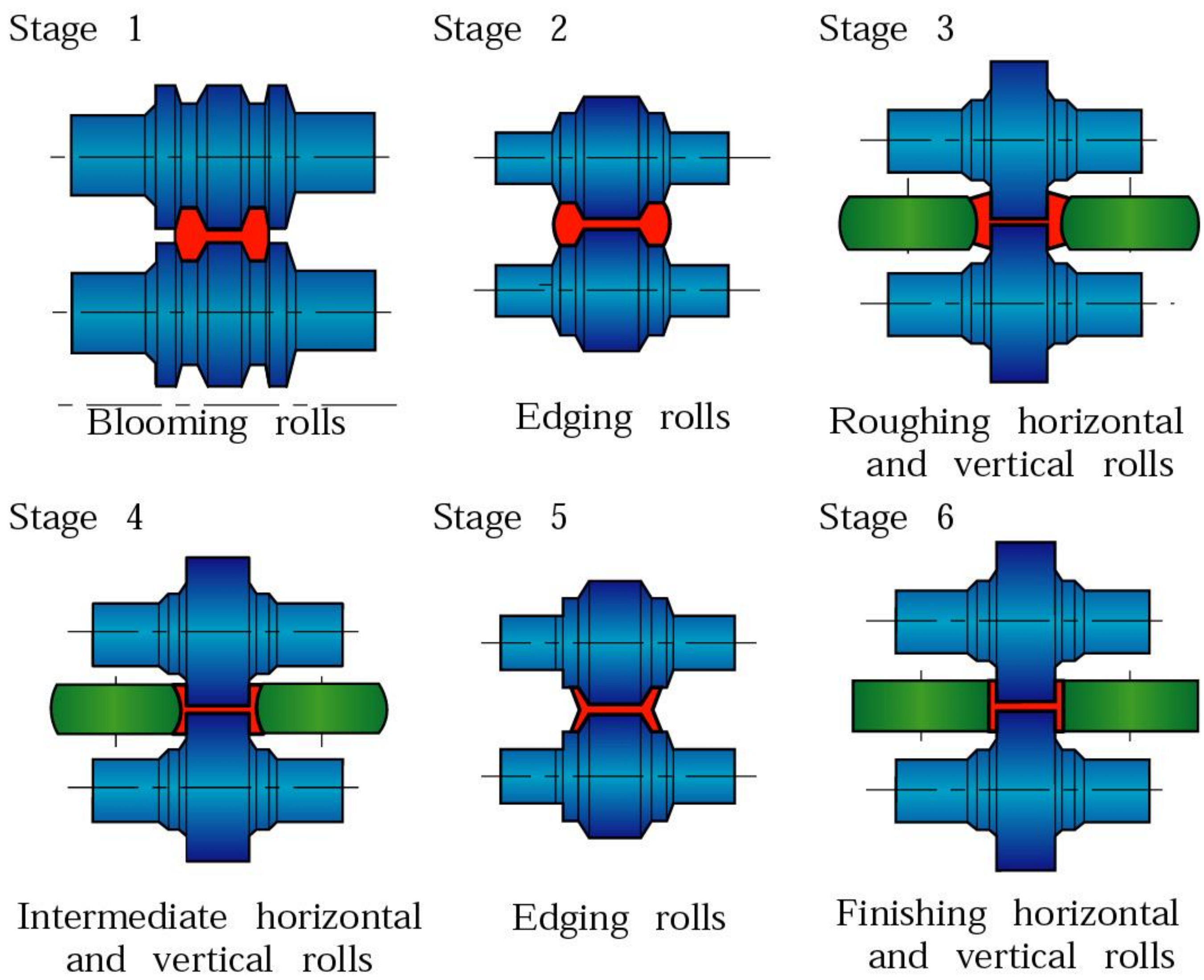
(a) wavy edges; (b) zipper cracks in the center of the strip; (c) edge cracks; and (d) alligatoring.

