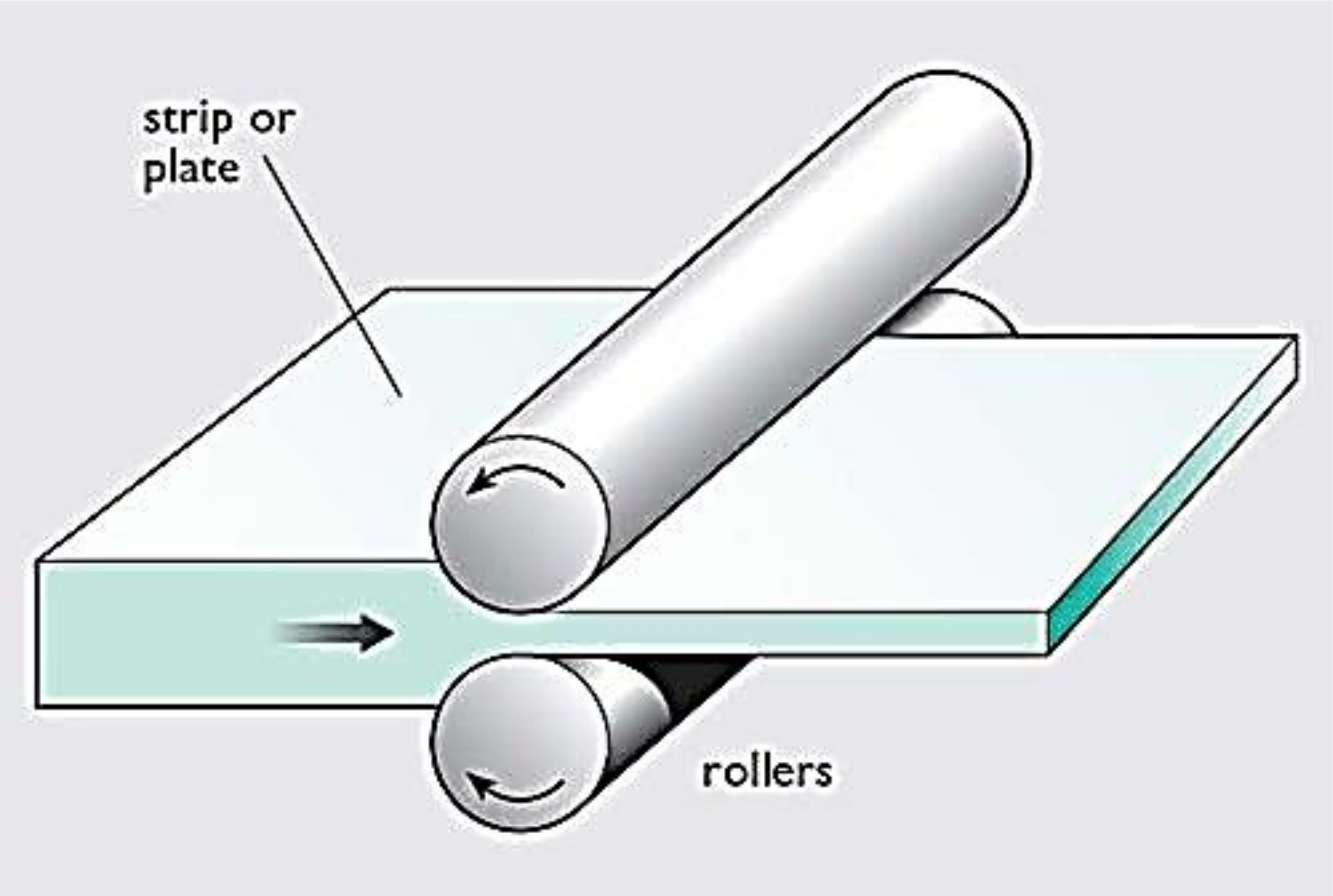
ROLLING



S.No	Hot Working	Cold Working
1	Working above recrystallization temperature	Working below recrystallization temperature
2	Formation of new crystals	No crystal formation
3	Surface finish not good	Good surface finish
4	No stress formation	Internal Stress formation
5	No size limit	Limited size

WHAT IS ROLLING??

The process of plastically deforming metal by passing it between rolls.

- The metal is subjected to high compressive stresses as a result of the friction between the rolls and the metal surface

Bloom is the product of first breakdown of ingot
(cross sectional area > 230 cm2).

Billet is the product obtained from a further reduction by hot rolling
(cross sectional area > 40x40 mm2).

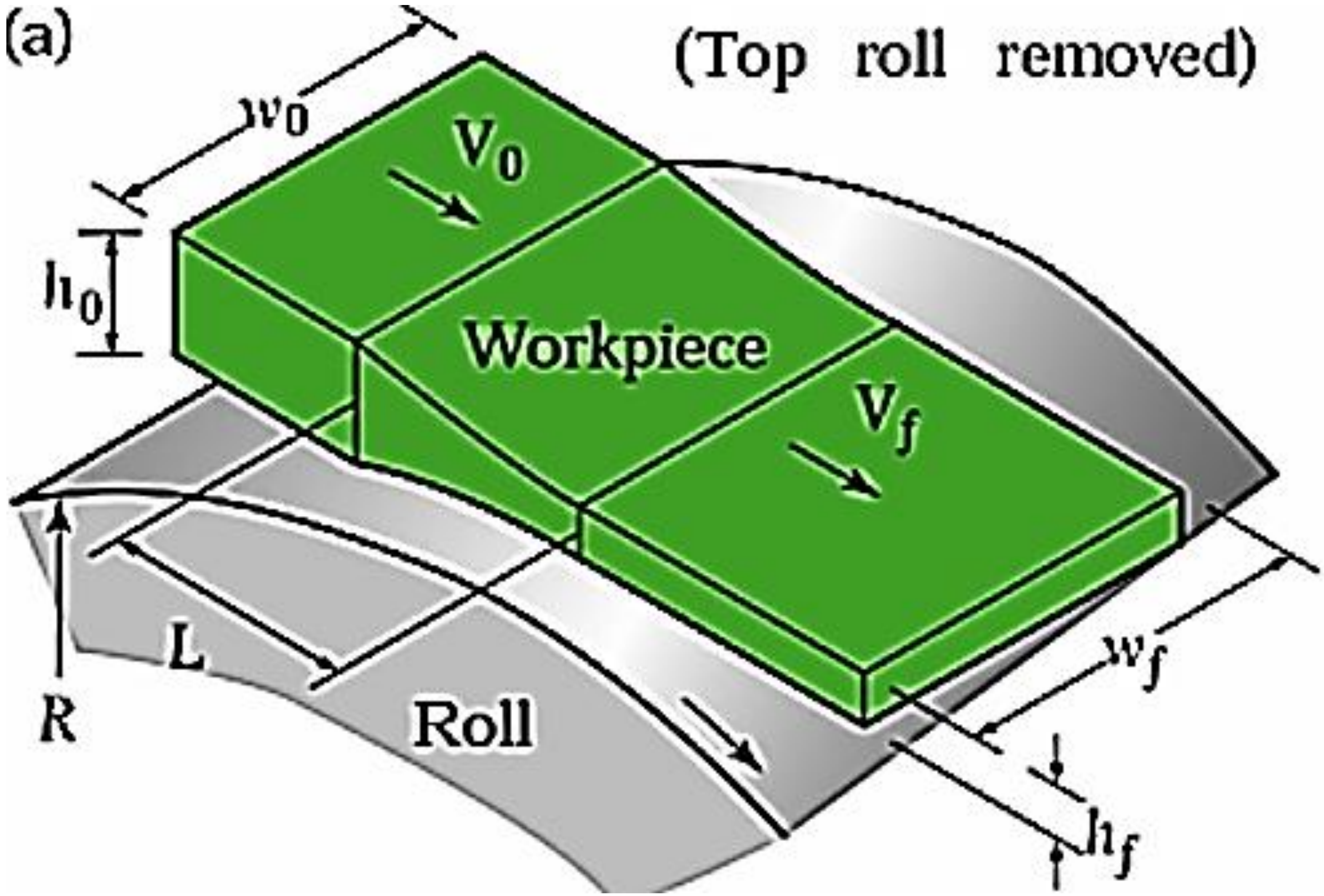
Slab is the hot rolled ingot
(cross sectional area > 100 cm2 and with a width ≥ 2 x thickness).

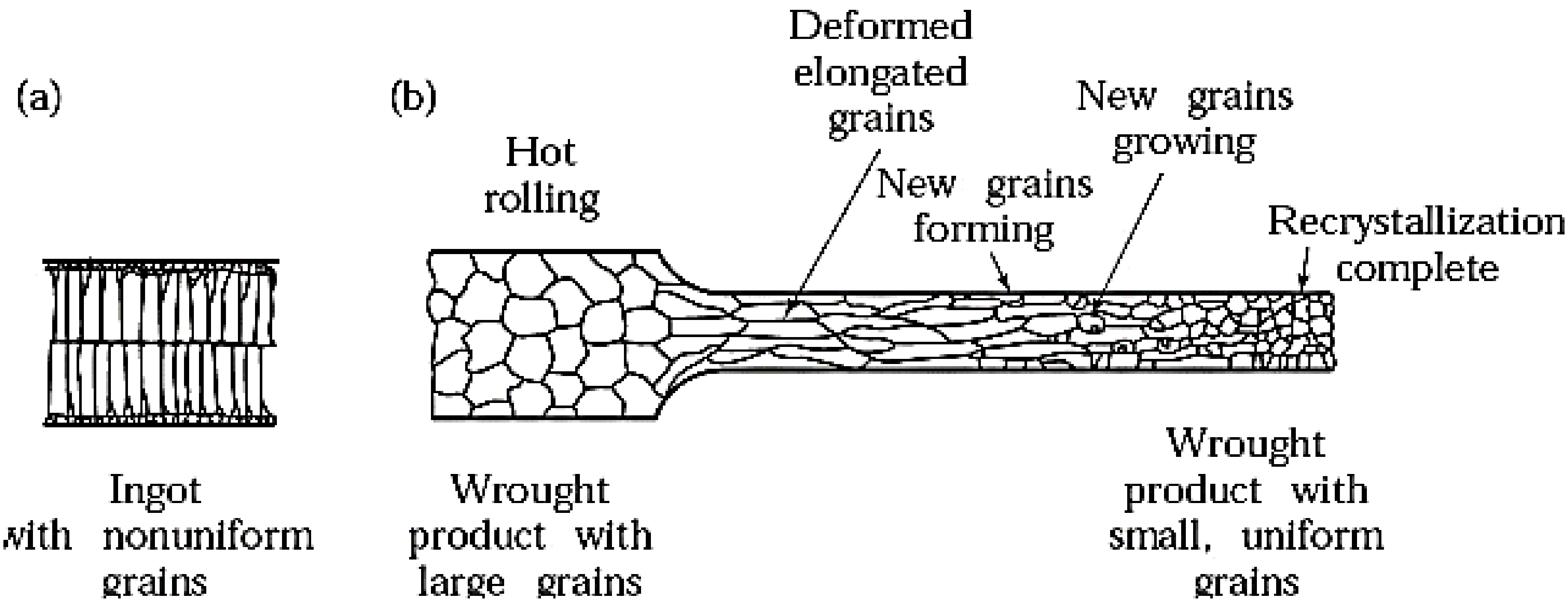
Plate is the product with a thickness > 6 mm.

Sheet is the product with a thickness < 6 mm and width > 600 mm.

Strip is the product with a thickness < 6 mm and width < 600 mm.

