



ME 333

Manufacturing Processes II



Chapter 5

Metal Working Processes

Prof. Dr. Ömer EYERCİOĞLU & Prof. Dr. Ali Tolga BOZDANA
Mechanical Engineering Department



- Metal forming involves large group of manufacturing processes in which **plastic deformation is used** to change the shape of metal parts.
- Deformation results from the use of **a tool (a die) that applies stresses exceeding the yield strength of metal**. Thus, the metals deforms to take a shape defined by the geometry of die.
- To be successfully formed, the metal must have certain properties. Desirable properties for forming are **low yield strength** and **high ductility**, which are affected by temperature. Ductility is increased and yield strength is reduced when the work temperature is raised.
- **Usually compressive stresses** are applied to plastically deform the metal. Depending upon purpose, forming processes are used to **stretch, bend, or shear** the metal.
- **Plastic Deformation Processes:** Operations that induce **shape change** on the workpiece by plastic deformation under forces applied by various tools and dies.
- **Bulk Deformation Processes:** Operations with large amount of plastic deformation. **Cross-sectional change without volume change**. Ratio of cross-section area to volume is small. Mostly hot or warm working conditions are preferred although some operations are carried out at room temperature.
- **Sheet Forming (Sheet Metal Working) Processes:** **No cross-sectional change, but only shape change**. Ratio of cross-section area to volume is high. Always performed as cold working operations, they are performed on thin (*less than 6 mm*) sheets, strips or coils of metal by means of a set of tools (*punch & die*) on machine tools (*stamping presses*).

Metal Forming

Bulk Deformation

Sheet Metal Working

Rolling

Forging

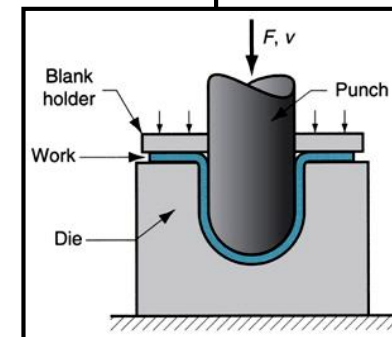
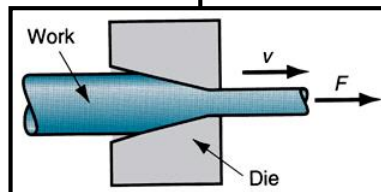
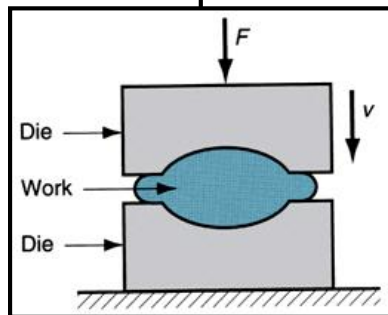
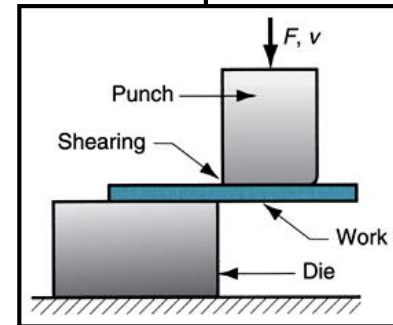
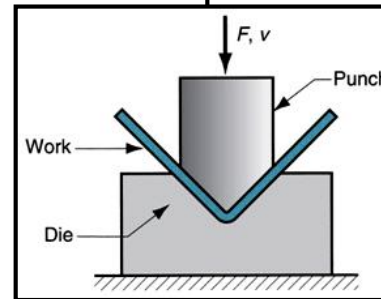
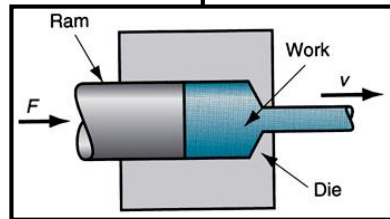
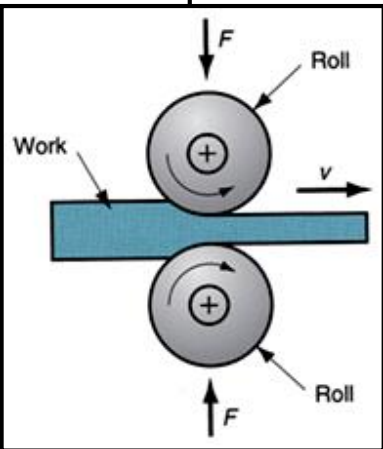
Extrusion

Drawing (Wire, Bar)

Bending

Drawing (Deep, Cup)

Shearing





- In plastic region, material behaviour is defined by **flow curve** (as shown in figure).
- **Flow stress** (the instantaneous stress required to continue deformation) can be obtained as follows (K and n are given in material property tables or calculated from material testing curves):

$$\sigma_f = K \varepsilon^n$$

σ_f : flow stress

K : strength coefficient

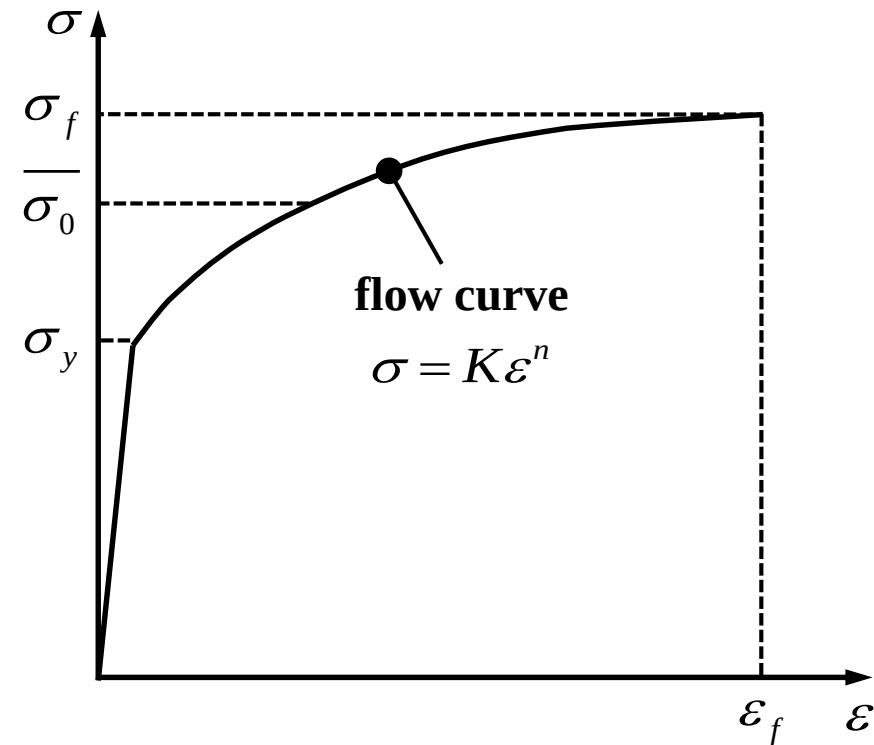
n : strain hardening coefficient

- Sometimes, analysis is based on **average (mean) stress** over strain-stress curve from beginning of strain to the final (max.) value during deformation:

$$\bar{\sigma}_0 = \frac{K \varepsilon_f^n}{1+n}$$

$\bar{\sigma}_0$: average (mean) flow stress

ε_f : max. strain during deformation



- **Strain or work hardening (cold working):**

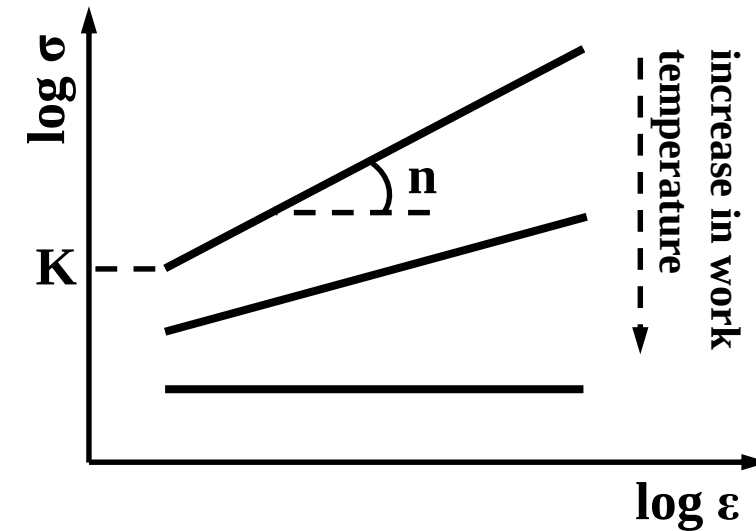
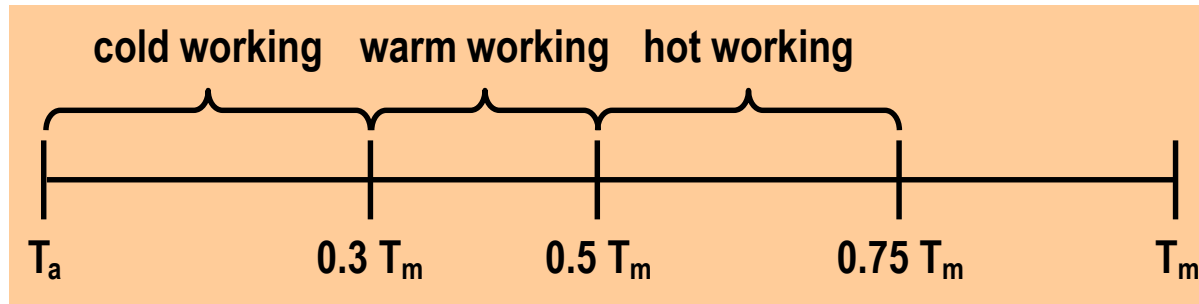
It refers to **strengthening of metals by plastic deformation** due to dislocation movements within the crystal structure. It is a significant material characteristic defining both material properties and process power, and it **can be removed by annealing**.



- Flow curve is valid for an ambient (room) temperature. For any material, K and n depend on the temperature. Thus, **material properties change with the work temperature**.

- Thus, metal forming processes can also be classified according to working temperature of the metal:

(T_a : ambient temperature, T_m : melting temperature)



- The effect of temperature gives rise to **distinctions between cold working, warm working, and hot working**. Hot and cold working of metals is of great importance in engineering production. Certain processes (e.g. forging, rolling, drawing, and extrusion) predominate in the primary stages of production, and they have been perfected through developments.



Cold Working

- ① It is performed at room temperature (or below the recrystallization temperature of metal).
- ☺ better accuracy and surface finish, increase in strength and hardness, no heating required.
- ☹ high forces and power required, decrease in ductility of metal, limitations on amount of forming, additional annealing required for some materials, not suitable for some materials.

Warm Working

- ① Performed at between room temperature and the recrystallization temperature.
- ☺ lower forces and power required, more complex part shapes, no annealing required.
- ☹ some investment in furnaces is needed.

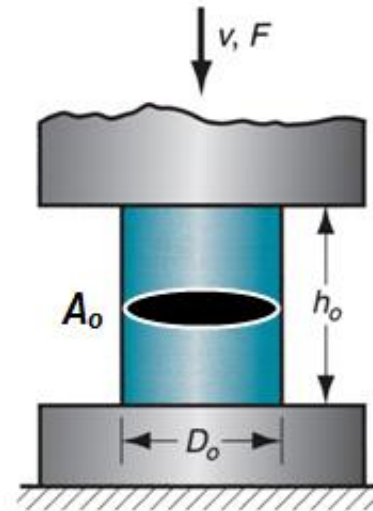
Hot Working

- ① Being performed at above the recrystallization temperature, it is the initial step in mechanical working of most metals and alloys.
- ☺ high amount of forming possible, lower forces and power required, forming of materials with low ductility, no work hardening (so no additional annealing) required.
- ☹ surface oxidation and decarburisation due to high temperatures, lower accuracy and surface finish, higher production costs, shorter tool life.