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

https://www.youtube.com/watch?v=6xnKmt_gsLs

Shape-Rolling Operations

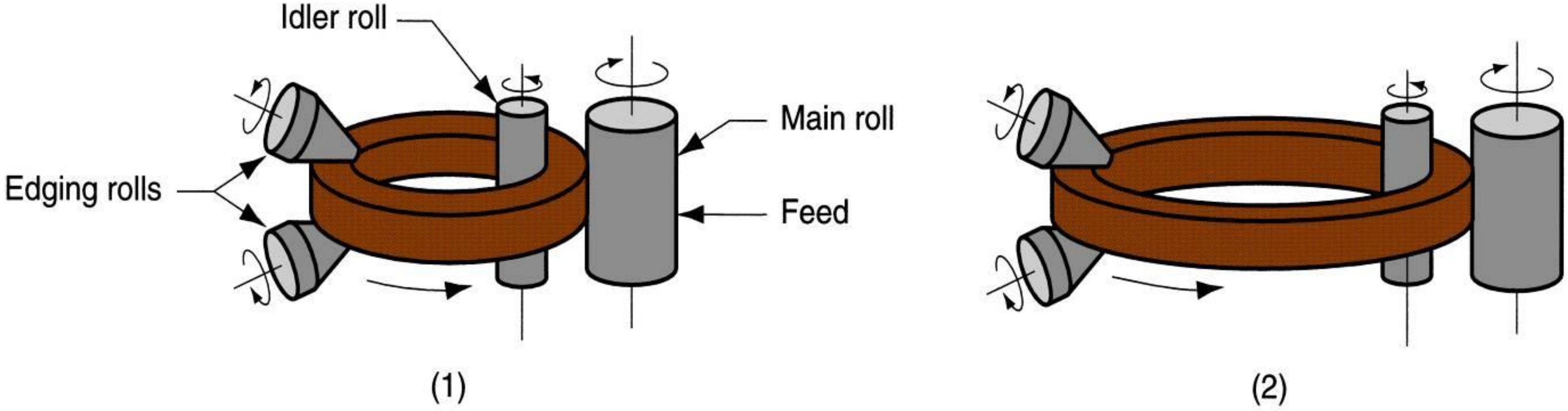


Ring Rolling

- 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

Ring Rolling



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

https://www.youtube.com/watch?v=aYYmzOYltsk

Thread Rolling

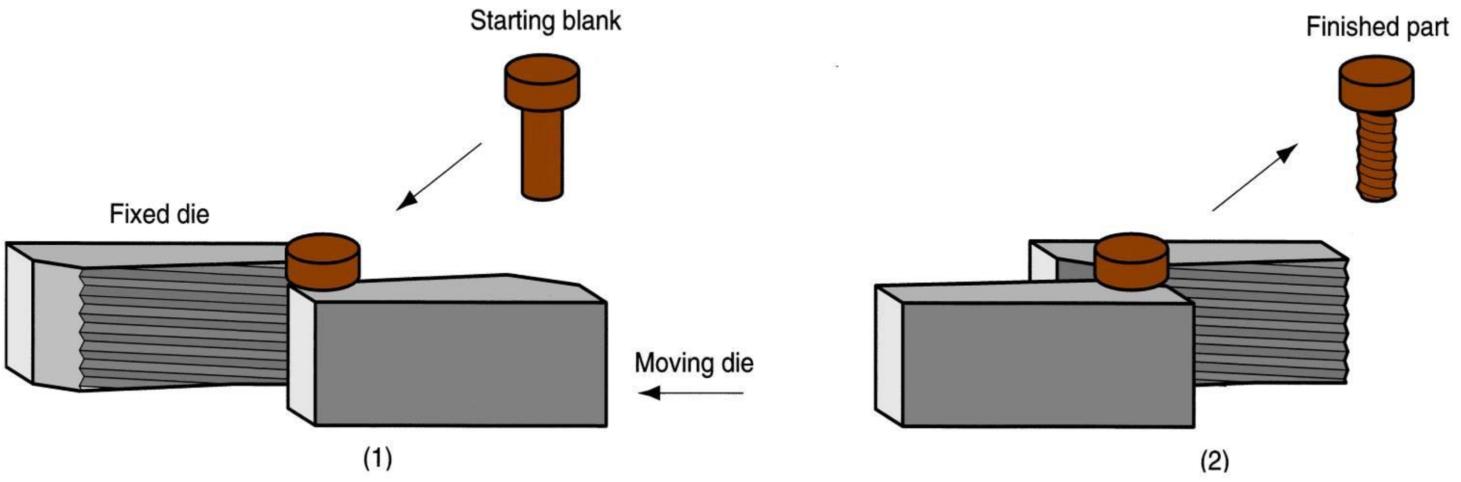
- Bulk deformation process used to form threads on cylindrical parts by rolling them between two dies
-