Flat-Rolling




(a)
(b)
Hot rolling
Deformed elongated grains
New grains forming
New grains growing
Recrystallization complete
Ingot with nonuniform grains
Wrought product with large grains
Wrought product with small, uniform grains

Flat Rolling

- Initial thickness h_o
- Final thickness h_f
- Roll gap L

- Surface speed of rolls V_r
- Entry velocity of strip V_o
- Final velocity of the strip V_f

- Neutral point, no-slip point – point along contact length where velocity of the strip equals velocity of the roll

- Draft: $h_o - h_f$
- Maximum draft possible: $h_o - h_f = \mu^2 R$
  - Coefficient of friction μ
  - Roll radius R

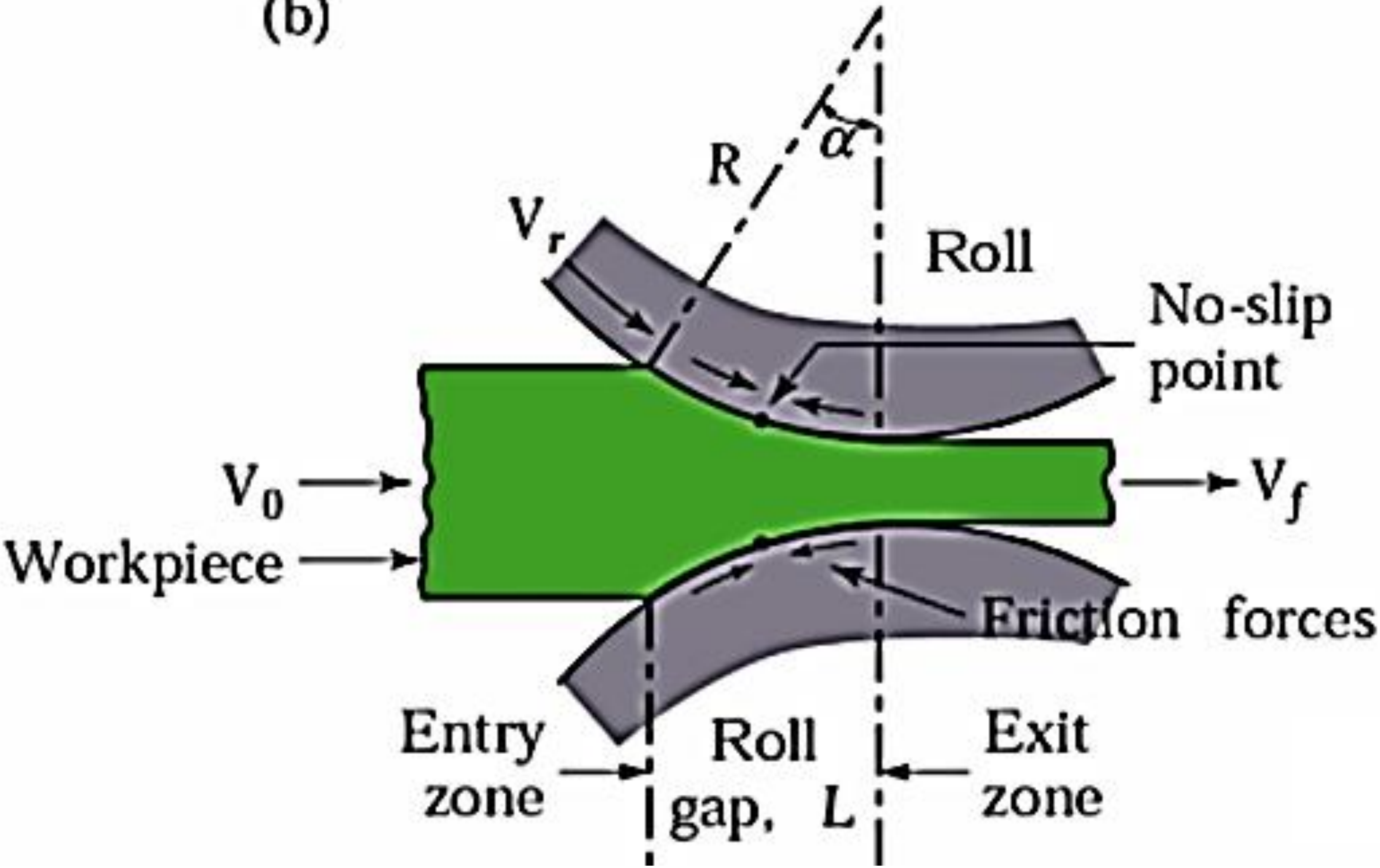
- The strip thickness is reduced at each rolling pass and the strip width increases slightly (around 2%)

- **Roll Force:** $\boldsymbol{F = LwY_{avg}}$
  - Roll-strip contact length L
  - **Contact length** $$L = \sqrt{R\left(h_0 - h_f\right)}$$
  - Average strip width w – despite the fact that spreading, or an increase in width, may actually occur if edger mills are not used
  - Average true stress of the strip in the roll gap Y_{avg}
  - Assumes no friction and thus predicts lower roll force than the actual value

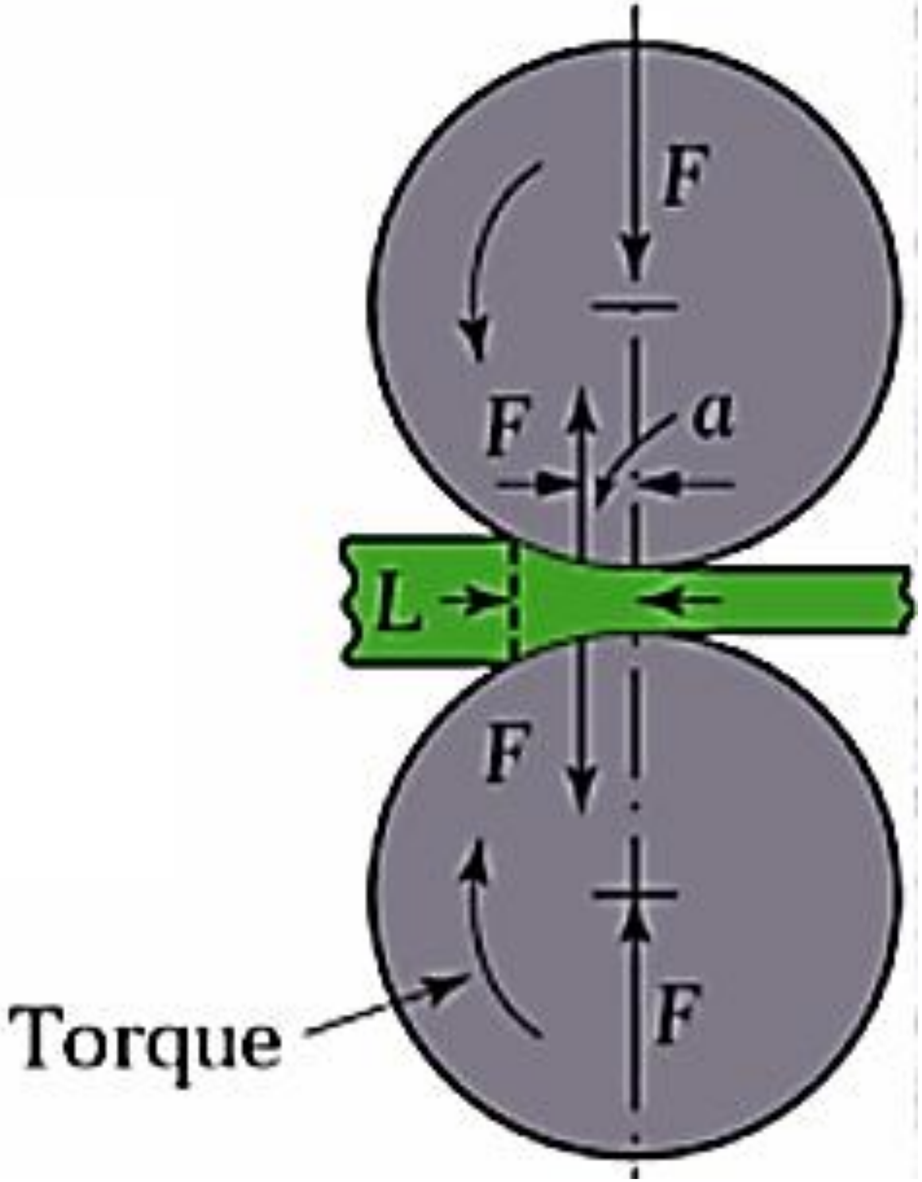
Power per roll (SI units) = $\pi FLN / 60{,}000$ ***kW***

Where F is in Newtons, L is in meters, and N is rpm of roll

(b)

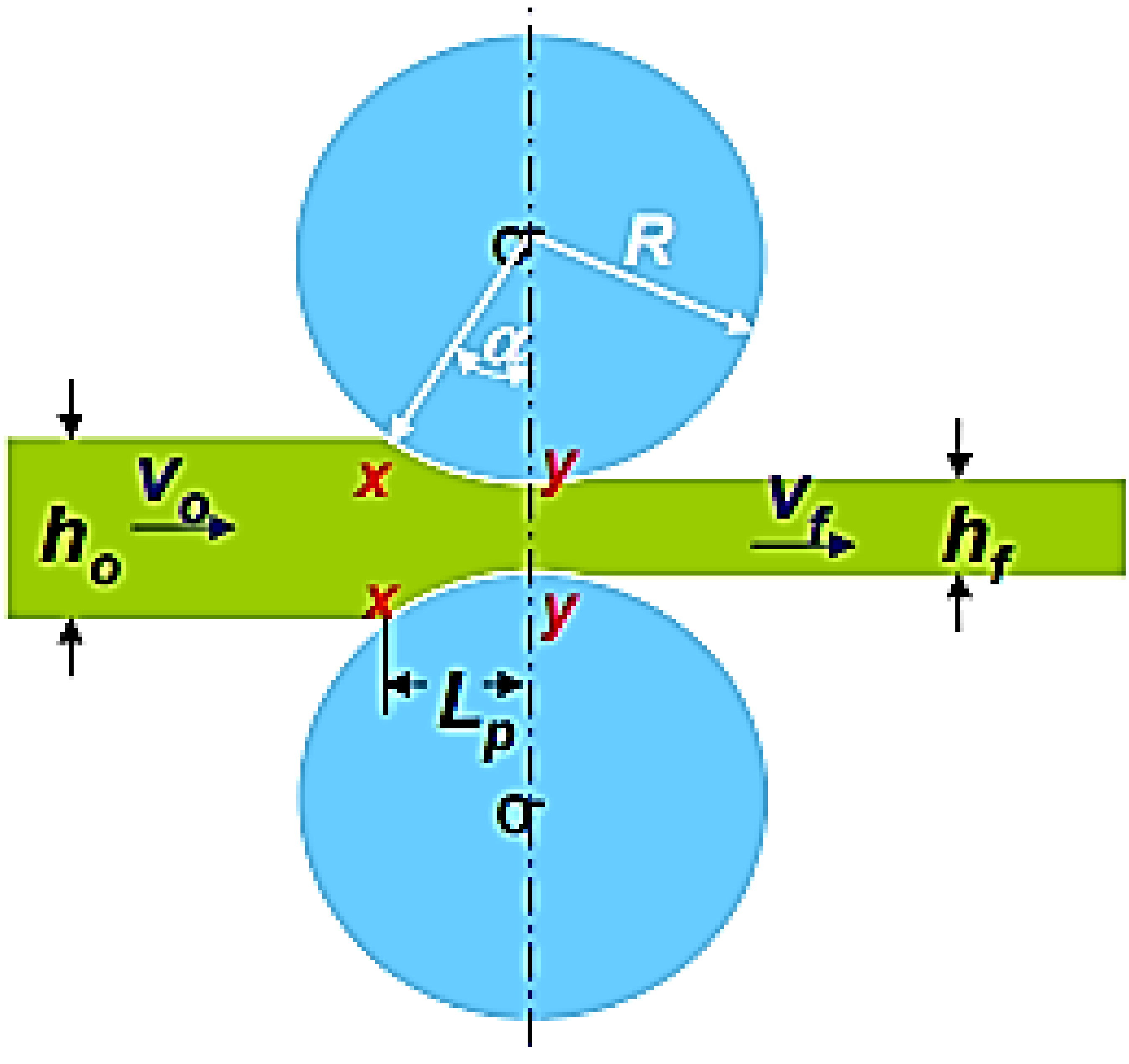

R
α
V r
Roll
No-slip
point
V 0
V f
Workpiece
Friction forces
Entry
zone
Roll
gap, L
Exit
zone

(c)



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***.
7) The ***cross sectional area*** normal to the rolling direction is not distorted.