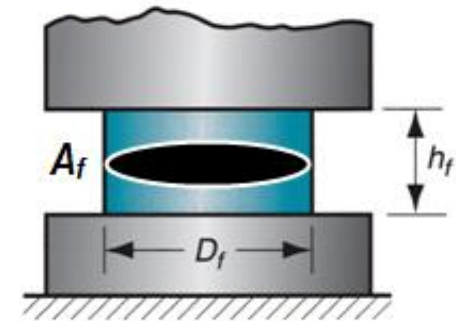


Homogeneous Deformation

- If a solid cylindrical part is placed between two flat platens and the load (F) is increased until reaching the flow stress (σ_o) of material, then its height will be reduced (from h_o to h_f).
- Under ideal conditions (i.e. **in absence of friction between platens and part**), any height reduction causes uniform increase in area (from A_o to A_f).

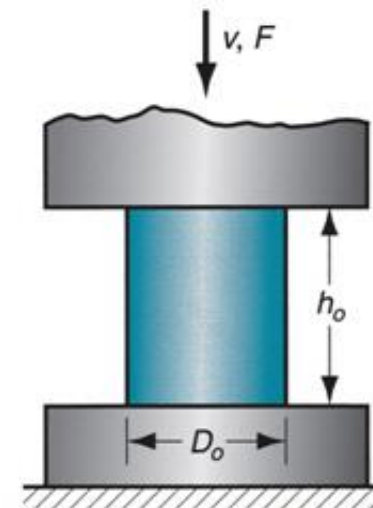


$$F = A\sigma_o = \frac{V}{h}\sigma_o$$

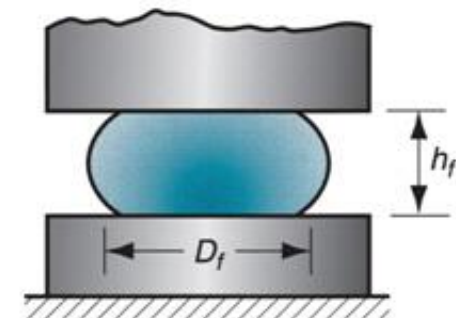


Inhomogeneous Deformation

- However, in practice, **friction between platens and part cannot be avoided**.
- The change in part geometry is not uniform, and the final part takes a **“barrel” shape**.
- The load required can be estimated based on friction coefficient (μ).

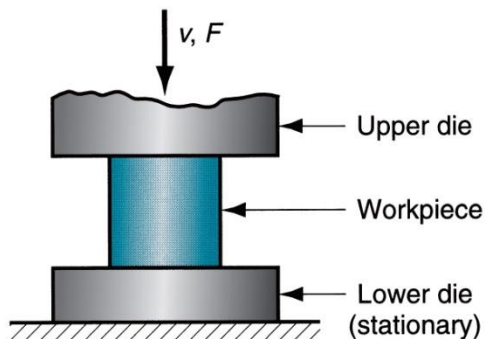


$$F = \frac{V}{h}\sigma_o \left(1 + \frac{\mu D}{3h} \right)$$

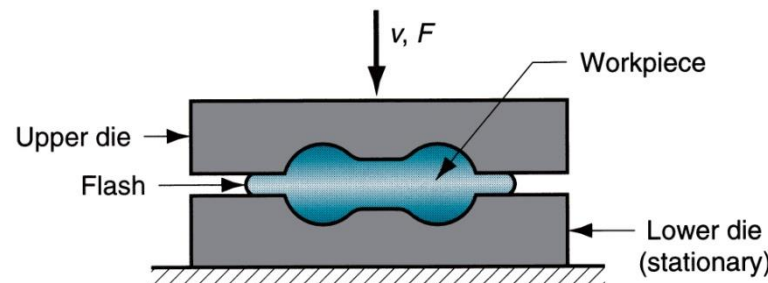




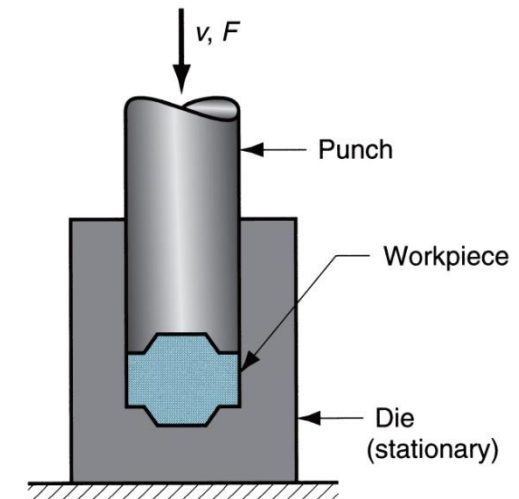
- Forging is the working of metal into a useful shape **by hammering or pressing**.
- It is **the oldest metal working process**. Most forging operations are carried out hot although certain metals may be cold forged.
- Two broad categories of forging processes are **open-die forging** and **closed-die forging**. Closed-die forging uses carefully machined matching die blocks to produce forging to close dimensional tolerances.
- **According to the degree to which flow of the metal is constrained by the dies**, there are three types of forging processes: **open-die**, **impression-die**, and **flashless**



open-die forging



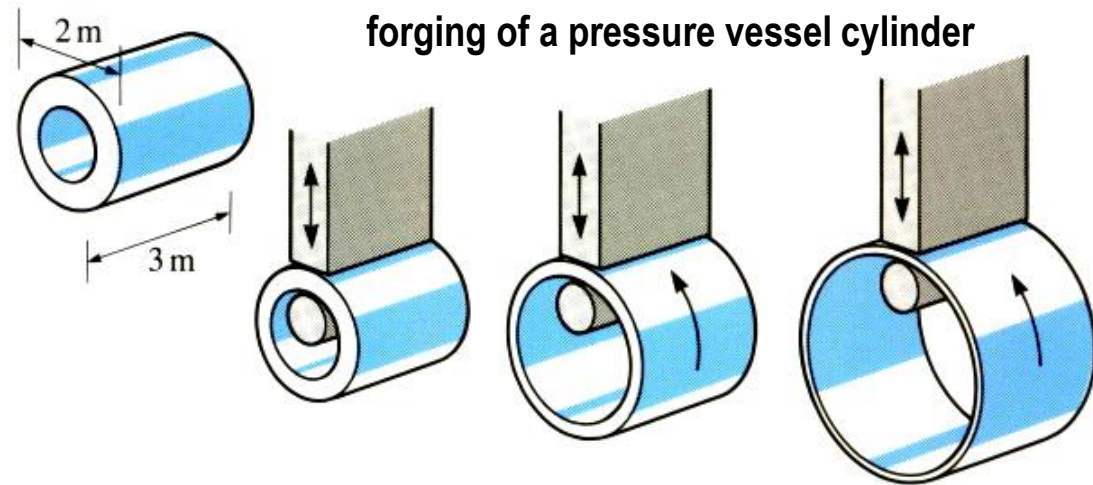
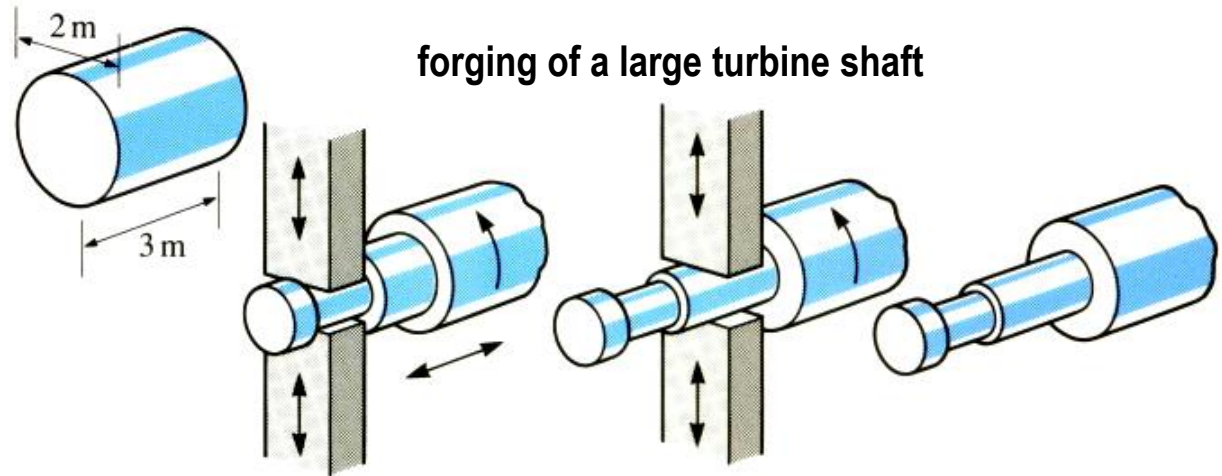
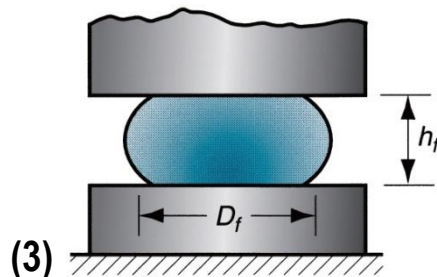
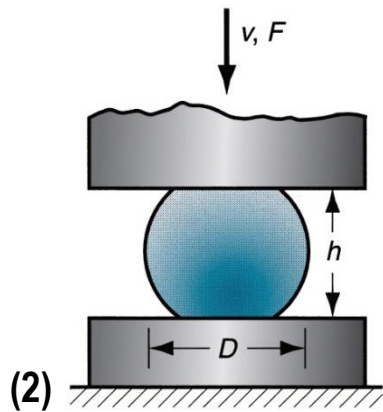
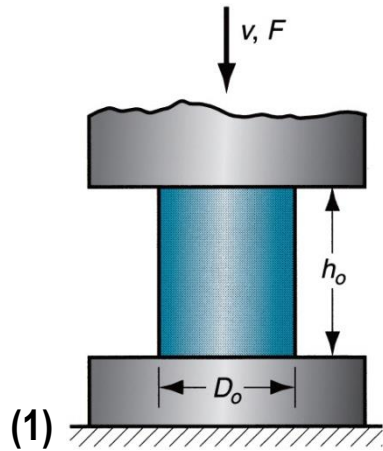
impression-die forging



flashless forging

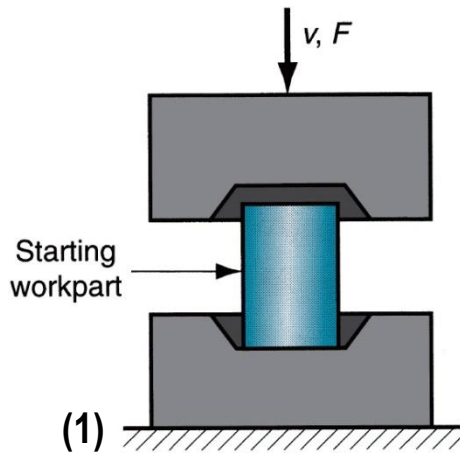


➤ Known as **upsetting**, it involves compression of a work between two flat dies or platens.

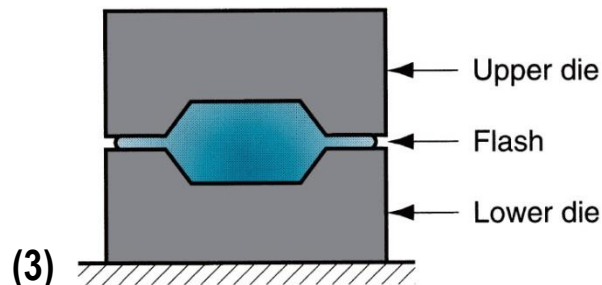
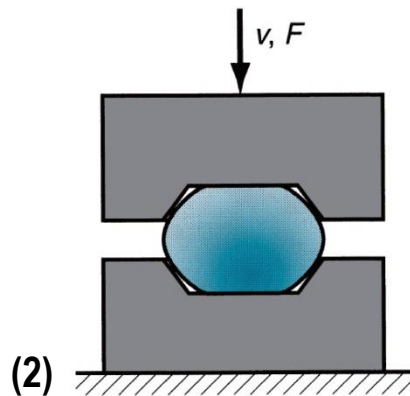




- In impression-die forging, some of the material flows radially outward to form a **flash** (çapak).