✓ 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

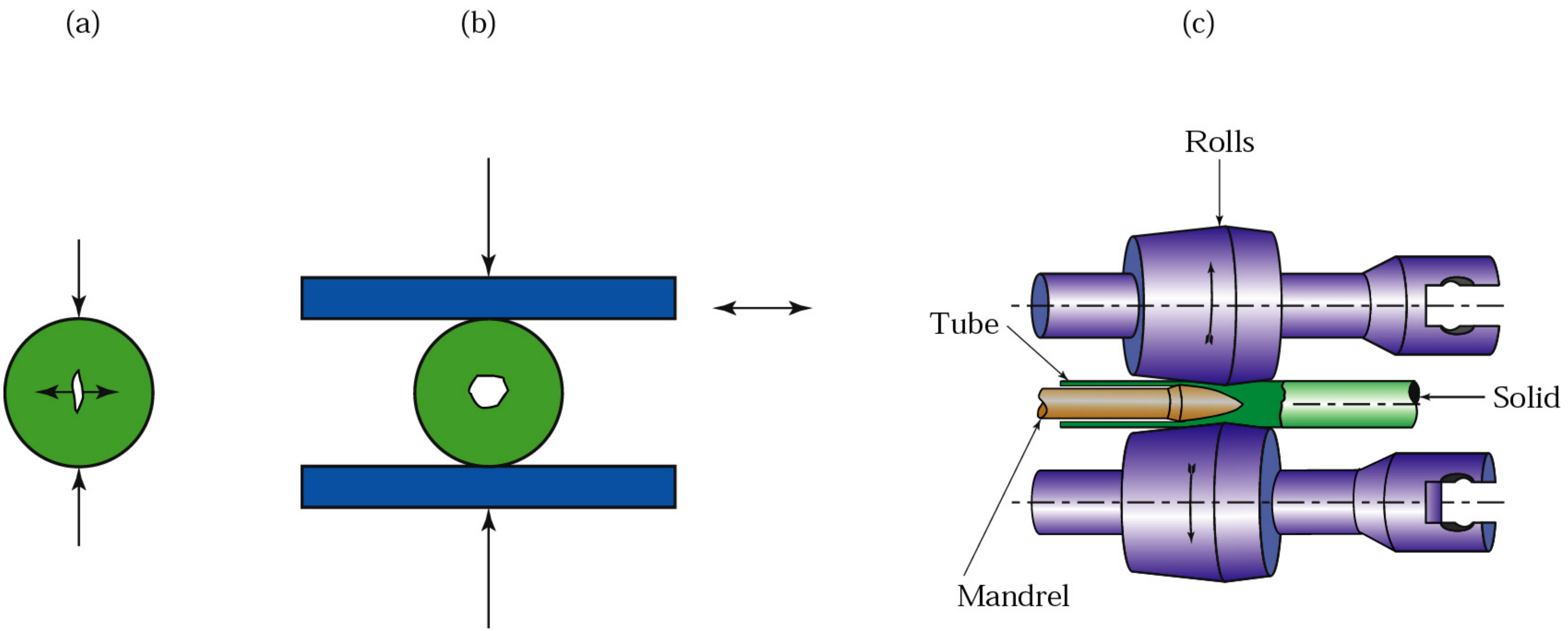
Thread Rolling



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

https://www.youtube.com/watch?v=bclnb_Cp4sE

Production of Seamless Tubing and Pipe



https://www.youtube.com/watch?v=lueB6RvqMSo