R
α
x
y
x
y
v_o
h_o
v_f
h_f
L_p

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

$$bh_o v_o = bhv = bh_f v_f$$

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*

$$b h_o v_o = b h_f v_f$$

Given that $b_o = b_f$

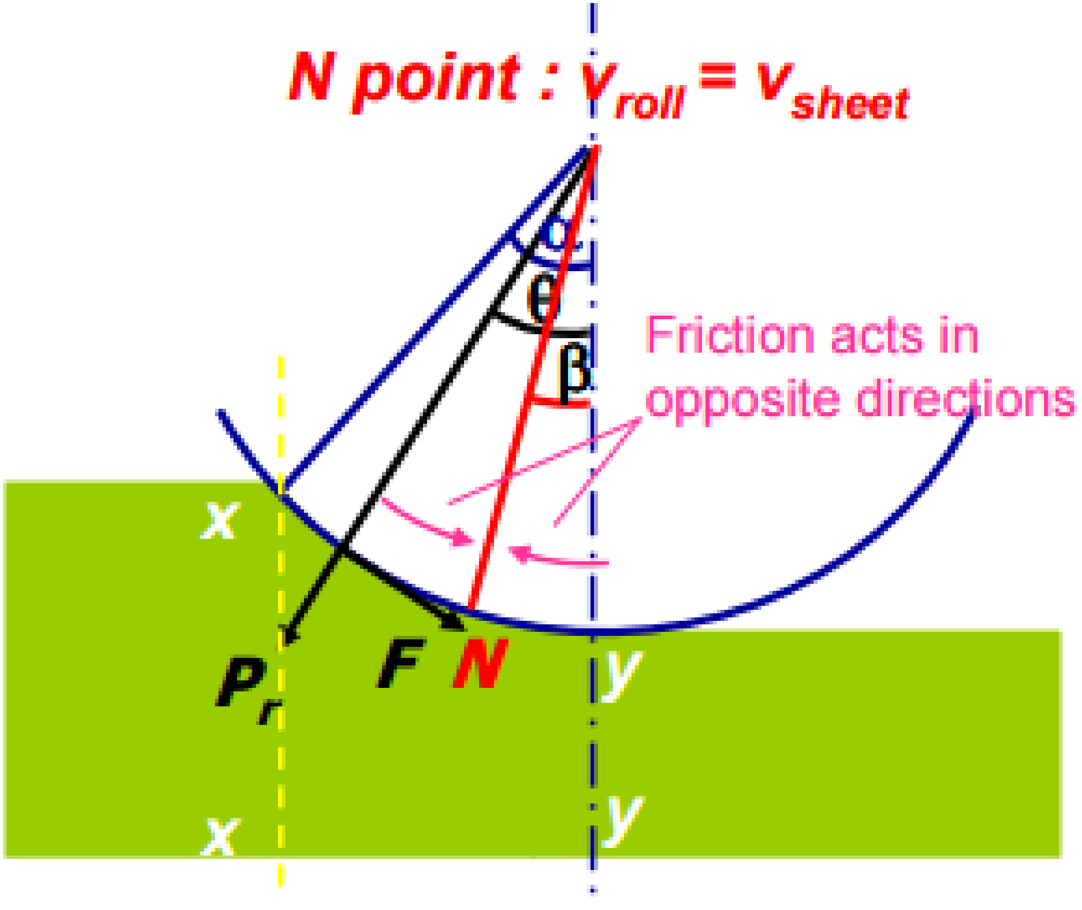
$$h_o \frac{L_o}{t} = h_f \frac{L_f}{t}$$

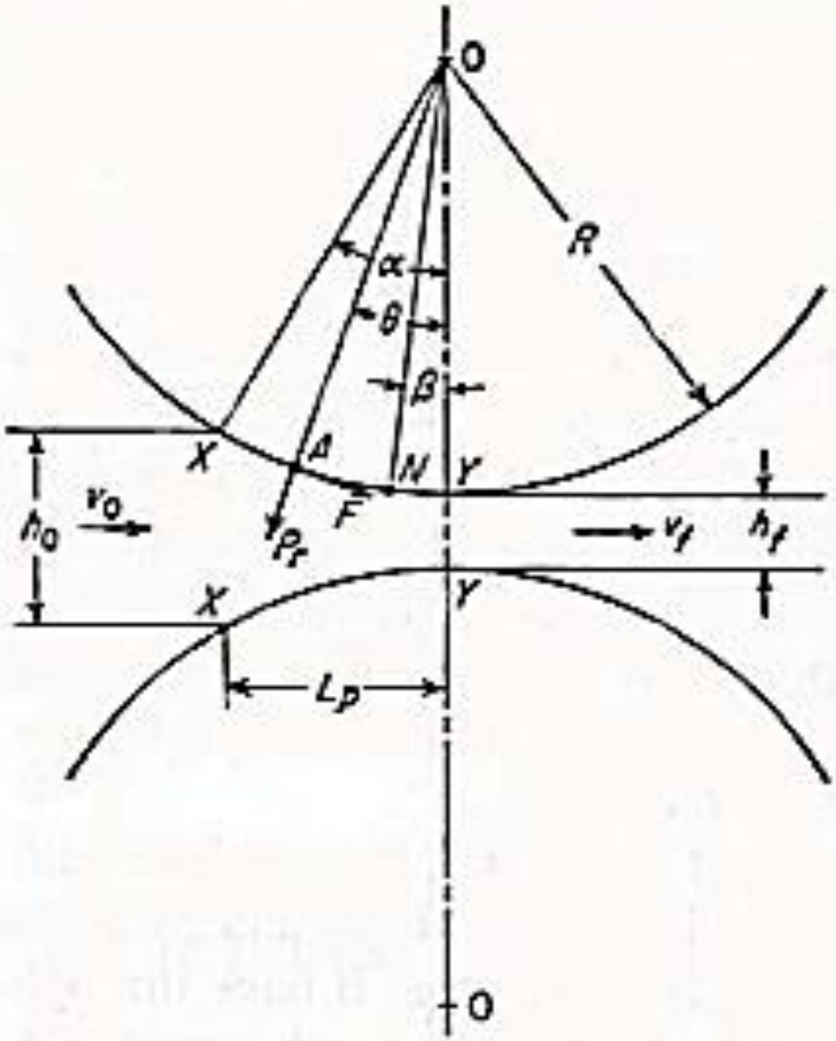
$$v_o h_o = v_f h_f$$

$$\frac{v_o}{v_f} = \frac{h_f}{h_o}$$

• At only one point along the surface of contact between the roll and the sheet, two forces act on the metal: 1) ***a radial force*** P_r and 2) ***a tangential frictional force*** F.

• If the surface velocity of the roll v_r equal to the velocity of the sheet, this point is called ***neutral point*** or ***no-slip point***. For example, point ***N***.





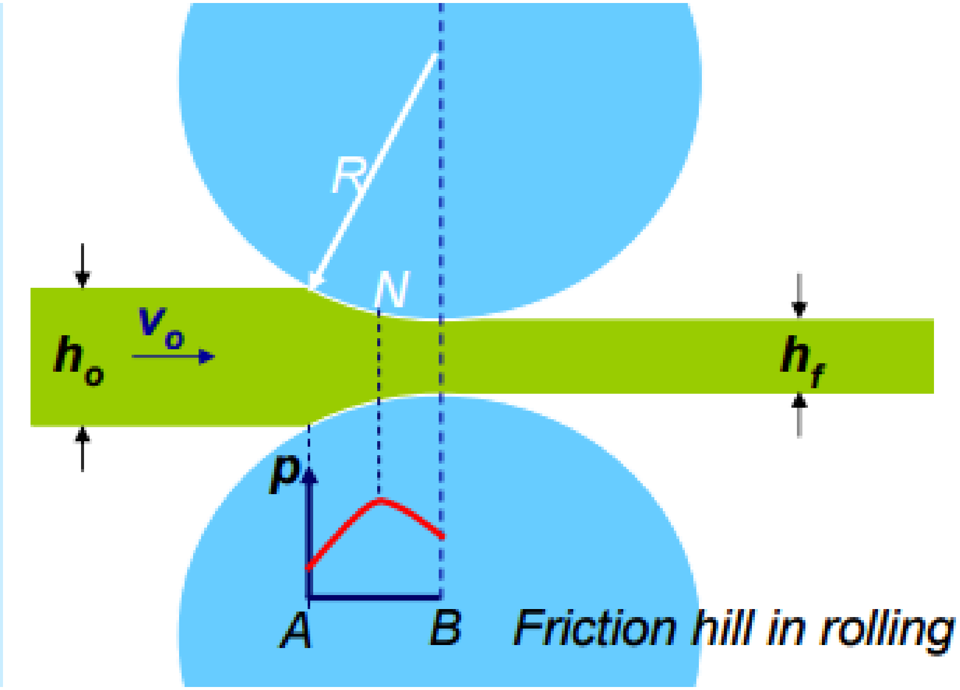
P_r is the radial force, with a vertical component ***P*** (***rolling load*** - the load with which the rolls press against the metal).

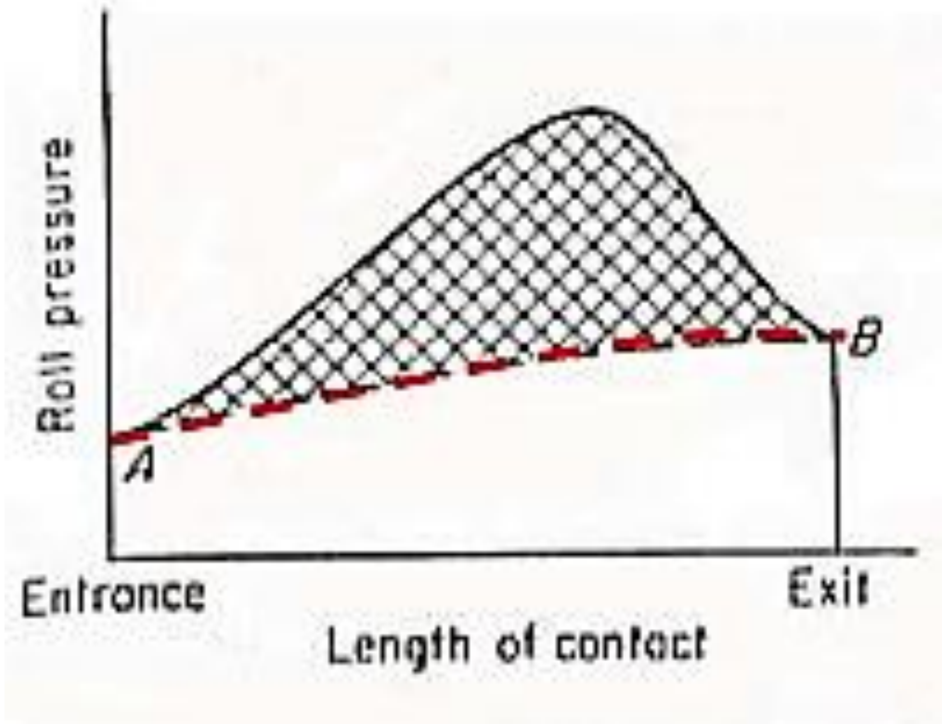
The ***specific roll pressure***, ***p***, is the rolling load divided by the contact area.

$$p = \frac{P}{bL_p}$$

Where ***b*** is the width of the sheet.
L_p is the projected length of the arc of contact.