Hot impression-die forging of a crankshaft (bottom to top)



Blank (bar stock)



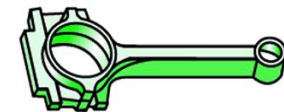
Edging



Blocking



Finishing

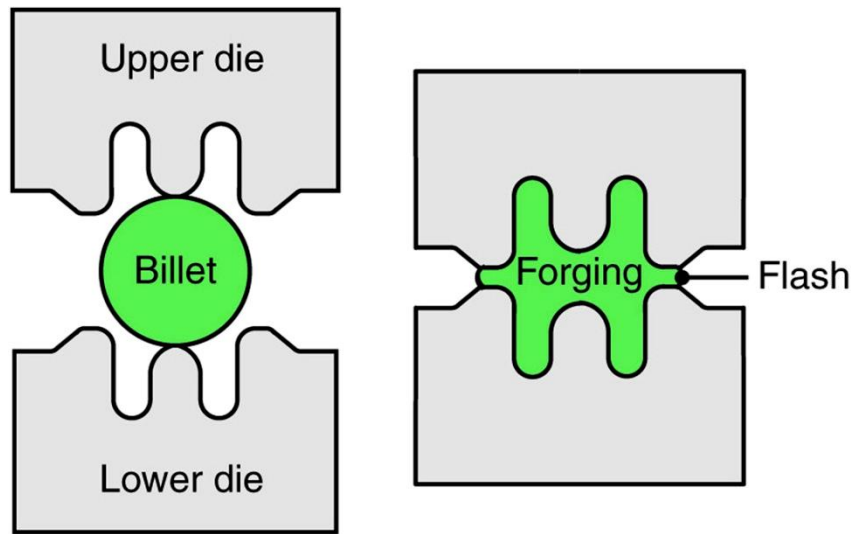
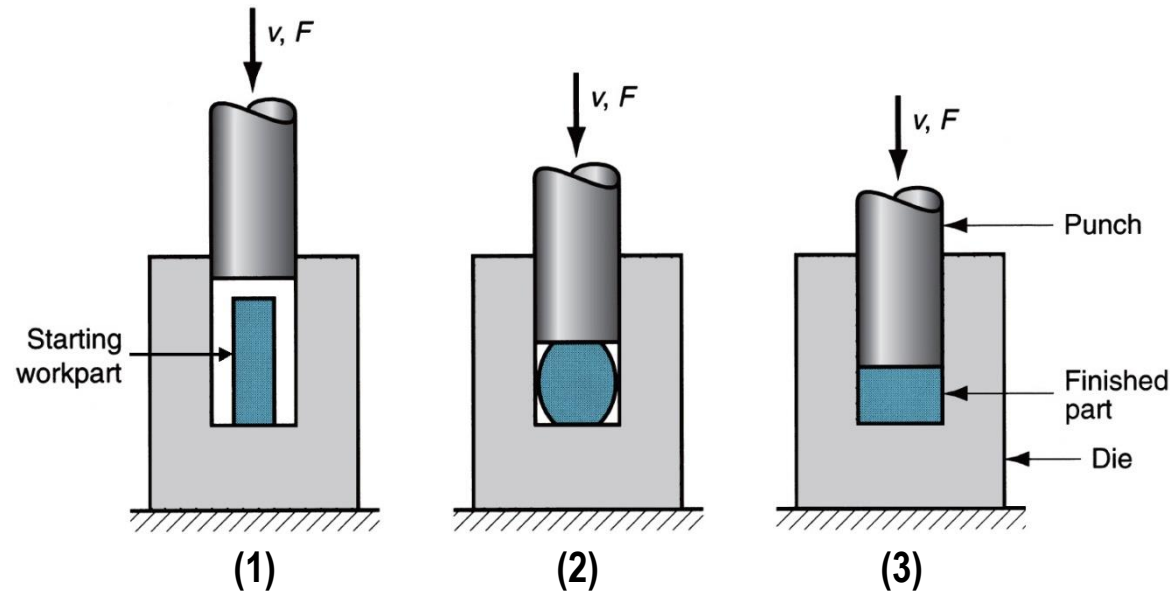


Trimming

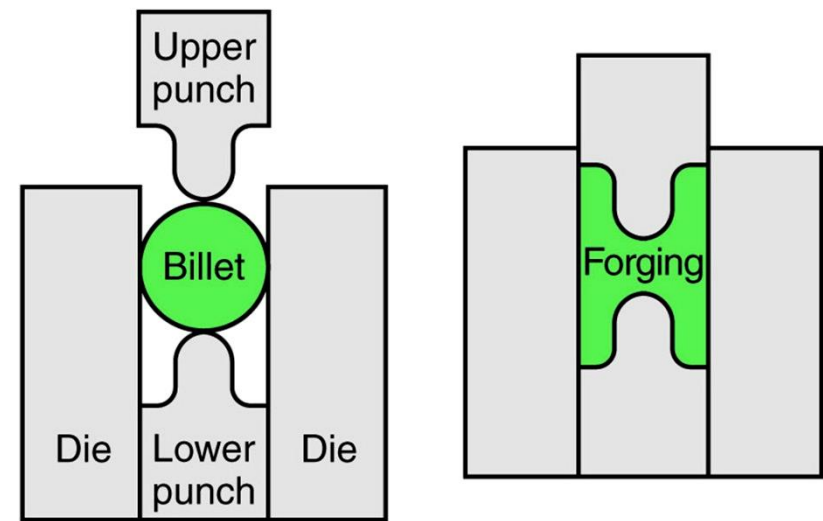
Impression-die forging of a connection rod (top to bottom)



- Work material is entirely surrounded by die cavity during compression (i.e. **no flash is formed**).
- In this operation, the most important requirement is that *the work volume must equal the space in die cavity to a very close tolerance*.



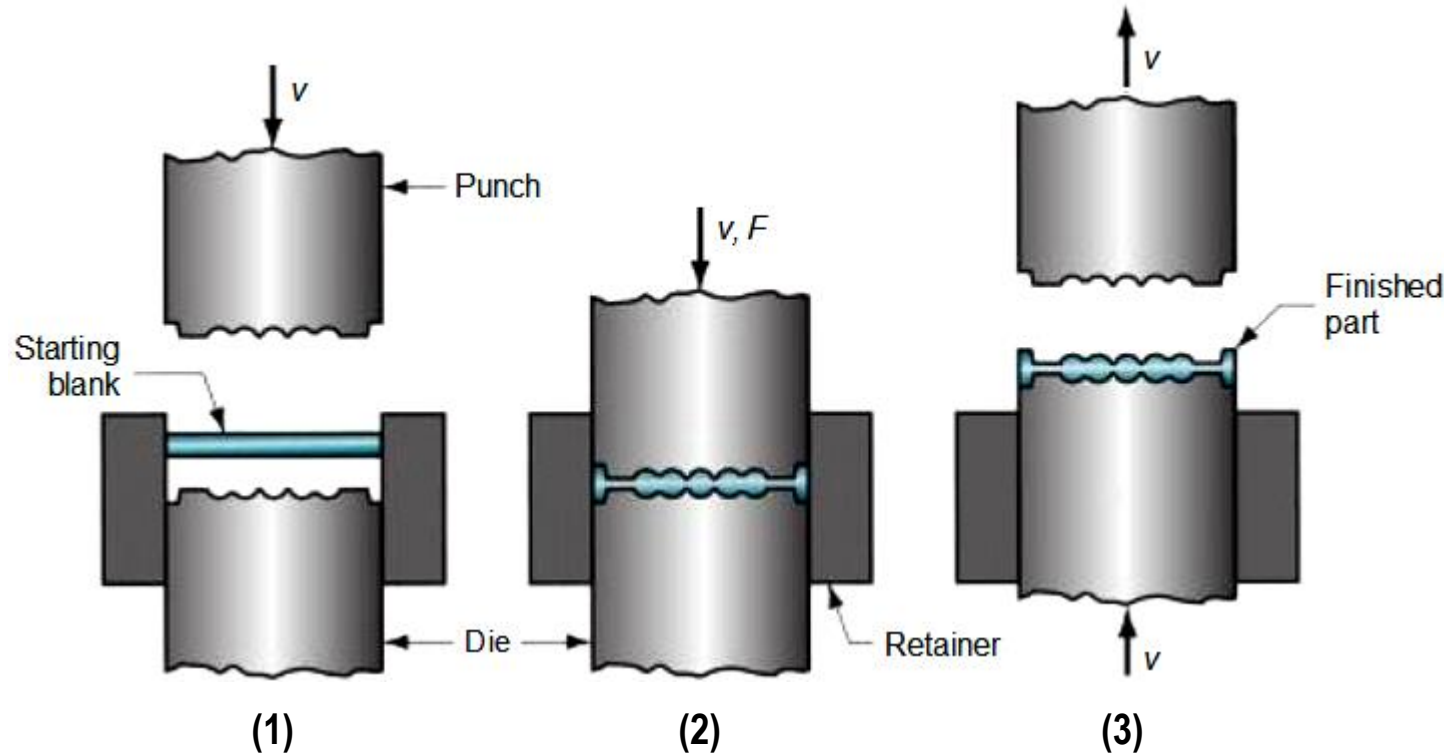
Closed-die forging with flash



Flashless (precision) forging



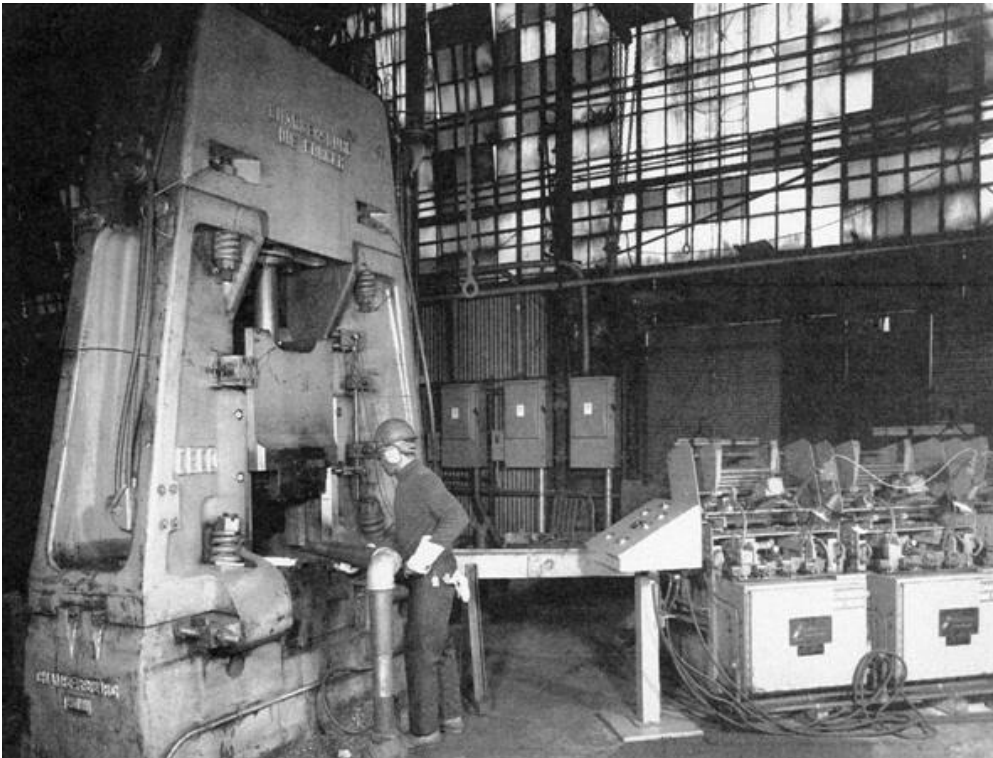
- This is a special application of flashless forging in which fine detail in the die are impressed into top and bottom surfaces of the workpiece. There is a little flow of metal in this process.