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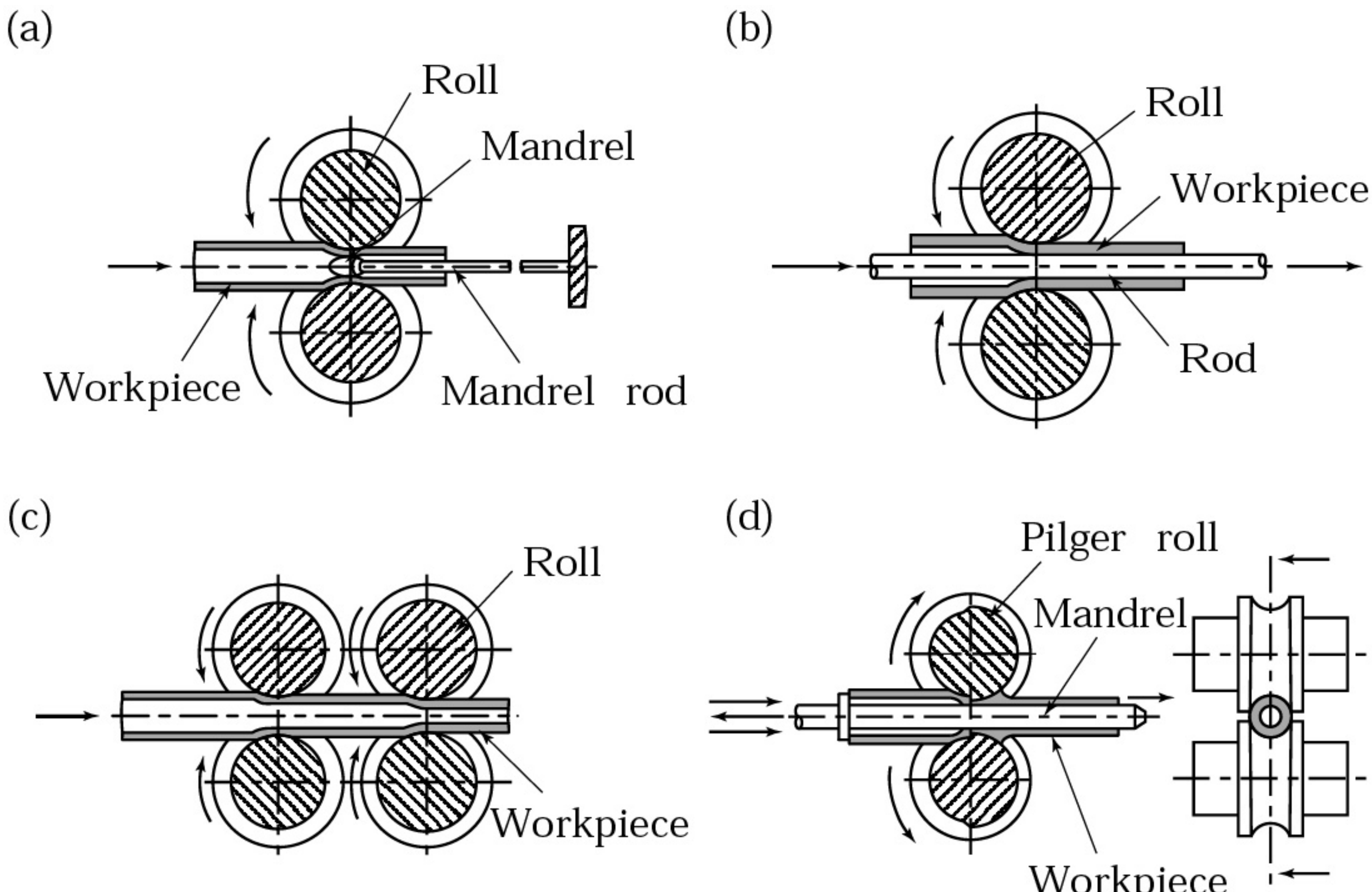
Production of Seamless Tubing



Example

- A 20 mm thick plate is to be rolled into a 4 mm thick sheet in a four stand continuous rolling mill. All rolls have equal diameters. Assume equal reduction in each stand by adjusting the gap between rollers, and coefficient of friction is 0.14.