ROLL PRESSURE DISTRIBUTION

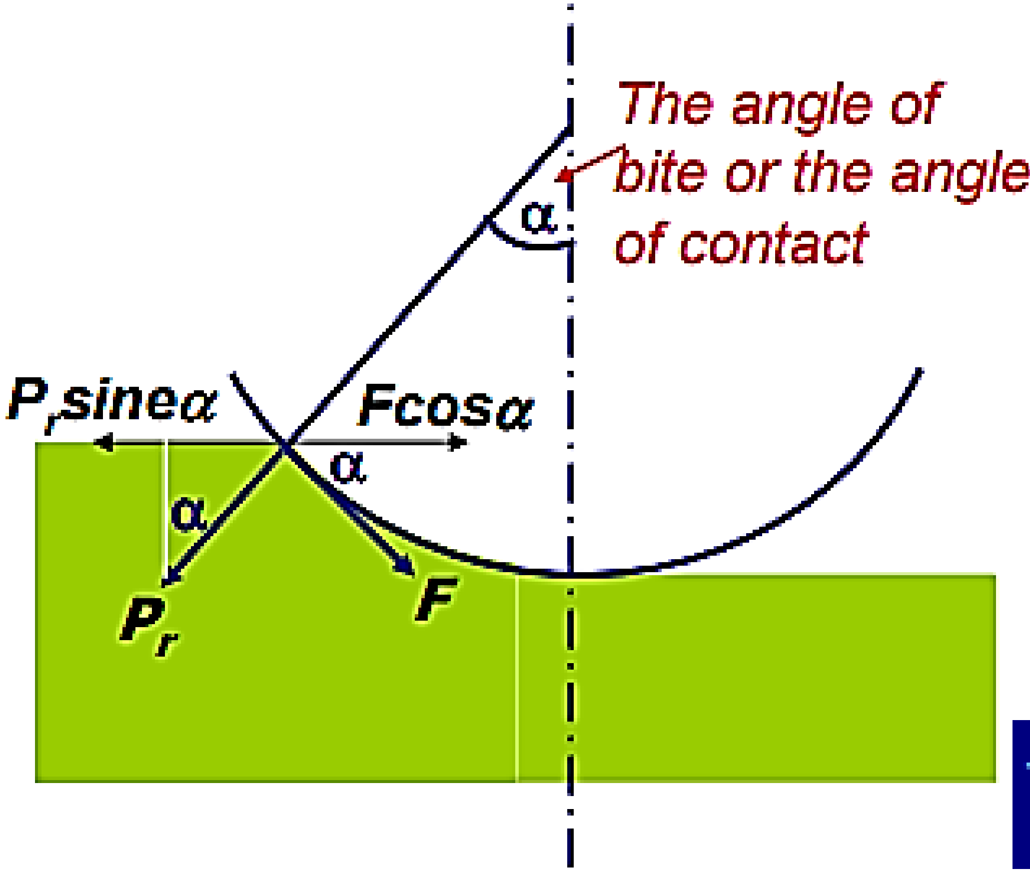




- The ***distribution of roll pressure*** along the arc of contact shows that the pressure rises to a maximum at the neutral point and then falls off.

- The area in ***shade*** represents the force required to overcome ***frictional forces*** between the roll and the sheet.
- The area ***under the dashed line AB*** represents the force required to deform the metal in plane homogeneous compression.

Roll bite condition



$$F\cos\alpha \geq P_r \sin\alpha$$

$$\frac{F}{P_r} \geq \frac{\sin\alpha}{\cos\alpha} \geq \tan\alpha$$

$$F = \mu P_r$$

Therefore $\mu = \tan\alpha$

F	is a tangential friction force
P_r	is radial force

- Average flow stress:

$$Y = k\varepsilon^n$$

$$Y_{ave} = \frac{\int_0^{\varepsilon_f} k\varepsilon^n d\varepsilon}{\varepsilon_f} = \left[\frac{k\varepsilon^{n+1}}{\varepsilon_f(n+1)}\right]_0^{\varepsilon_f} = k\frac{\varepsilon_f}{n+1}$$

- In rolling:

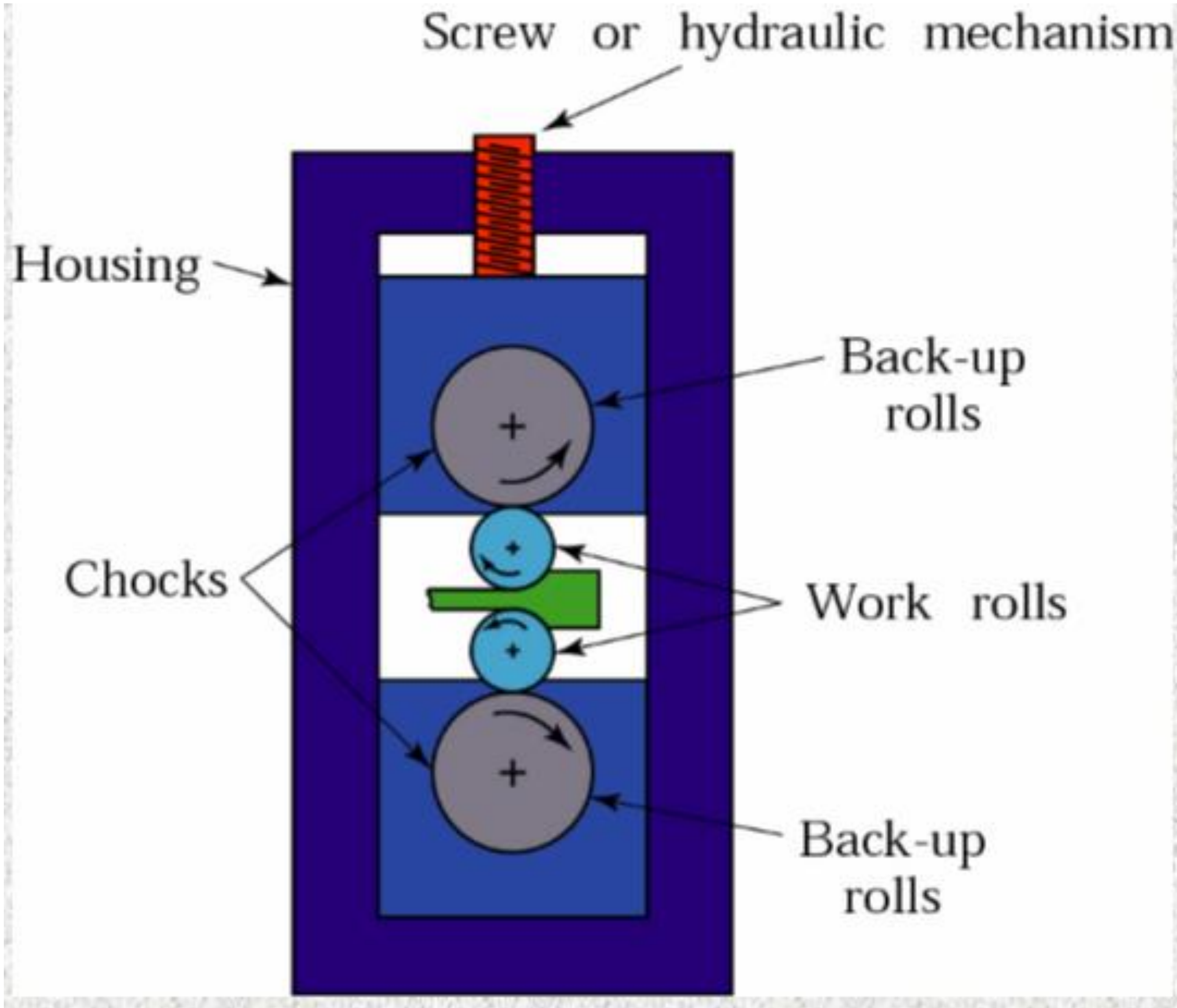
$$\varepsilon_f = \ln\frac{h_0}{h_f}$$

PROBLEM

An annealed copper strip 228 mm wide and 25 mm thick is rolled to a thickness of 20 mm in one pass. The roll radius is 300 mm, and the rolls rotate at 100 rpm. Calculate the roll force and the power required.

For annealed copper, it has a true stress of about 80 Mpa in the unstrained condition and at a true strain of 0.223, true stress is 280 Mpa.

FOUR HIGH ROLLING MILL



Simplified analysis of rolling load

The main variables in rolling are:

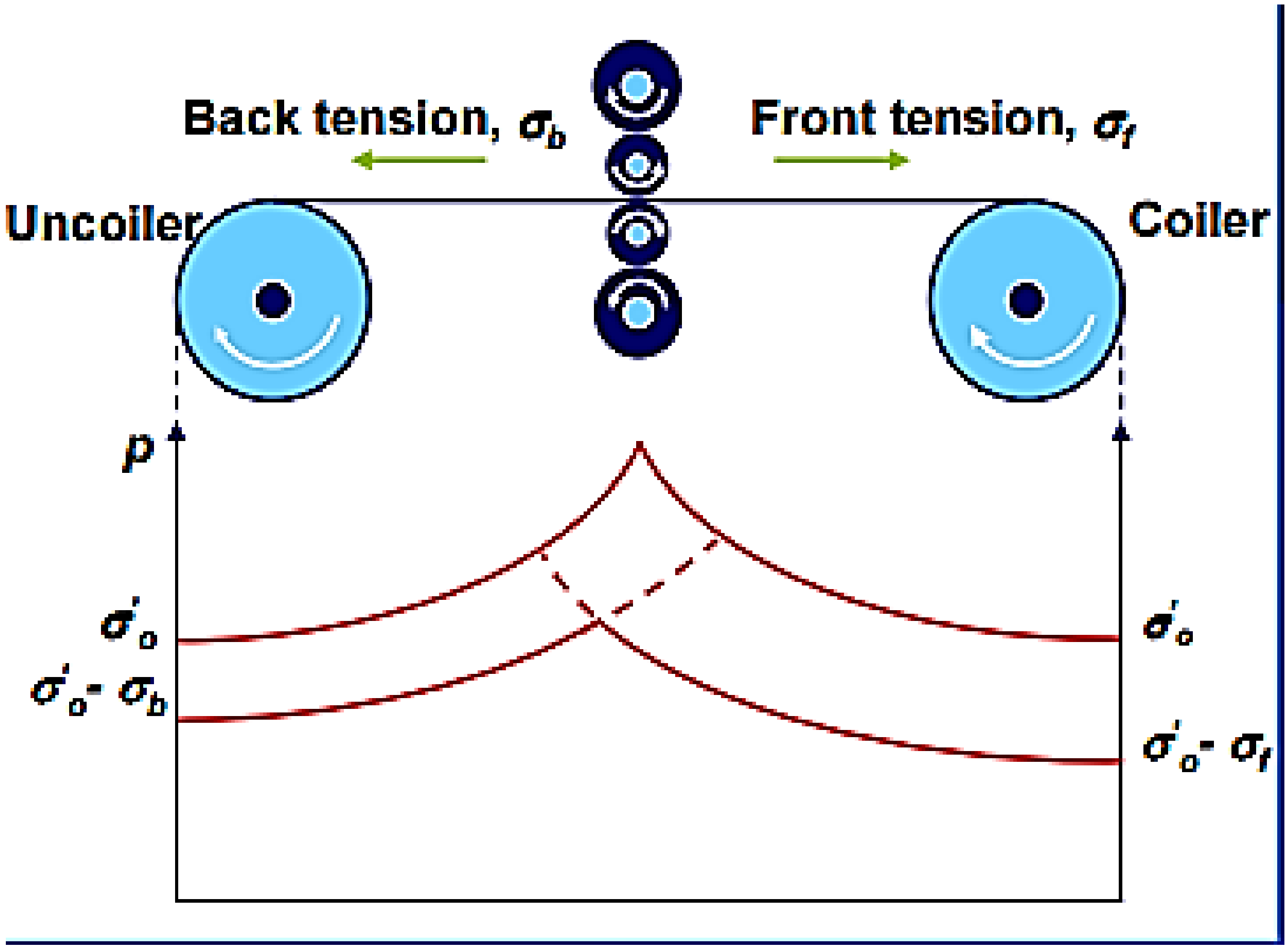
- The roll diameter.
- The deformation resistance of the metal as influenced by metallurgy, temperature and strain rate.
- The friction between the rolls and the workpiece.
- The presence of the front tension and/or back tension in the plane of the sheet.