Forging (Drop) Hammers (Şahmerdan)

- Force is applied **by means of a falling weight**.
- They are **energy-restricted machines** since deformation results from dissipating kinetic energy of the ram.
- Their capacity is **expressed with energy units**.



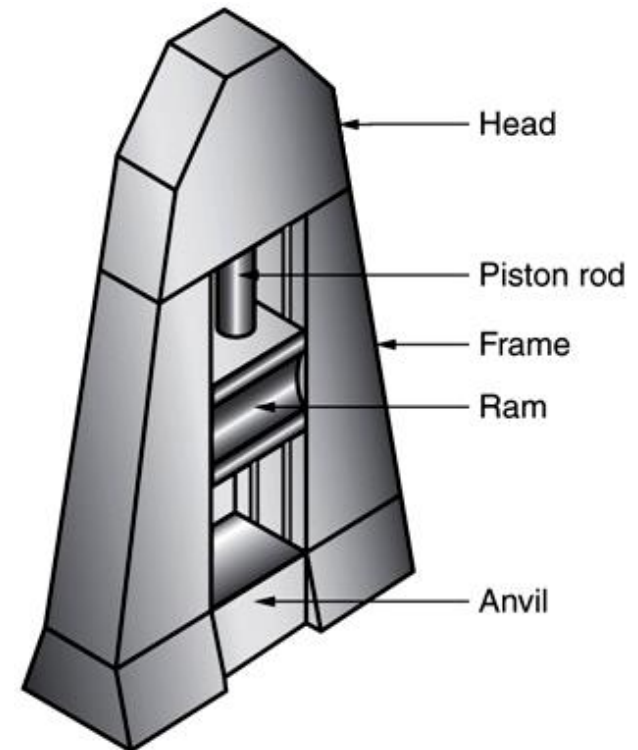
$$PE = Wh = mgh$$

PE : potential energy (Nm)

m : mass of the ram (kg)

g : gravitational acceleration (m / s^2)

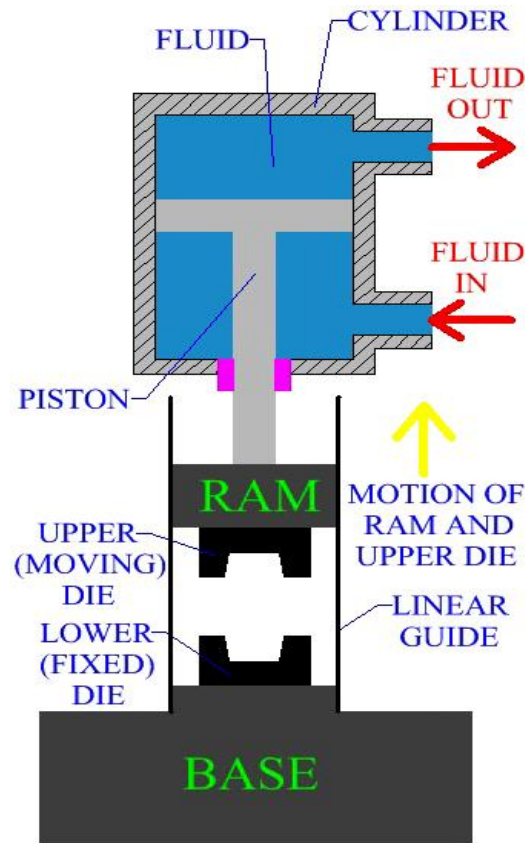
h : drop height (m)



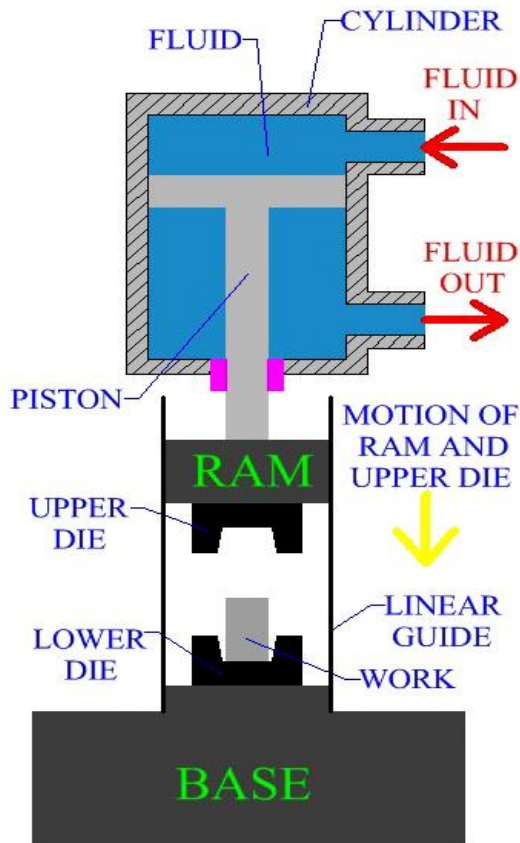


Hydraulic Presses

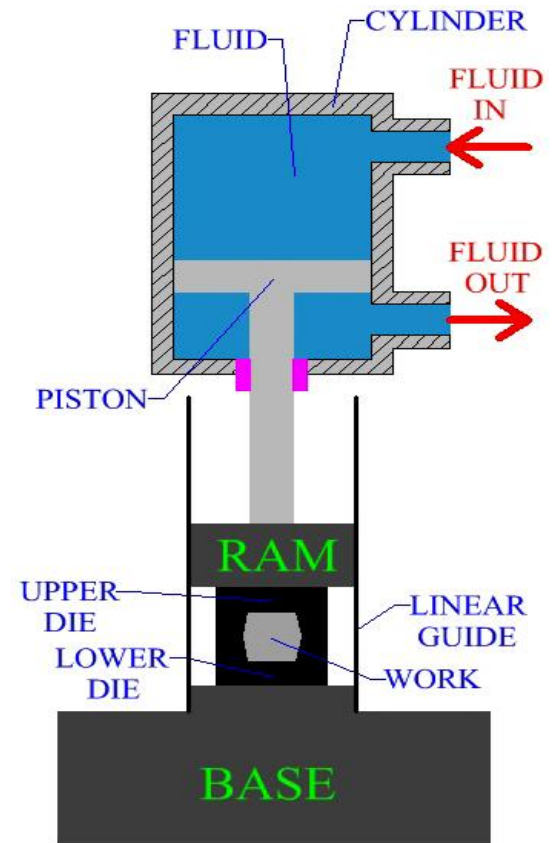
- They are **load-restricted machines** due to pressure in oil.
- Their capacity **is expressed with load**.



A HIGHER PRESSURE OF THE FLUID BELOW THE PISTON THAN THE FLUID ABOVE IT CAUSES THE PISTON TO RISE



A HIGHER PRESSURE OF THE FLUID ABOVE THE PISTON THAN THE FLUID BELOW IT MOVES THE PISTON DOWNWARD

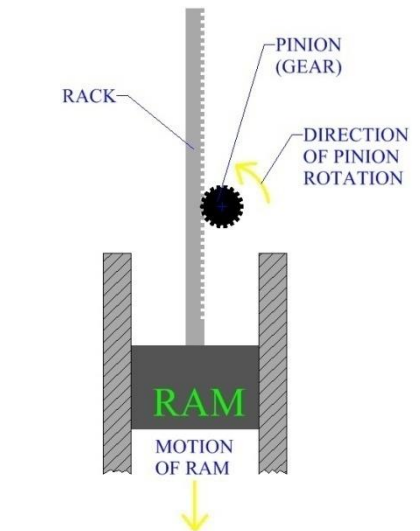
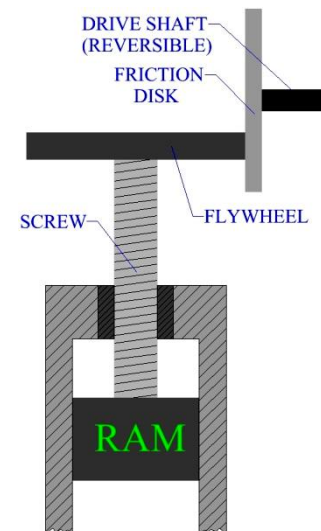
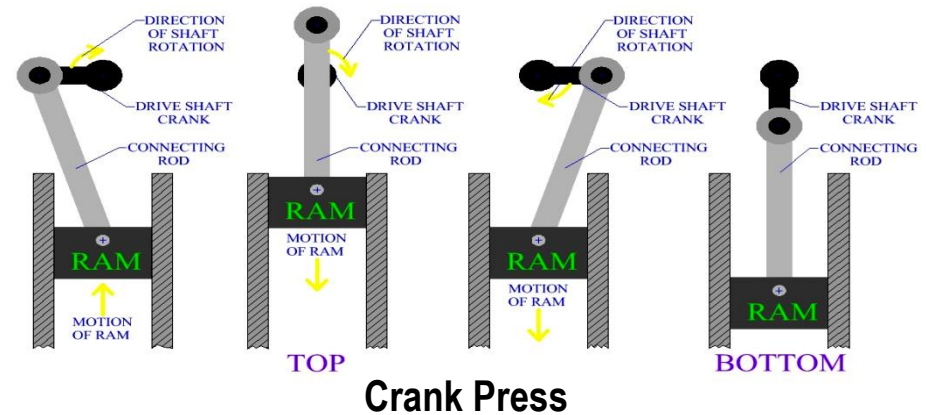
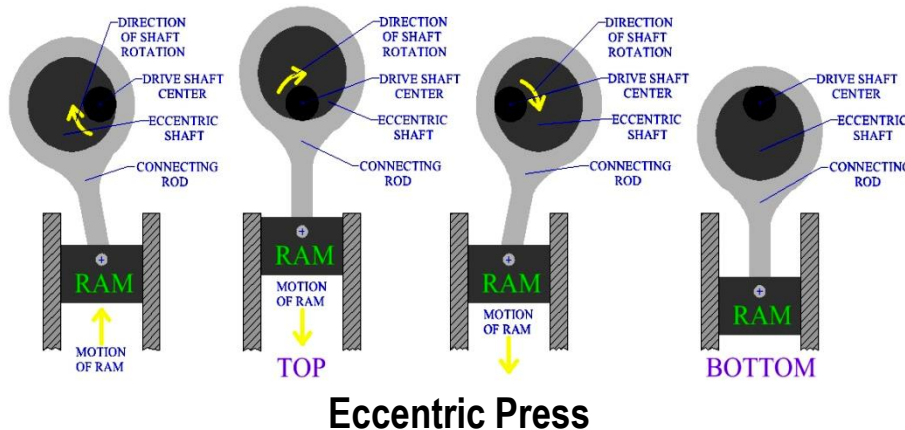
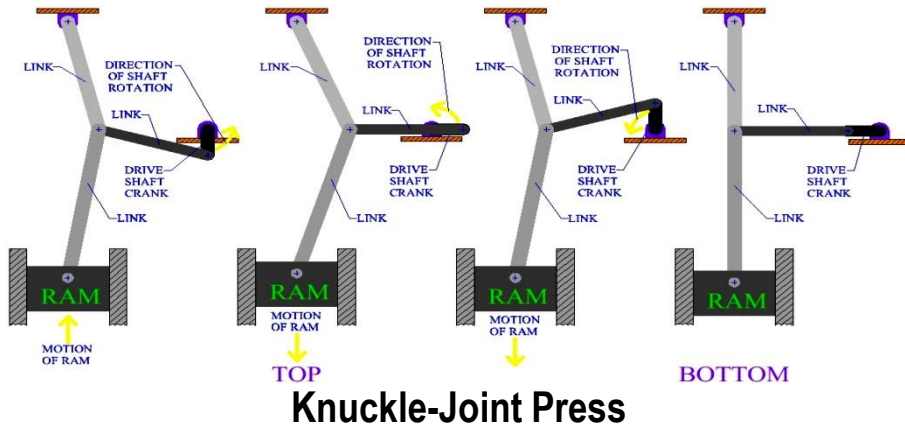


THE FLUID PRESSURE DELIVERED THROUGH THE APPARATUS CLOSES THE MOLD AND FORMS THE PART



Mechanical Presses

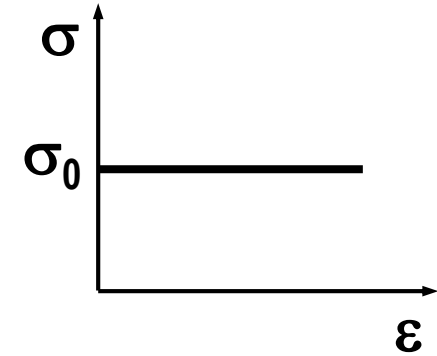
- They are **stroke-restricted machines** as the length of stroke and available load at positions of stroke represent their capacity.
- Their capacity is **expressed with load**.