– Find the diameter of rolls.

– Assume no change in the width of sheet, determine the velocity of final rolled sheet if the feed velocity of 20 mm thick plate is 5 m/min.

Solution

Intial thickness = 20, Final thickness = 4, No. of Stands = 4, μ = 0.14

- Reduction in thickness at each stand = (20-4)/4 = 4mm
- Thickness (t1) after stand 1= 20 - 4 = 16
- Thickness (t2) after stand 2= 16 – 4 =12, so t3 = 8 and t4 = 4 mm
- Max. Draft = μ^2R
- **R = 4/ (0.14)2 = 204.081, Diameter = 408.163 mm**
- AiVi = A1V1= A2V2= A3V3= A4V4
- **V4 = (AiVI)/A4 = (20 X 5)/4 = 25 m/min**

- A 42.0 mm thick plate made of low carbon steel is to be reduced to 34.0 mm in one pass in a rolling operation. As the thickness is reduced, the plate widens by 4%. The yield strength of the steel plate is 174 MPa and the tensile strength is 290 MPa. The entrance speed of the plate is 15.0 m/min. The roll radius is 325 mm and the rotational speed is 49.0 rev/min. Determine (a) the minimum required coefficient of friction that would make this rolling operation possible, (b) exit velocity of the plate.

Solution: (a) Maximum draft $d_{max} = \mu^2 R$

Given that $d = t_o - t_f = 42 - 34 = 8.0$ mm,

$\mu^2 = 8/325 = 0.0246$

$\mu = (0.0246)^{0.5} =$ **0.157**

(b) Plate widens by 4%.

$t_o w_o v_o = t_f w_f v_f$

$w_f = 1.04\ w_o$

$42(w_o)(15) = 34(1.04w_o)v_f$

$v_f = 42(w_o)(15)/\ 34(1.04w_o) = 630/35.4 =$ **17.8 m/min**

A 2.0 in thick slab is 10.0 in wide and 12.0 ft long. Thickness is to be reduced in three steps in a hot rolling operation. Each step will reduce the slab to 75% of its previous thickness. It is expected that for this metal and reduction, the slab will widen by 3% in each step. If the entry speed of the slab in the first step is 40 ft/min, and roll speed is the same for the three steps, determine: (a) length and (b) exit velocity of the slab after the final reduction.

Solution: (a) After three passes, $t_f = (0.75)(0.75)(0.75)(2.0) = 0.844$ in

$w_f = (1.03)(1.03)(1.03)(10.0) = 10.927$ in

$t_o w_o L_o = t_f w_f L_f$

$(2.0)(10.0)(12 \text{ x } 12) = (0.844)(10.927)L_f$

$L_f = (2.0)(10.0)(12 \text{ x } 12)/(0.844)(10.927) = 312.3$ in = **26.025 ft**

(b) Given that roll speed is the same at all three stands and that $t_o w_o v_o = t_f w_f v_f$,

Step 1: $v_f = (2.0)(10.0)(40)/(0.75 \text{ x } 2.0)(1.03 \text{ x } 10.0) = 51.78$ ft/min

Step 2: $v_f = (0.75 \text{ x } 2.0)(1.03 \text{ x } 10.0)(40)/(0.75^2 \text{ x } 2.0)(1.03^2 \text{ x } 10.0) = 51.78$ ft/min

Step 3: $v_f = (0.75^2 \text{ x } 2.0)(1.03^2 \text{ x } 10.0)(40)/(0.75^3 \text{ x } 2.0)(1.03^3 \text{ x } 10.0) =$ **51.78 ft/min**

Thanks