Relationship of μ, rolling load and torque

$$\mu = \frac{M_T}{PR}$$

- We have known that the location of the neutral point ***N*** is where the direction of the friction force changes.
- If ***back tension*** is applied gradually to the sheet, the neutral point ***N*** ***shifts toward the exit plane***.

Back and front tensions in sheet



- The presence of back and front tensions in the plane of the sheet reduces the rolling load.
- ***Back tension*** may be produced by controlling the speed of the uncoiler relative to the roll speed.
- ***Front tension*** may be created by controlling the coiler.
- ***Back tension*** is ~ twice as effective in reducing the rolling load ***P*** as front tension.

• If a high enough ***back tension*** is applied, the neutral point moves toward the roll exit —> rolls are moving faster than the metal.

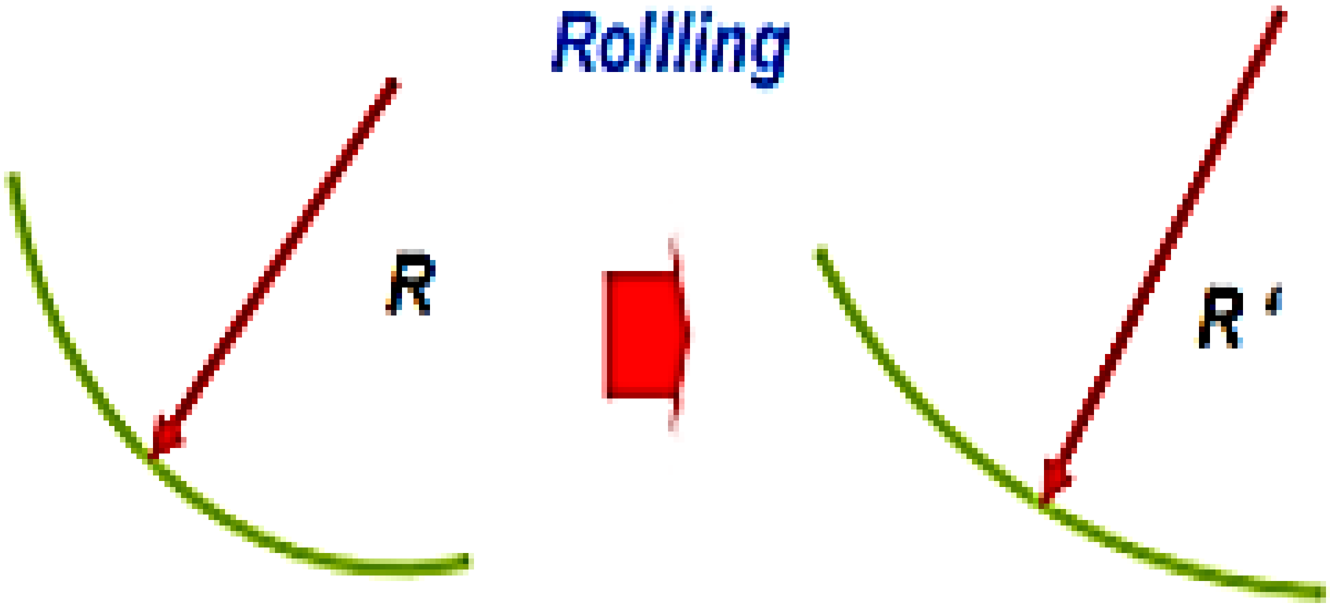
• If the ***front tension*** is used, the neutral point will move toward the roll entrance.

Problem with roll flattening

When high forces generated in rolling are transmitted to the workpiece through the rolls, there are two major types of elastic distortions:

1) The rolls tends to bend along their length because the workpiece tends to separate them while they are restrained at their ends. → ***thickness variation.***

2) The rolls flatten in the region where they contact the workpiece. The radius of the curvature is increased $R \rightarrow R'$. *(roll flattening)*



Roll flattening

Example: Determine the maximum possible reduction for cold-rolling a 300 mm-thick slab when $\mu = 0.08$ and the roll diameter is 600 mm. What is the maximum reduction on the same mill for hot rolling when $\mu = 0.5$?

Example: *Determine the maximum possible reduction for cold-rolling a 300 mm-thick slab when μ = 0.08 and the roll diameter is 600 mm. What is the maximum reduction on the same mill for hot rolling when μ = 0.5?*

From *Eq.7*,

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

For cold-rolling

$$(\Delta h)_{max} = (0.08)^2 (300) = 1.92mm$$

For hot-rolling

$$(\Delta h)_{max} = (0.5)^2 (300) = 75mm$$

Alternatively, we can use the relationship below

$$\sin\alpha = \frac{L_p}{R} = \frac{\sqrt{R\Delta h}}{R}, \alpha = \tan^{-1}(\mu)$$

$$\Delta h = 1.92mm$$

PROBLEMS AND DEFECTS IN ROLLED PRODUCTS

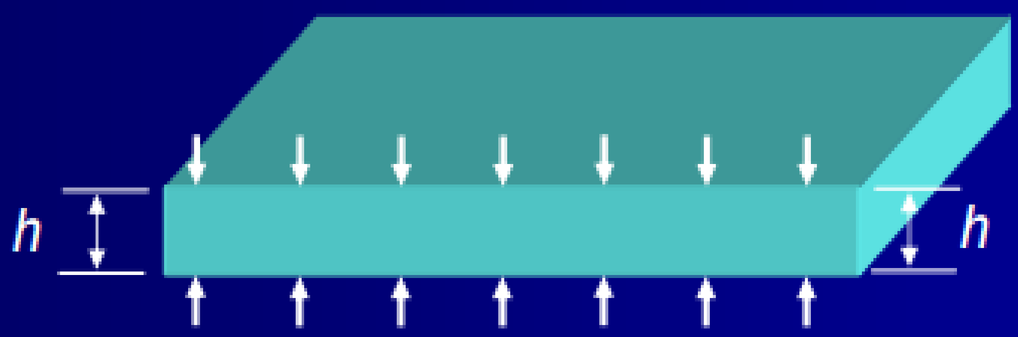
Porosity, Cavity, Blow Holes occurred in the cast ingot will be closed up during the rolling processes.

Longitudinal stringers of non-metallic inclusions or pearlite banding are related to melting and solidification practices. In several cases, these defects can lead to laminations which drastically reduce he strength in the thickness direction.

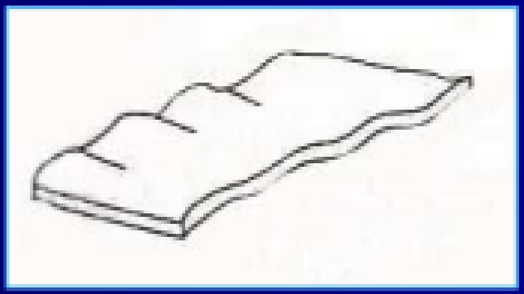
Defects during rolling

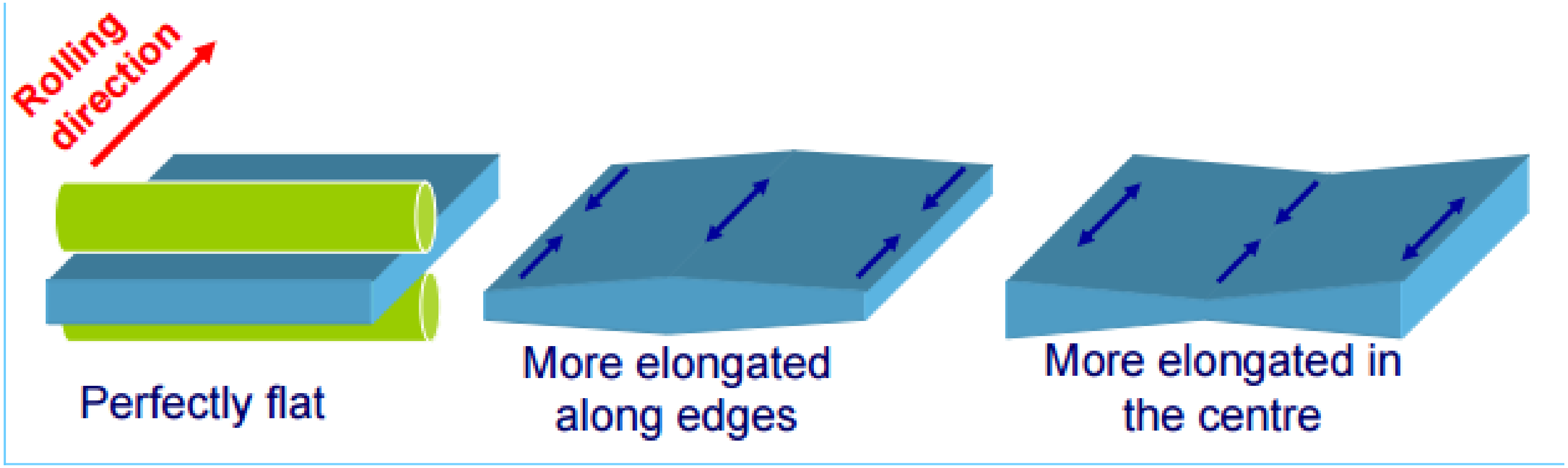
*There are **two aspects** to the problem of the shape of a sheet.*

1) ***Uniform thickness*** over the width and thickness – can be precisely controlled with modern gage control system.