➤ For simplicity in determination of the forging load for free upsetting (**open-die forging**), two assumptions can be made:

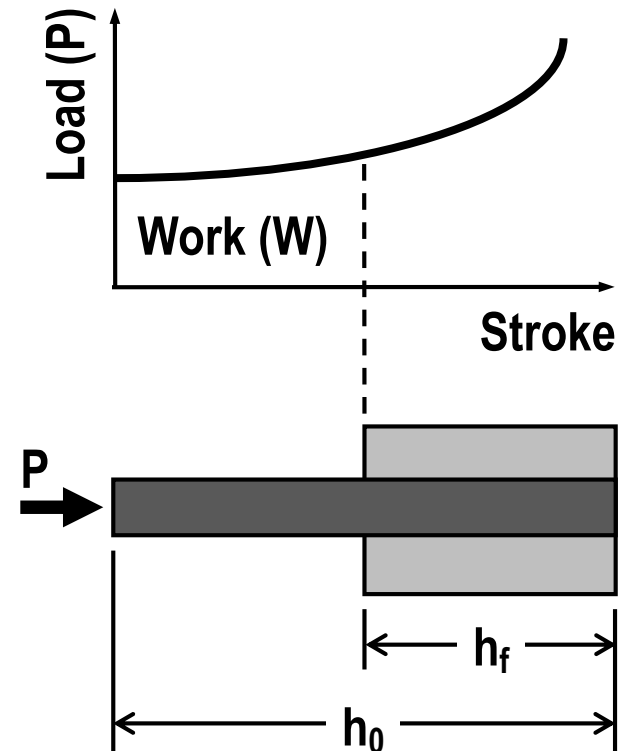
1. Material is **perfectly plastic** (i.e. *the flow stress remains constant*).
2. **No friction** between part and die surfaces (i.e. *radial flow of material is uniform throughout height*). Thus, **true strain** is: $\varepsilon' = \ln (h_0 / h_f)$



$$\text{Volume} = A_0 h_0 = Ah \Rightarrow A = \frac{V}{h}$$

$$P_0 = A_0 \sigma_0 \quad \& \quad P = A \sigma_0 \Rightarrow P = \frac{\sigma_0 V}{h}$$

$$W = \int_{h_f}^{h_0} P dh = \bar{\sigma}_0 V \ln \left(\frac{h_0}{h_f} \right) = \bar{\sigma}_0 V \varepsilon'$$





- If the friction is taken into account in open-die forging, then **Schey Equation** is used:

$$P = \frac{\sigma_0 V}{h} \left(1 + \frac{\mu D}{3h} \right)$$

- In such case, the work done can be calculated proportionally:

$$\left[\frac{P}{W} \right]_{\text{without friction}} = \left[\frac{P}{W} \right]_{\text{with friction}}$$

- For **closed-die forging**, the forging load is estimated by:

$$P = c \sigma_0 A_T$$

A_T : total cross-section area

$c = 1.2 - 2.5$ (for open-die forging)

$c = 3.0 - 8.0$ (for simple shape closed-die forging)

$c = 8.0 - 12.0$ (for complex shape closed-die forging)

Example:

A cylindrical billet (diameter of 90 mm, height of 100 mm) will be forged to height of 60 mm. Flow stress of material is: $\sigma_f = 50 \varepsilon^{0.12}$ (MPa). Calculate **required load (kN) & work done (kJ)**:
a) no friction condition ($\mu = 0$) **b)** with friction condition ($\mu = 0.2$)

Solution:

- Given parameters:
 $d_0 = 90 \text{ mm}$, $h_0 = 100 \text{ mm}$, $h_f = 60 \text{ mm}$
- Calculate volume:
 $V = [\pi(d_0)^2/4] * h_0 = 636172.51 \text{ mm}^3$
- Determine final diameter:
 $V_0 = V_f \rightarrow d_f = 116.19 \text{ mm}$
- Calculate true strain:
 $\varepsilon' = \ln(h_0/h_f) = 0.51$
- Calculate flow stress:
 $\sigma_f = 50 \varepsilon^{0.12} = 46.13 \text{ MPa}$
- Calculate mean flow stress:
 $\overline{\sigma}_f = \sigma_f/(1 + n) = 41.19 \text{ MPa}$

a) no friction condition:

- The required load:
 $P_{(\mu=0)} = \sigma_f * V/h_f = 489.09 \text{ kN}$
- The work done:
 $W_{(\mu=0)} = \overline{\sigma}_f * V * \varepsilon' = 13.38 \text{ kJ}$

b) with friction condition:

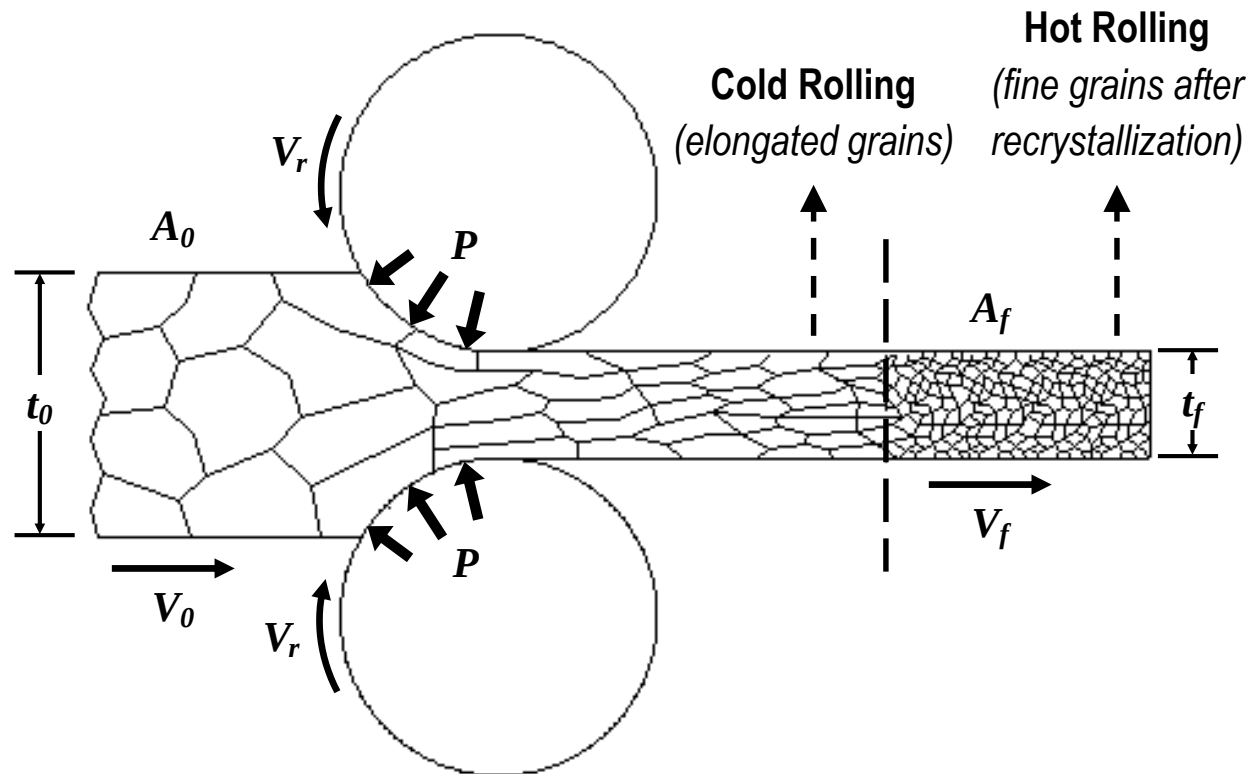
- The required load:
 $P_{(\mu=0.2)} = P_{(\mu=0)} * \left(1 + \frac{\mu d_f}{3 h_f}\right) = 552.23 \text{ kN}$
- The work done:
 $\left[\frac{P}{W}\right]_{(\mu=0)} = \left[\frac{P}{W}\right]_{(\mu=0.2)} \rightarrow W_{(\mu=0.2)} = 15.11 \text{ kJ}$



- It is a metal deformation process where **thickness of a metal plate is reduced by successive passes from rolls**:

$$\text{Reduction ratio } (r) : \frac{t_0 - t_f}{t_0} * 100 \quad \text{or} \quad \frac{A_0 - A_f}{A_0} * 100$$

- Work (metal plate) **exits from rolls at a higher speed** than it enters: $V_f > V_0$
- The grains are elongated **after cold rolling**, and grain size is reduced **after hot rolling**.