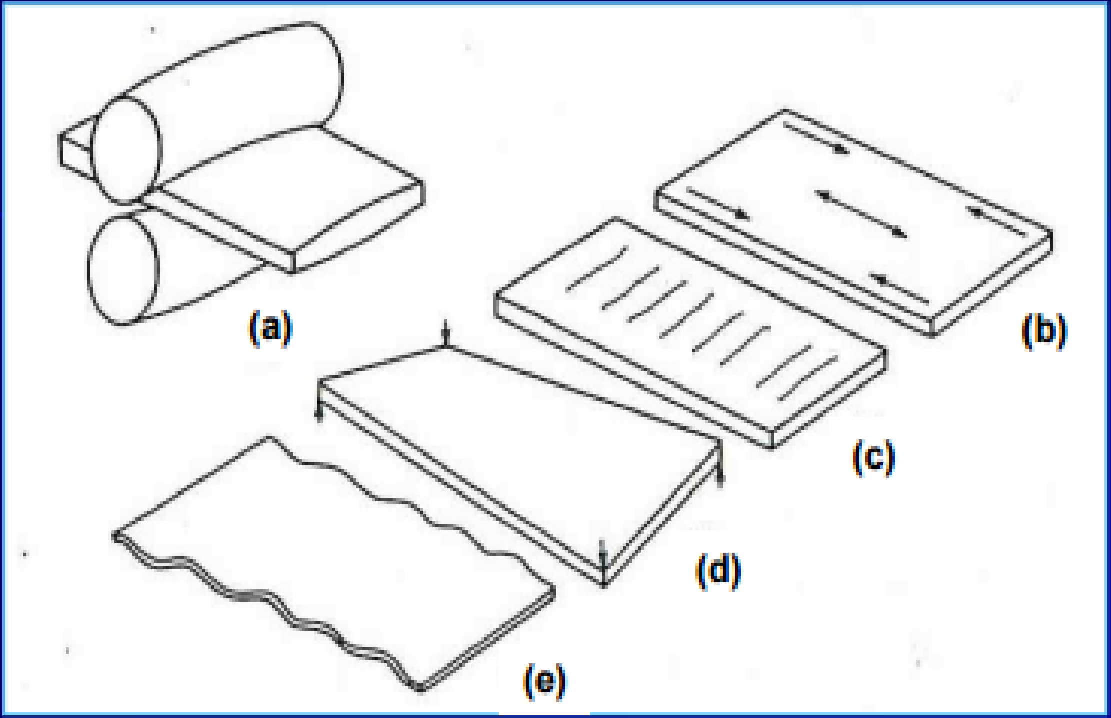


2) ***Flatness*** – difficult to measure accurately.




Rolling direction
Perfectly flat
More elongated along edges
More elongated in the centre

Possible effects when rolling with insufficient camber

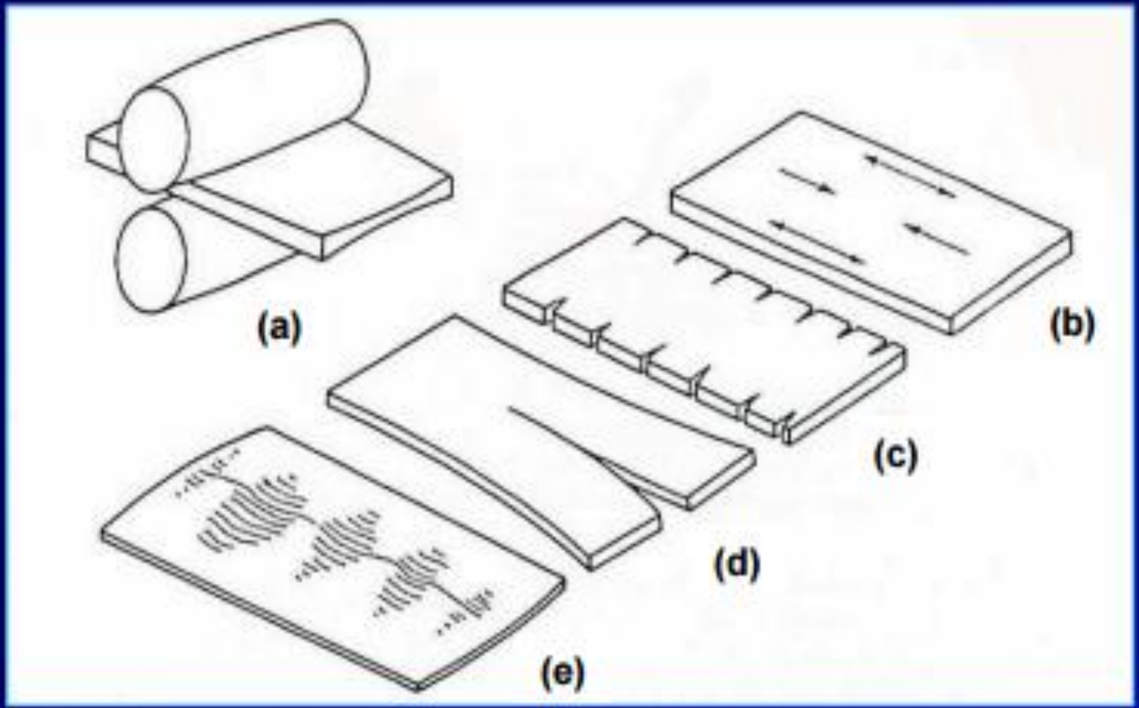


• Thicker centre means the edges would be plastically elongated more than the centre, normally called ***long edges***.

• This induces the residual stress pattern of compression at the edges and tension along the centreline.

• This can cause ***centreline cracking*** (c), ***warping*** (d) or ***edge wrinkling*** or ***crepe-paper effect*** or ***wavy edge*** (e).

Possible effects when rolls are over-cambered.

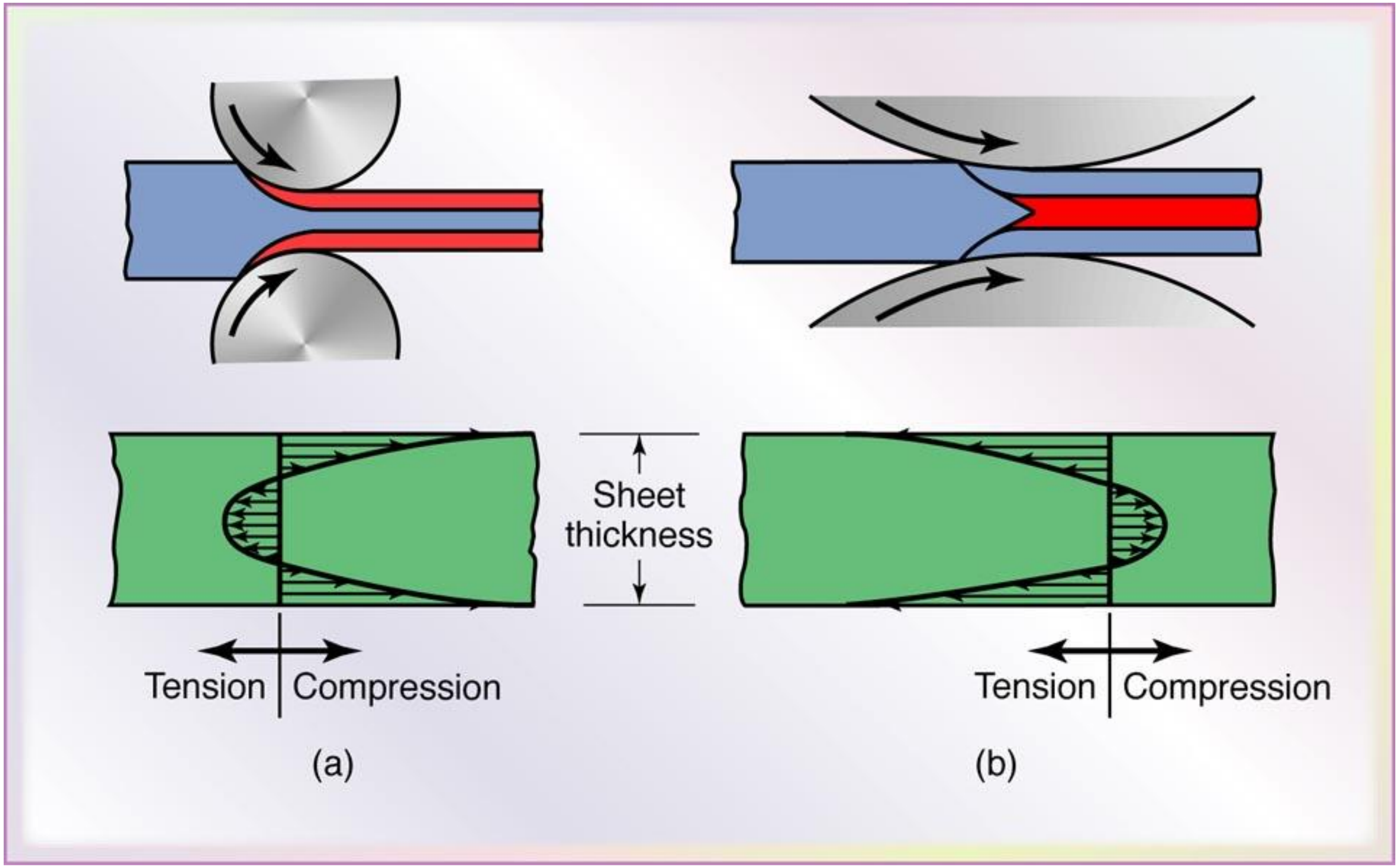


- Thicker edges than the centre means the centre would be plastically elongated more than the edges, resulting in ***lateral spread***.

- The *residual stress pattern* is now under compression in the centreline and tension at the edges (b).

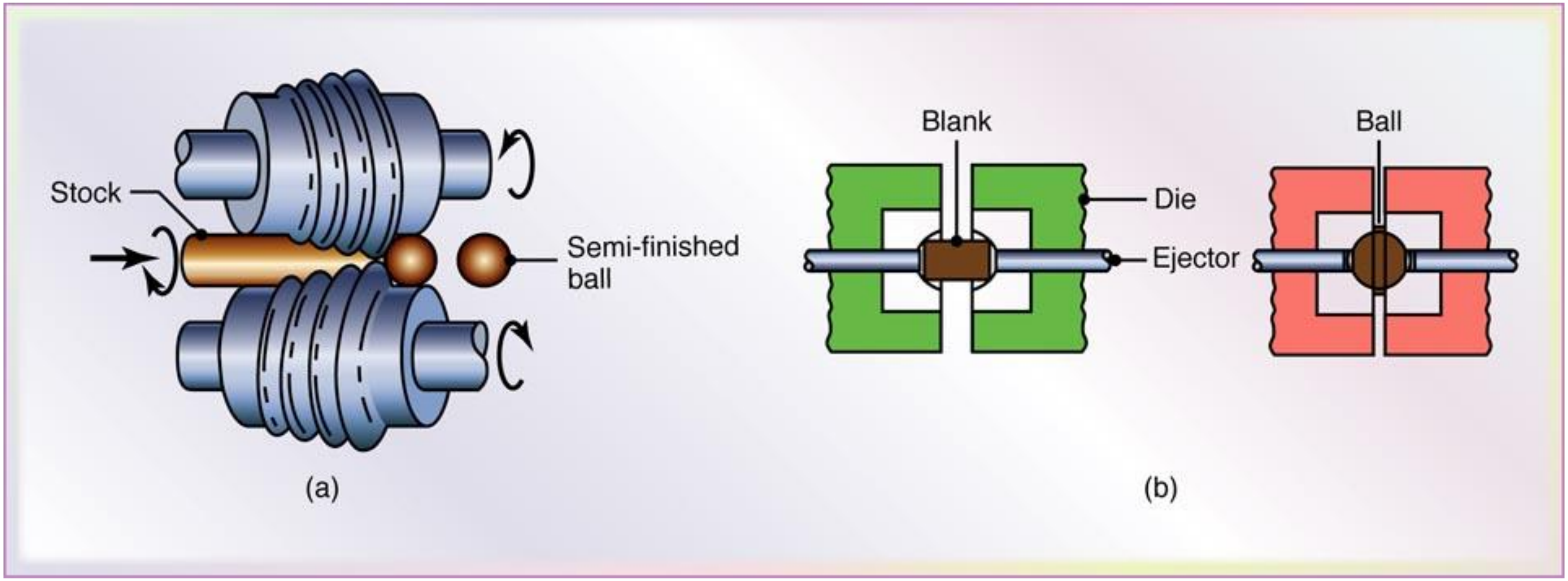
- This may cause ***edge cracking*** (c), ***centre splitting*** (d), ***centreline wrinkling*** (e).