A_0 : cross-sectional area before rolling

A_f : cross-sectional area after rolling

t_0 : plate thickness before rolling

t_f : plate thickness after rolling

P : rolling load

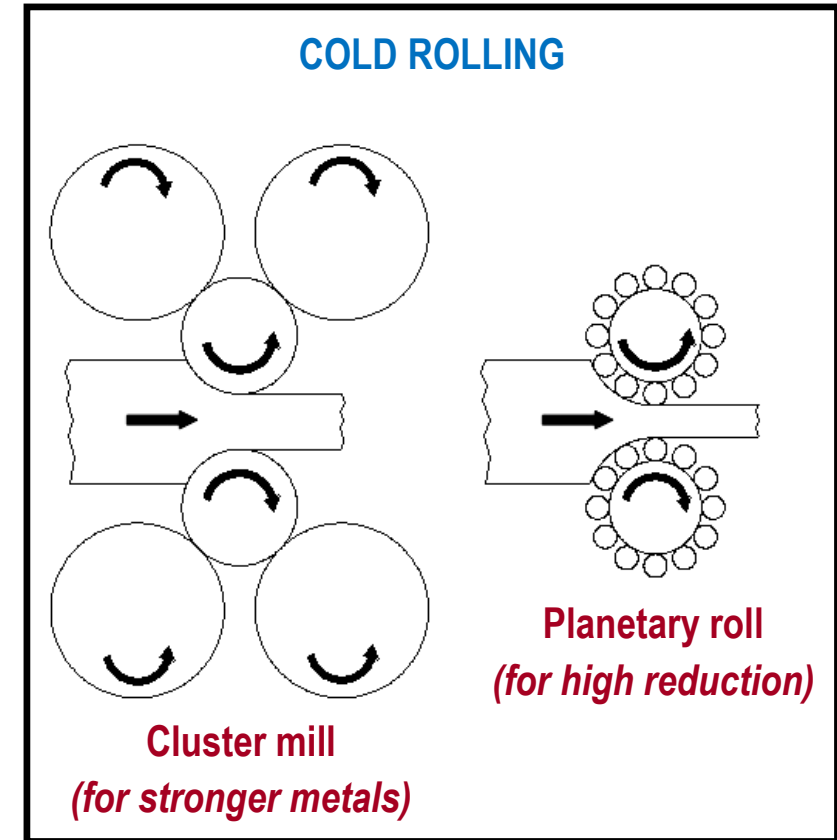
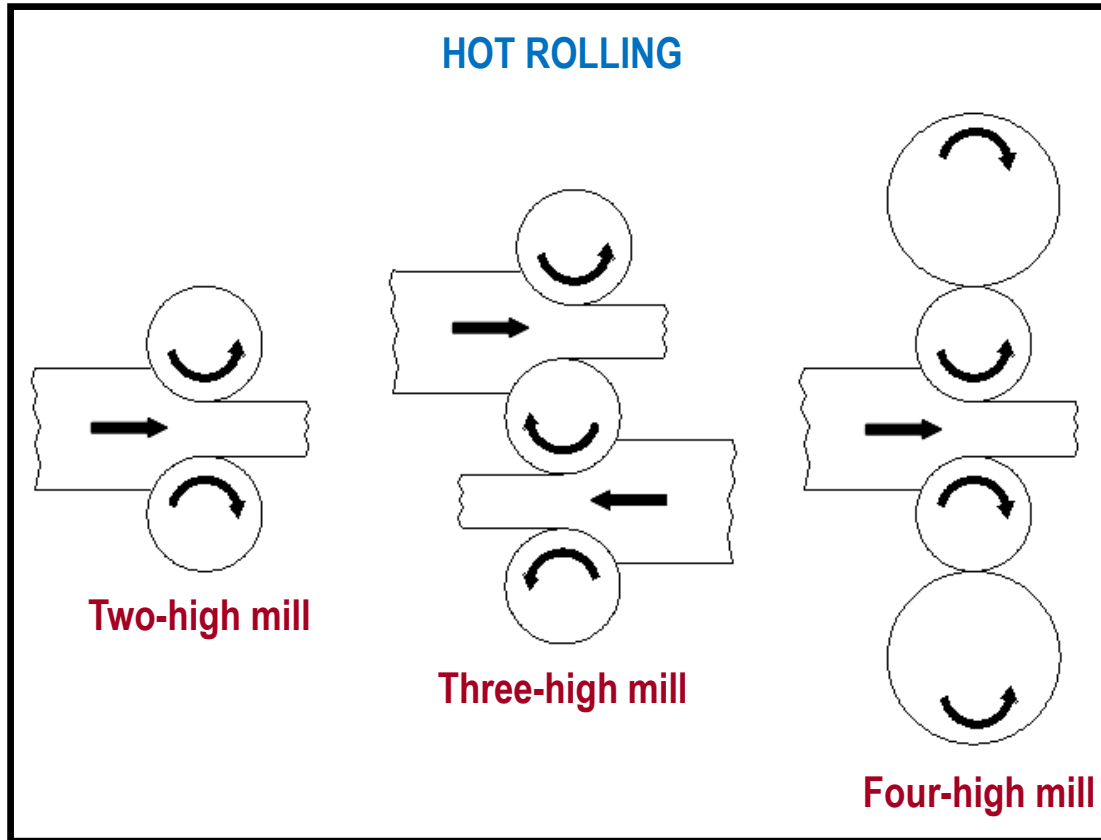
V_0 : speed of work at entering into rolls

V_f : speed of work at exiting from rolls

V_r : rotational speed of rolls

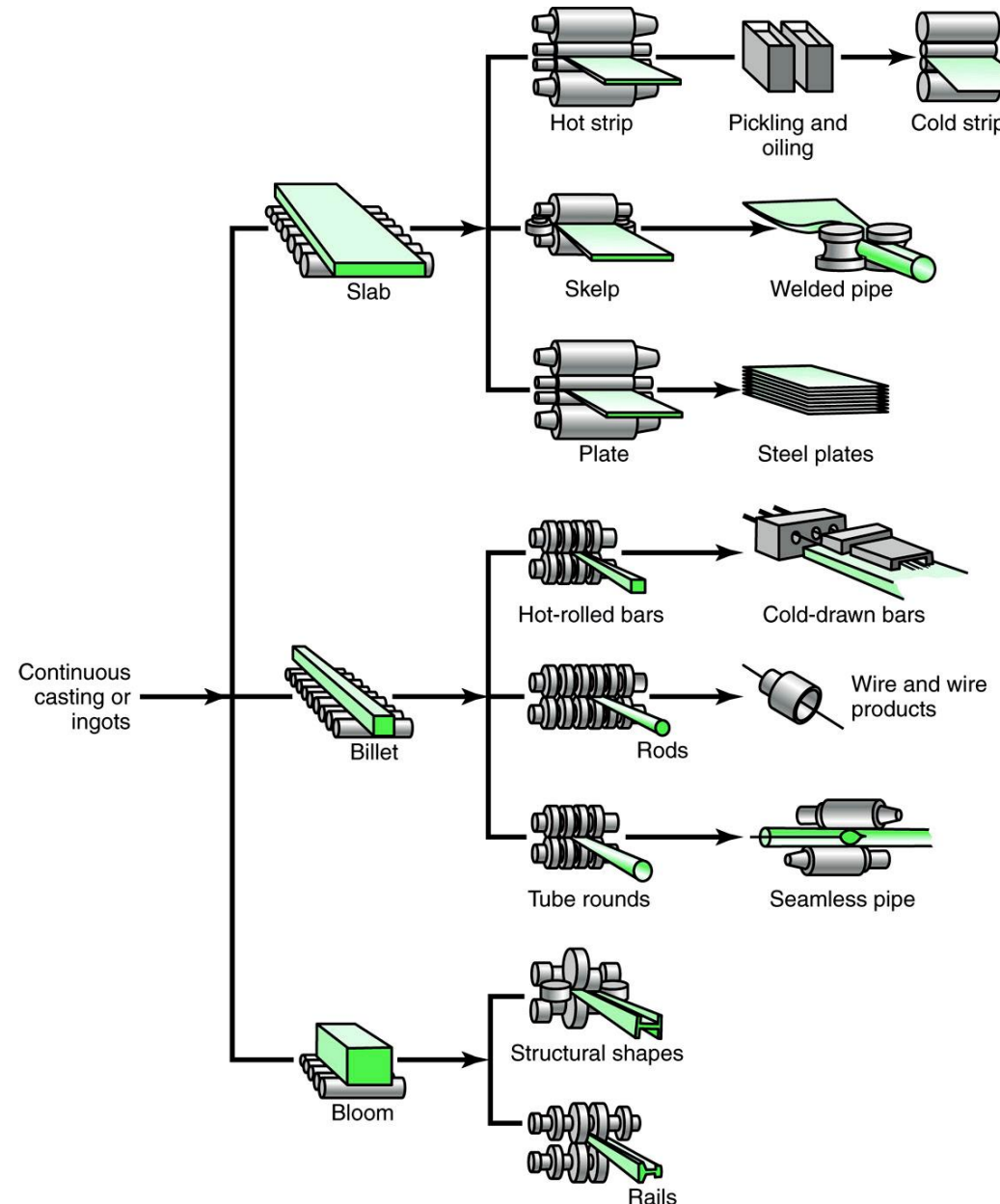


➤ Various configurations of rolling mills are available in **cold rolling** and **hot rolling**:



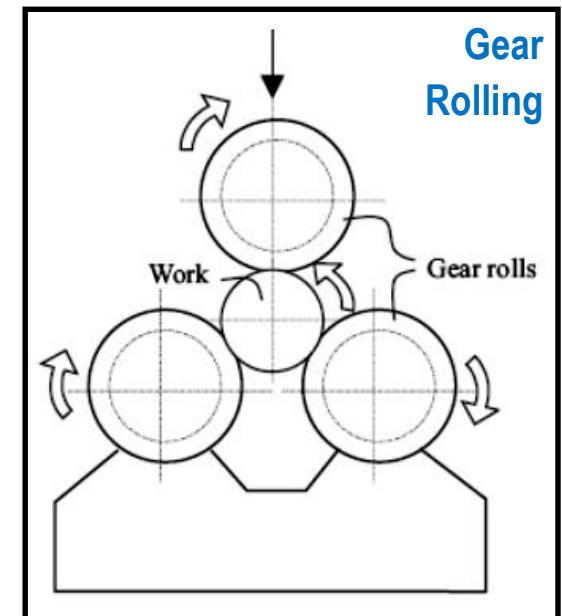
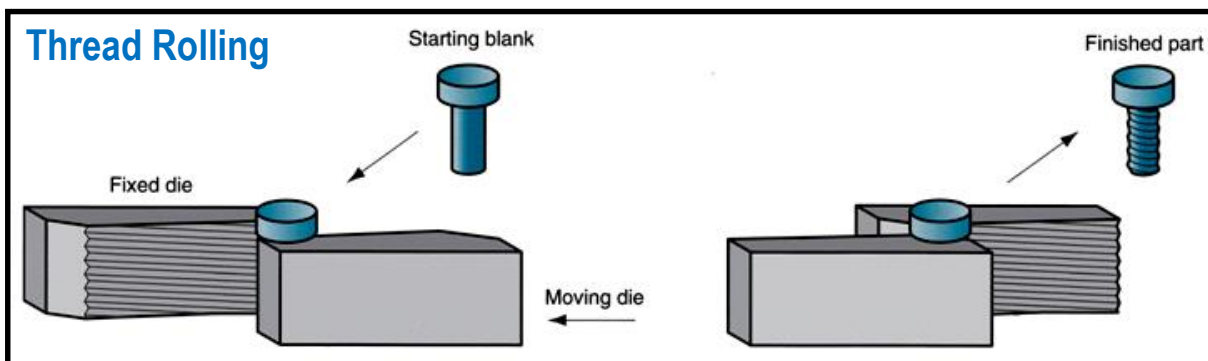
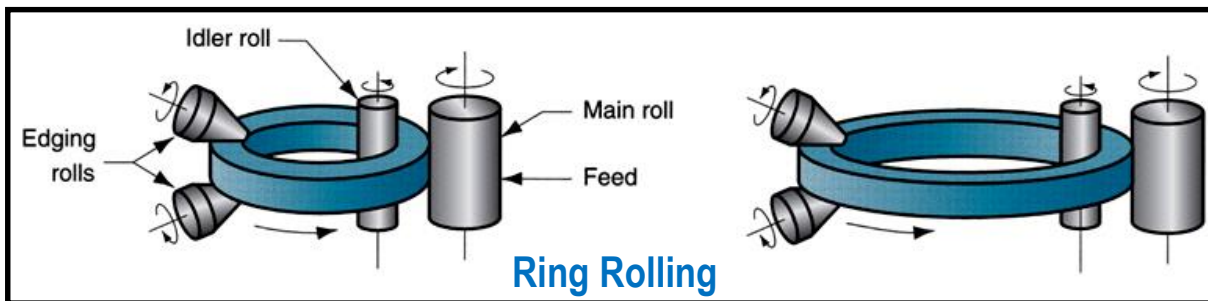


- First, steel is cast into **ingots** and stored in such shape.
- **Soaked ingots** (preheated at 1200 °C) are then rolled into intermediate shapes: **blooms**, **slabs**, or **billets**.
- A **bloom** (*rolled from ingot*) has a square section of larger than 150x150 mm.
- A **billet** (*rolled from bloom*) has a square section of 40x40 mm up to size of bloom.
- A **slab** (*rolled from ingot or bloom*) has a rectangular section with min. width of 250 mm and min. thickness of 40 mm.
- Finally, these intermediate shapes are rolled into different products as *illustrated in figure*.





- Other versions of steel rolling are as follows:
- **Shape rolling:** The work is deformed by gradual reduction into a contoured cross section (such as I-beams, L-beams, U-channels, rails, round, square bars and rods, etc.).
- **Ring rolling:** Thick-walled ring of small dia. is rolled into a thin-walled ring of larger dia.
- **Thread rolling:** Threads are formed on cylindrical parts by rolling between two thread dies.
- **Gear rolling:** Similar to thread rolling with three gear rolls forming gear profile on the work.