Residual Stresses Developed in Rolling



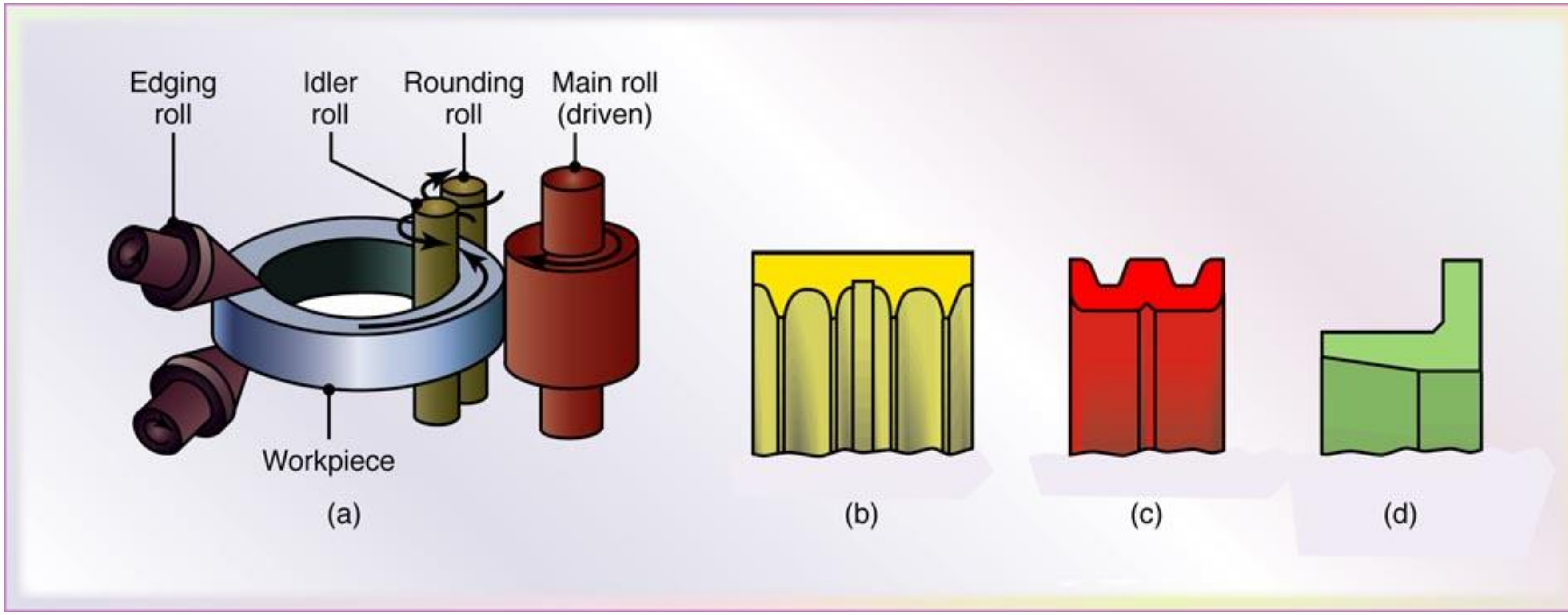
(a) Residual stresses developed in rolling with small-diameter rolls or at small reductions in thickness per pass. (b) Residual stresses developed in rolling with large-diameter rolls or at high reductions per pass. Note the reversal of the residual stress patterns.

Production of Steel Balls



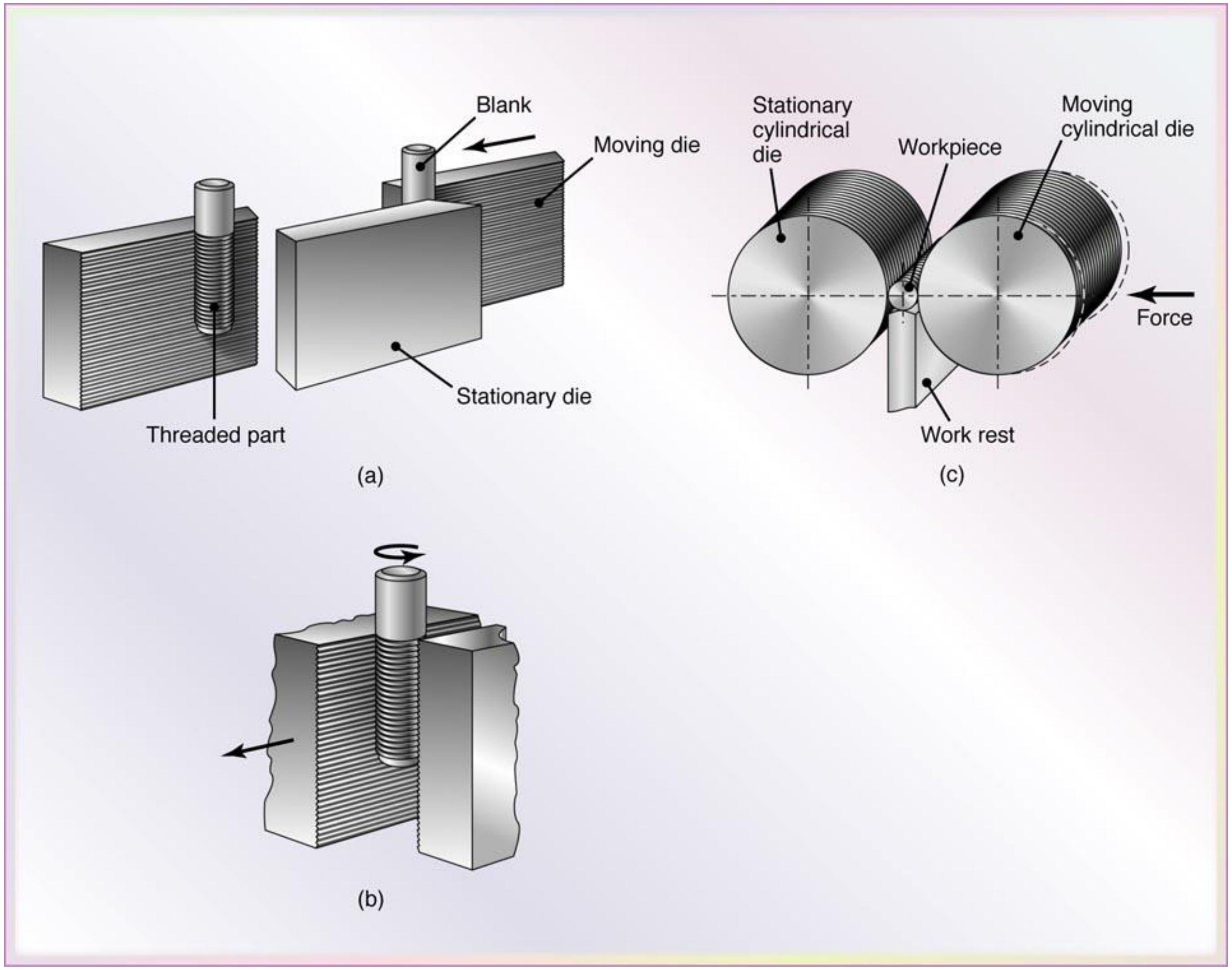
(a) Production of steel balls by the skew-rolling process. (b) Production of steel balls by upsetting a cylindrical blank. Note the formation of flash. The balls made by these processes subsequently are ground and polished for use in ball bearings.

Ring-Rolling



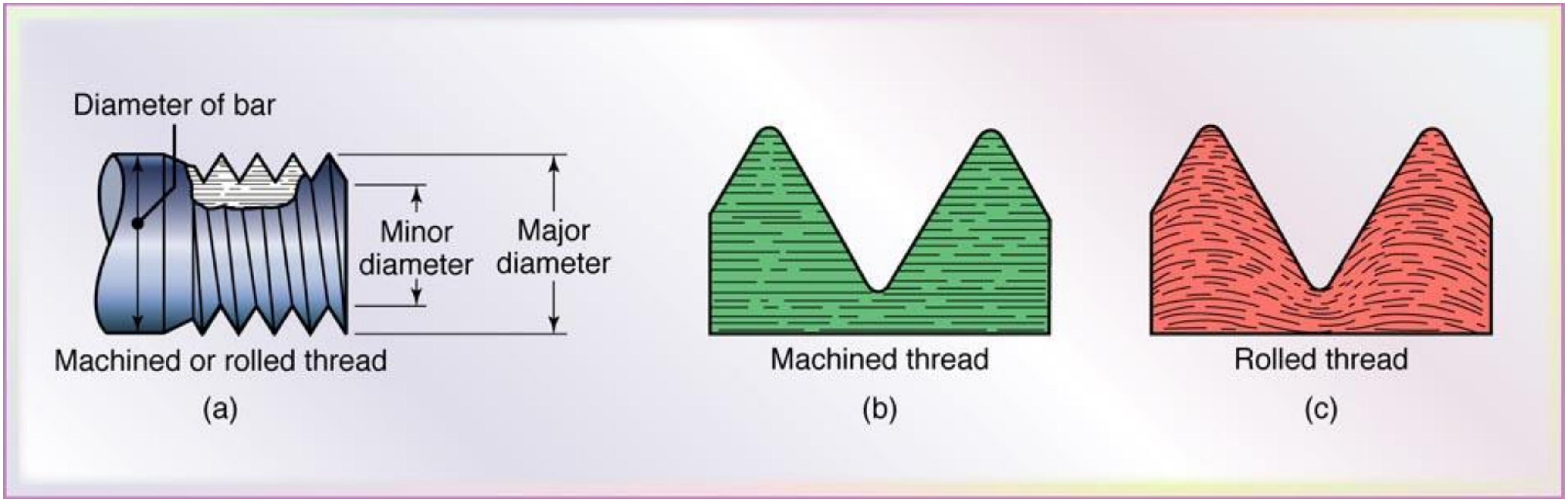
(a) Schematic illustration of a ring-rolling operation. Thickness reduction results in an increase in the part diameter. (b-d) Examples of cross-sections that can be formed by ring-rolling.

Thread-Rolling Processes



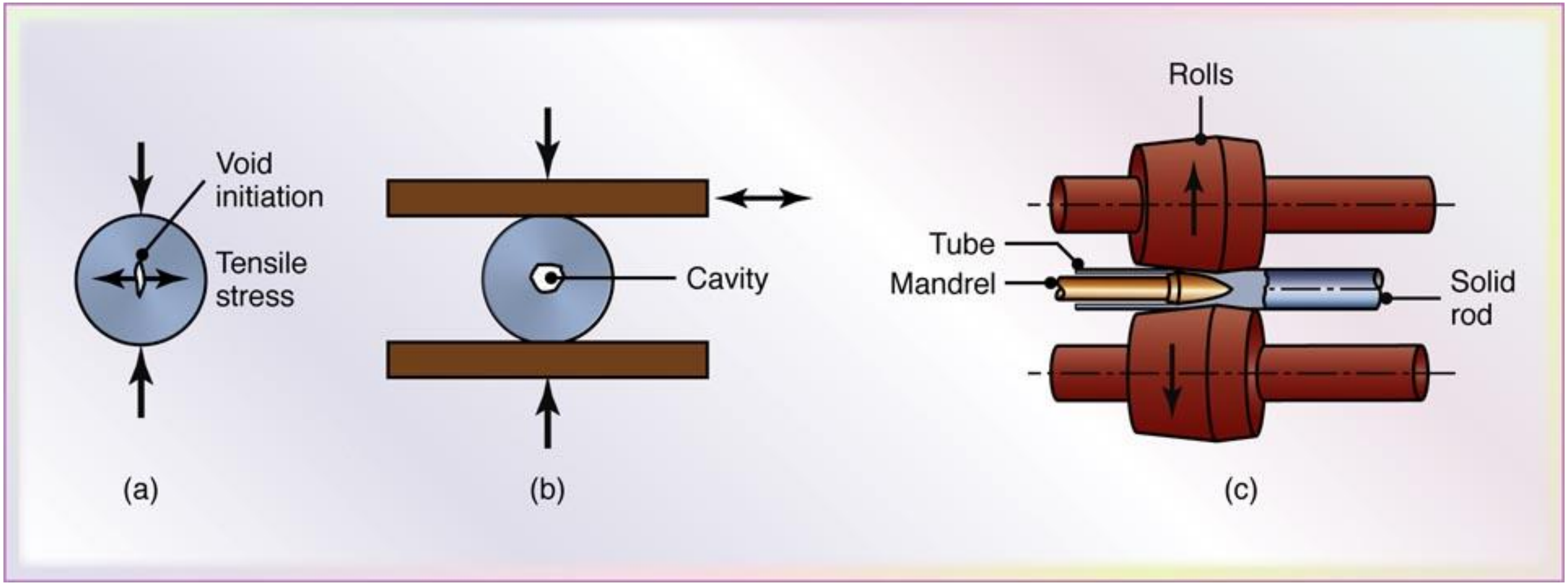
Thread-rolling processes: (a) and (c) reciprocating flat dies; (b) two-roller dies. (d) Threaded fasteners, such as bolts, are made economically by these processes at high rates of production. *Source*: Courtesy of Central Rolled Thread Die Co.

Machined and Rolled Threads



(a) Features of a machined or rolled thread. Grain flow in (b) machined and (c) rolled threads. Unlike machining, which cuts through the grains of the metal, the rolling of threads imparts improved strength because of cold working and favorable grain flow.

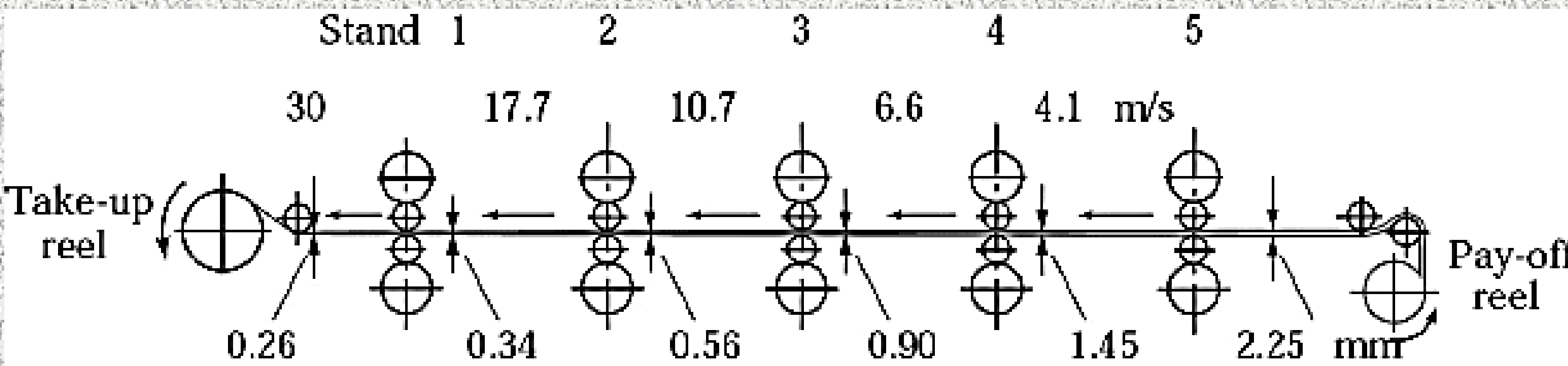
Cavity Formation in Bar



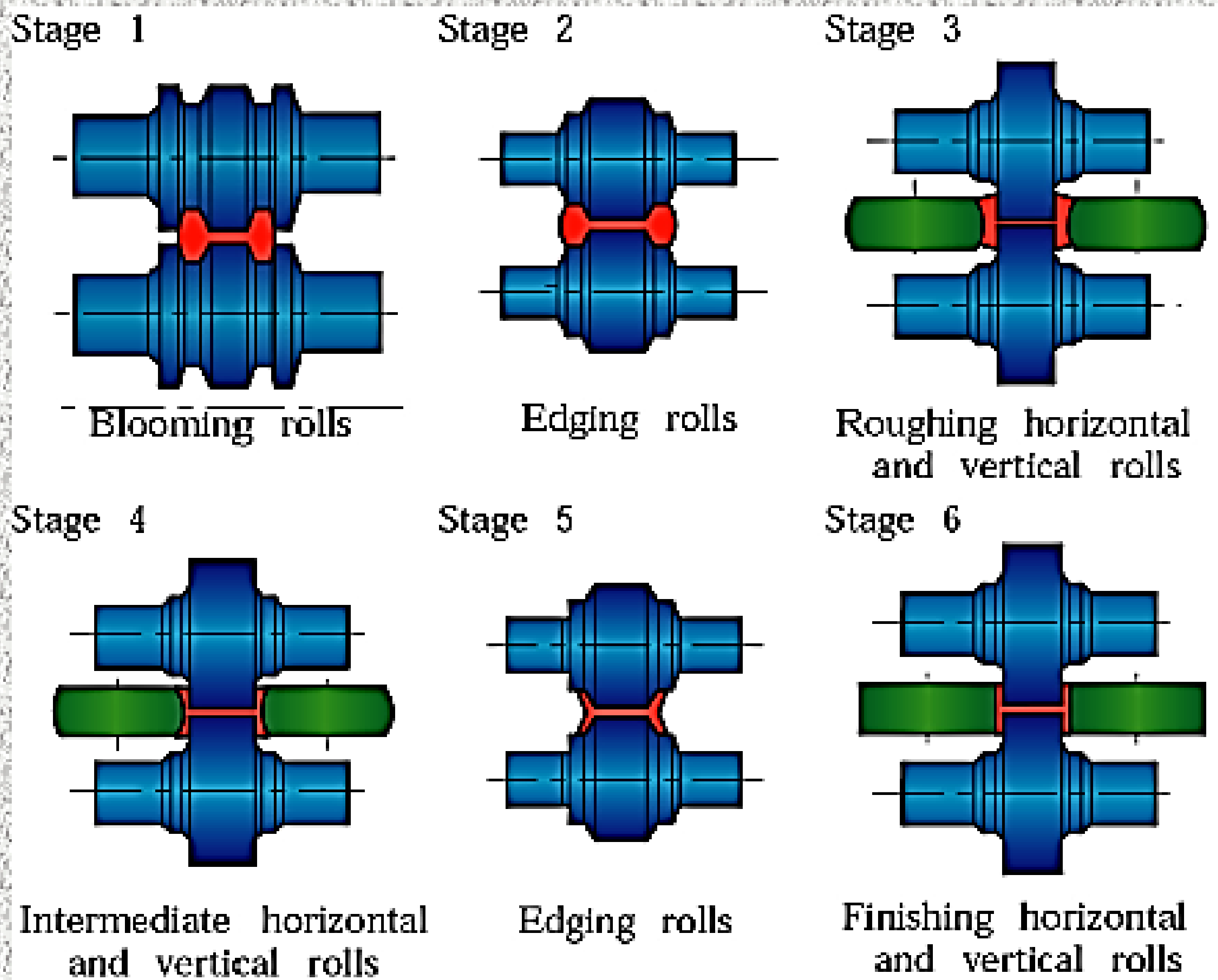
Cavity formation in a solid, round bar and its utilization in the rotary tube-piercing process for making seamless pipe and tubing.

Mannesmann Process

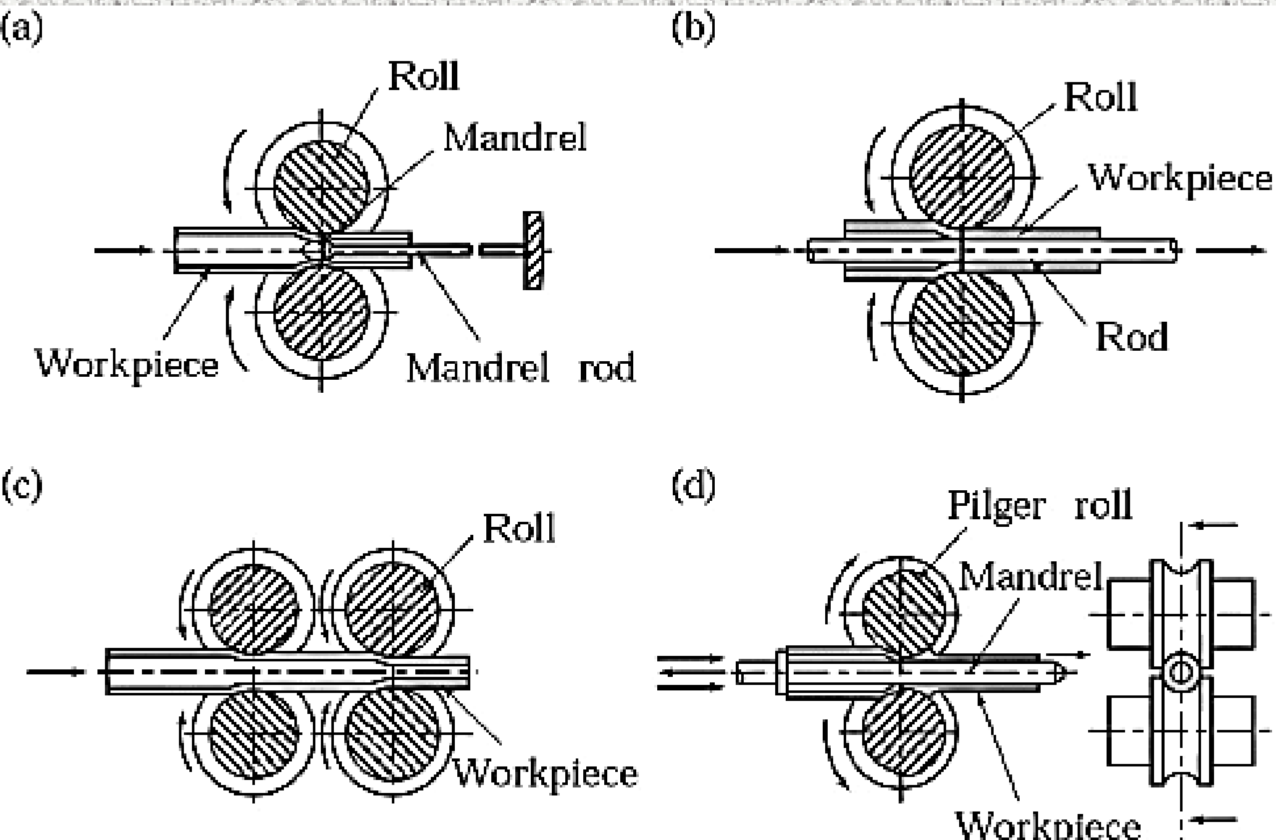
Tandem Rolling



Shape Rolling



Tube-Rolling



Schematic illustration of various tube-rolling processes: (a) with fixed mandrel; (b) with moving mandrel; (c) without mandrel; and (d) pilger rolling over a mandrel and a pair of shaped rolls. Tube diameters and thicknesses can also be changed by other processes, such as drawing, extrusion, and spinning.