- Rolling takes place throughout the arc of contact, which is defined by **angle of contact (angle of bite)**.
- At **neutral (no-slip) point**, speed of work is equal to speed of rolls. Before/after this point, slipping/friction occur between rolls and work.
- **Plane-strain conditions** are valid (i.e. *assuming no change in width of work*). Thus, *volume rate of work metal is constant* at any point throughout rolling:

$$bt_0V_0 = btV = bt_fV_f$$

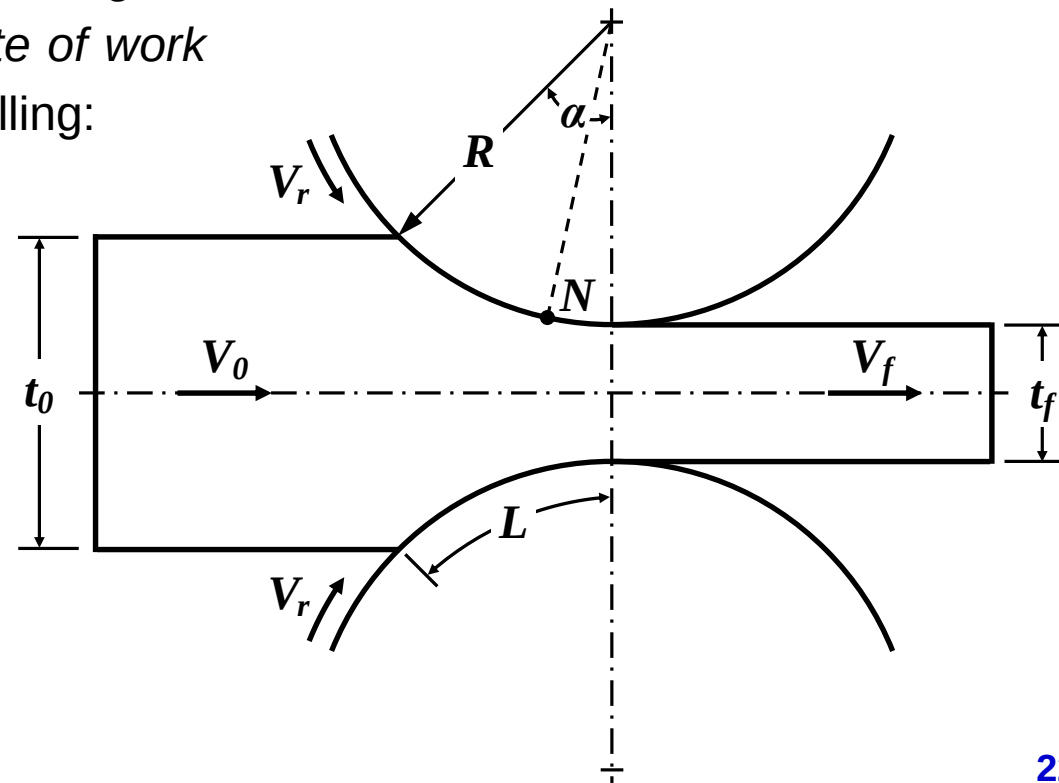
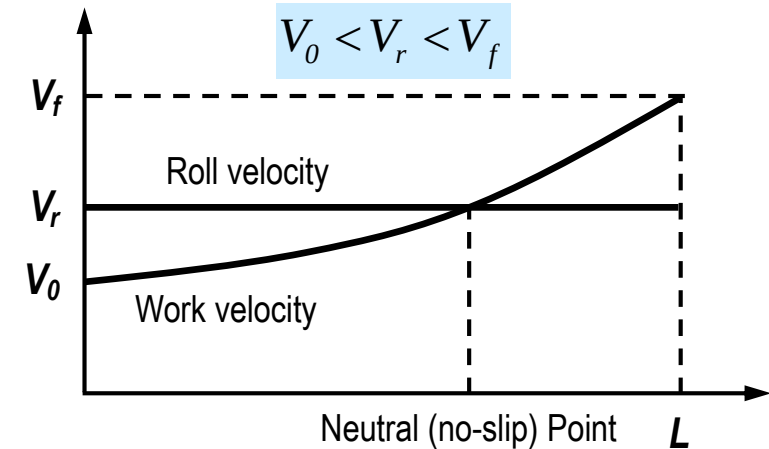
N : neutral (no-slip) point

α : contact (bite) angle

R : radius of rolls

L : length of arc contact

b : width of work

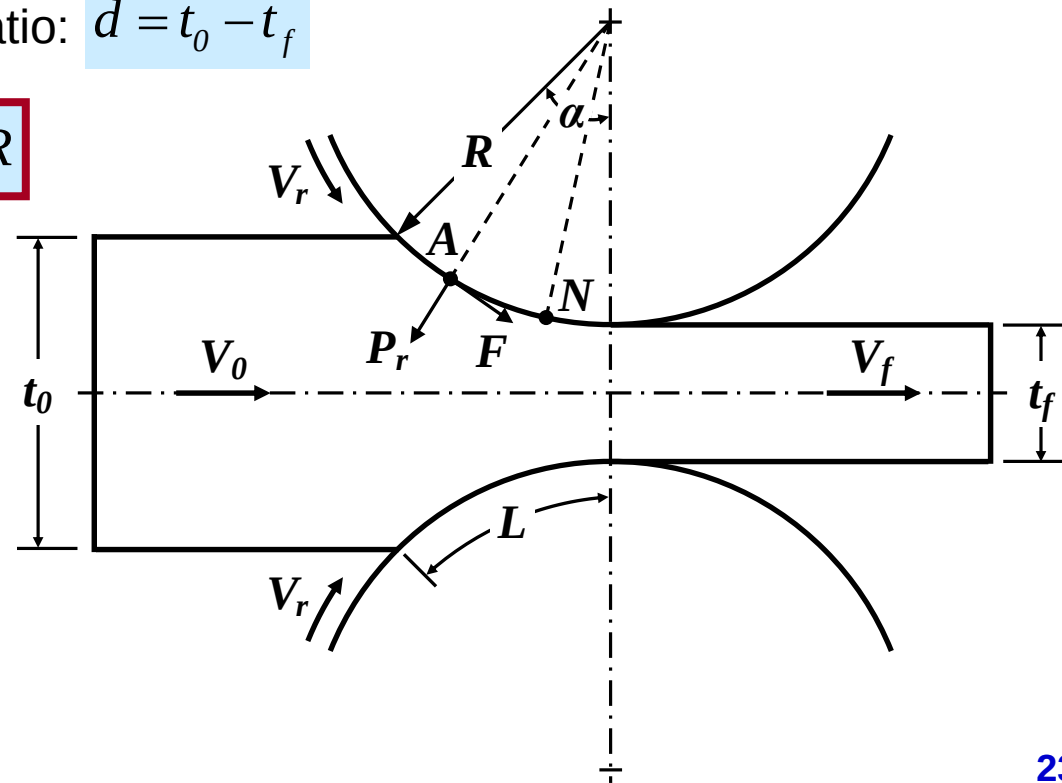




- Friction force (F) depends on the coefficient of friction (μ) between rolls and work: $F = \mu P_r$
- At arbitrary point (A), *horizontal components* of rolling force (P_r) and friction force (F) are related: $F \cos \alpha \geq P_r \sin \alpha \Rightarrow \frac{F}{P_r} \geq \frac{\sin \alpha}{\cos \alpha} \geq \tan \alpha \Rightarrow \mu \geq \tan \alpha$
- The amount of slip (s) can also be measured by means of *forward slip*: $s = (V_f - V_r) / V_r$
- **Draft (d)** is sometimes used as reduction ratio: $d = t_0 - t_f$
- In practice, **max. draft ($d_{\max}$)** is: $d_{\max} = \mu^2 R$

$\mu = 0 \Rightarrow$ no draft (no rolling)

Cold Rolling	Warm Rolling	Hot Rolling
$\mu \approx 0.1$	$\mu \approx 0.2$	$\mu \approx 0.4$





- The following parameters should be considered in rolling force calculations:
 - **Roll diameter** (*affects rolling force and contact length*)
 - **Flow strength of work material** (*affected by strain rate and temperature*)
 - **Friction between rolls and work** (*varies in cold, warm, or hot rolling*)
 - **Presence of front and/or back tension** (*related with work material behaviour*)
- **Rolling load (P)** based on plane strain condition with friction:

$$P = \frac{2}{\sqrt{3}} \bar{\sigma}_0 \left[\frac{1}{Q} (e^Q - 1) b L_p \right]$$



$$Q = \frac{\mu L_p}{\bar{t}}$$



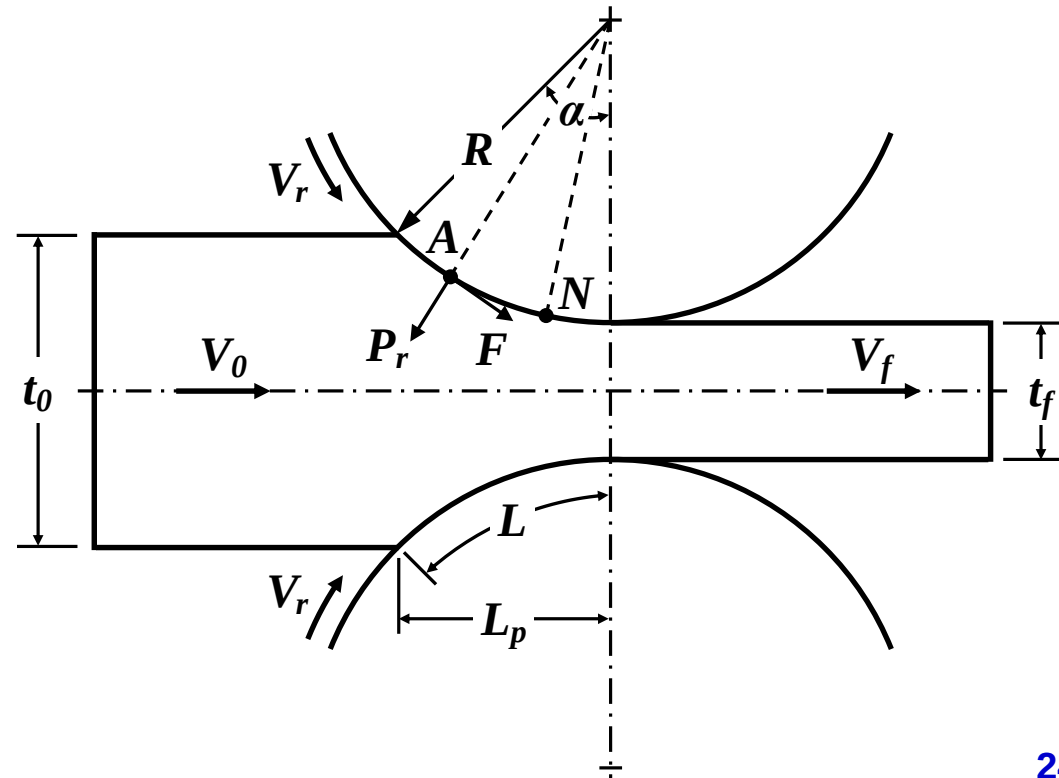
$$L_p \approx \sqrt{R(t_0 - t_f)} = \sqrt{R\Delta t}$$

$\bar{\sigma}_0$: mean flow stress

L_p : projected arc length

$\bar{t}$: mean thickness

Δt : reduction in thickness





➤ The rolling force calculations can be simplified as follows:

➤ Rolling force: $F = \overline{\sigma_0} bL$

➤ Length of contact: $L = R\alpha$ α : angle of contact (rad)

➤ Torque: $T = (F/2)L$

➤ Arc length (**L**) and projected length (**L_p**) are close: $L \approx L_p$

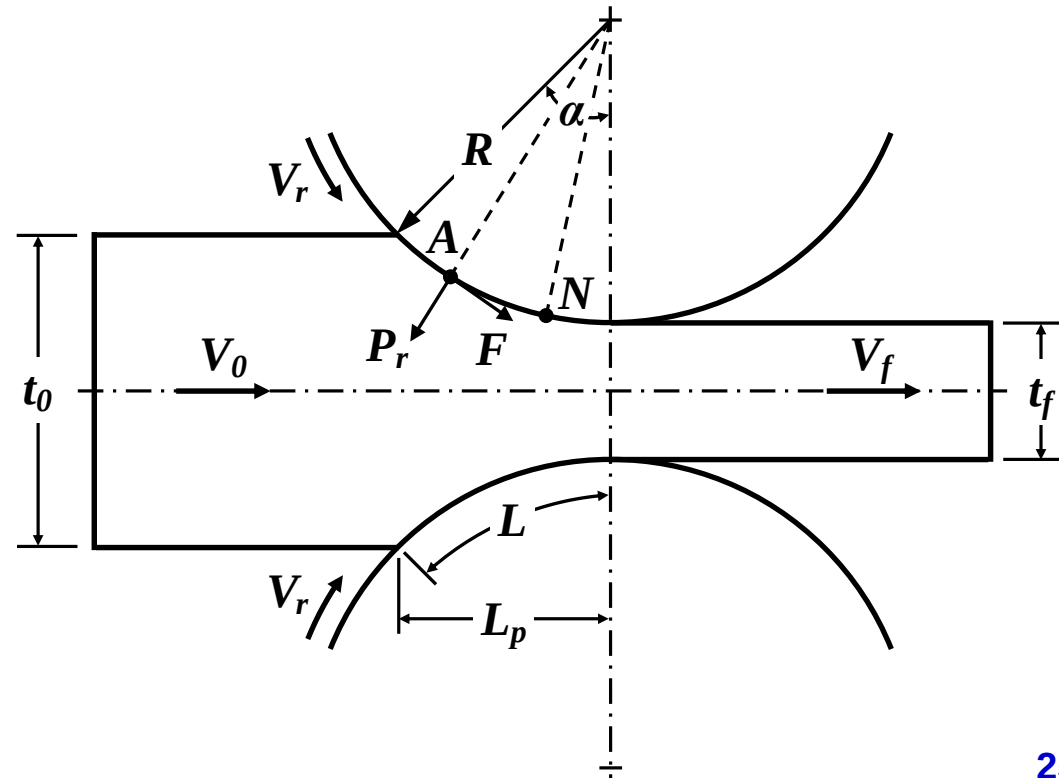
➤ Power (on each roll):

$$P = T\omega = (0.5FL)\omega$$

➤ Power (on two rolls):

$$P = 2[(0.5FL)\omega] = FL\omega$$

ω : rotational speed of roll (rpm)



Example:

A strip ($300 \times 25 \text{ mm}$) is fed through rolling mill with two powered rolls (each of 250 mm radius). The work thickness is to be reduced to 22 mm (in one pass) at a roll speed of 50 rpm . The flow stress of work material is 180 MPa , and the coefficient of friction between roll and work is 0.12 .

- Determine whether the friction is sufficient to permit rolling operation to be accomplished.
- If so, calculate roll force, torque and horsepower.

Solution:

- Determine *angle of contact* (α):

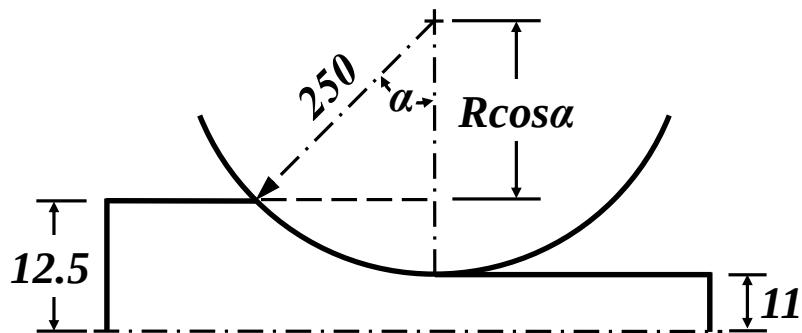
$$R \cos \alpha = R - \left[(t_0 - t_f) / 2 \right]$$



$$250 \cos \alpha = 250 - [12.5 - 11]$$



$$\alpha = 6.28^\circ$$



- Limiting conditions:

$$\mu \geq \tan \alpha$$



$$0.12 \geq \tan (6.28^\circ)$$



$$0.12 \geq 0.11$$



feasible

$$d \leq d_{\max}$$



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

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



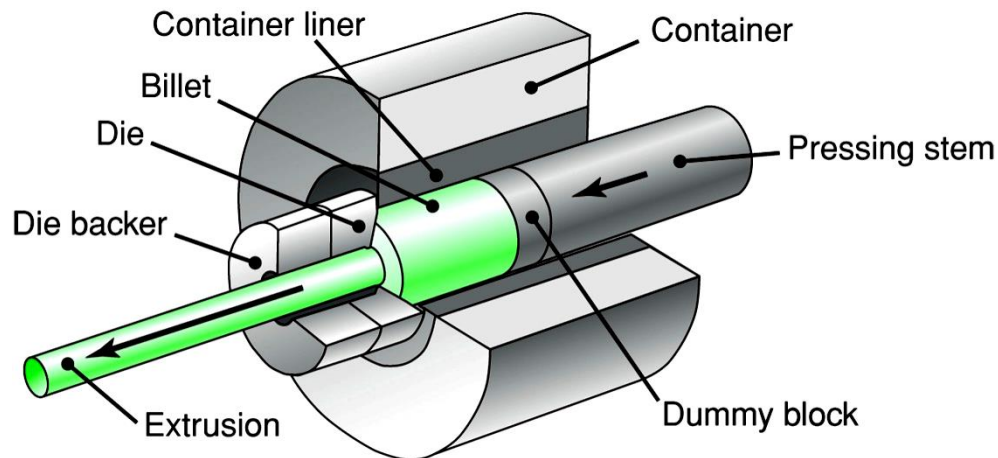
feasible

Solution (continued):

- Calculate *arc length of contact (L)*: $L = R\alpha = (250 \text{ mm}) * \left(6.28^\circ * \frac{\pi}{180} \text{ rad} \right) = 27.4 \text{ mm}$
- Calculate *rolling force (F)*: $F = \overline{\sigma}_0 bL = \left(180 \frac{\text{N}}{\text{mm}^2} \right) (300 \text{ mm}) (27.4 \text{ mm}) = 1.4796 * 10^6 \text{ N}$
- Calculate *torque (T)*: $T = 0.5FL = 0.5 \left(1.4797 * 10^6 \text{ N} \right) \left(27.4 \text{ mm} \frac{1 \text{ m}}{10^3 \text{ mm}} \right) = 20.270 * 10^3 \text{ Nm}$
- Calculate *power (P)*:
$$P = FL\omega = \left(1.4796 * 10^6 \text{ N} \right) \left(27.4 \text{ mm} \frac{1 \text{ m}}{10^3 \text{ mm}} \right) \left(50 \frac{\text{rev}}{\text{min}} \frac{1 \text{ min}}{60 \text{ s}} \frac{2\pi \text{ rad}}{1 \text{ rev}} \right) = 212.27 \text{ kW}$$
- *Power in hp*:
$$1 \text{ kW} \approx 1.341 \text{ hp} \quad \Rightarrow \quad (212.27 \text{ kW}) * 1.341 \quad \Rightarrow \quad P = 284.65 \text{ hp}$$



- It is a process in which **the work is forced to flow through a die opening** to produce a desired cross-sectional shape. In other words, *a block of metal is reduced in cross-section by forging it to flow through a die under pressure.*
- It can be used to produce **cylindrical bars or hollow tubes**, as well as **irregular cross-sections**.
- **Lead, tin, aluminum alloys** can be cold extruded.
- **Horizontal type presses** are used.
- **Speed of extrusion** depends on temperature and type of material used.





- Extrusion is performed in different ways, and hence **different classifications** are available:
direct or **indirect**; **hot** or **cold**; **continuous** or **discrete**

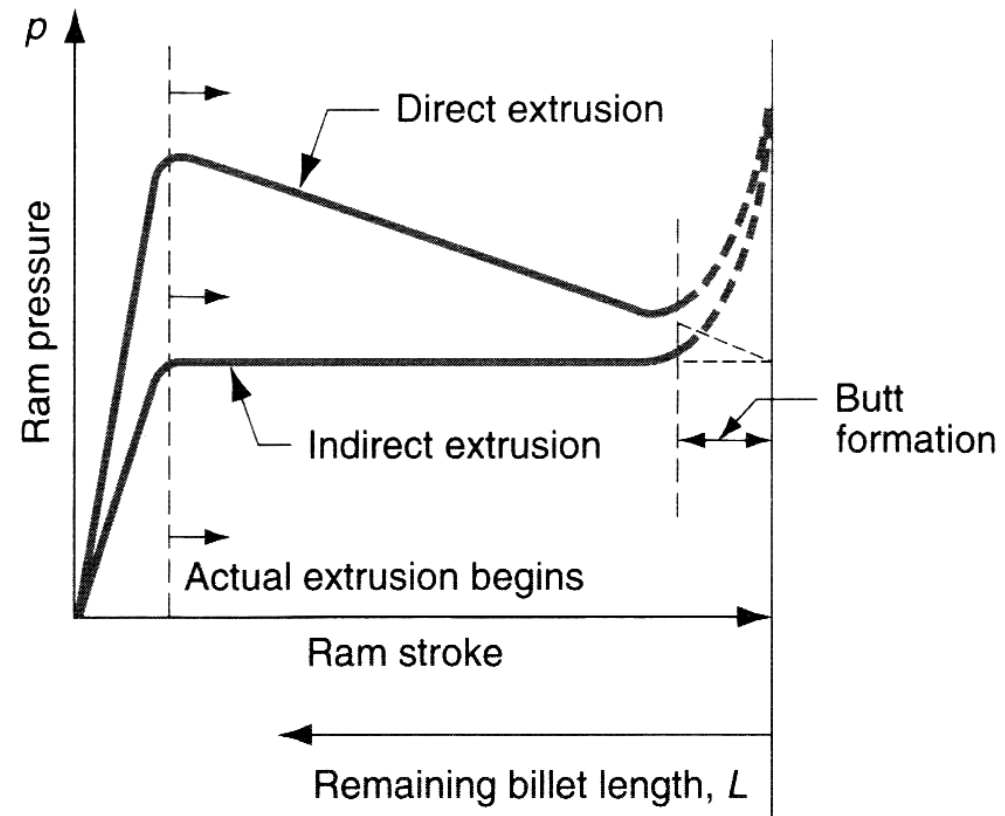
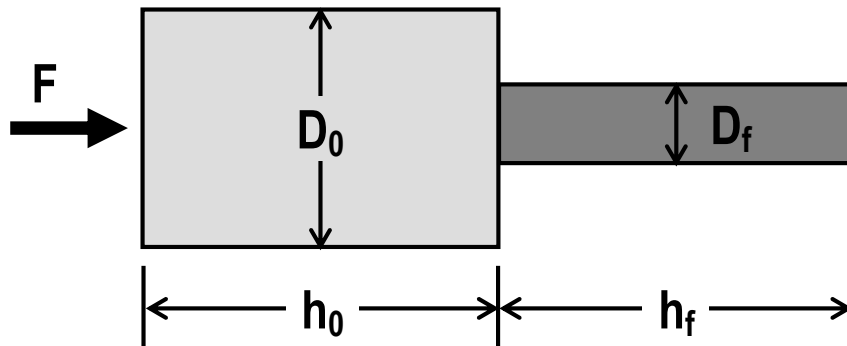
Process	Direct (Forward) Extrusion	Indirect (Backward) Extrusion
Principle	The work is forced to flow through a die opening.	The work flows in the reverse direction of ram.
Solid Parts	Labels: Container, Ram, Final work shape, Die, Work billet, v, F	Labels: Container, Hollow ram, Final work shape, Die, Work billet, F, v
Hollow Parts	Labels: Container, Ram, Final work shape, Die, Work billet, Mandrel, v, F	Labels: Container, Ram, Final work shape, Die, Work billet, v, F



- Figure shows a typical plot of **ram pressure vs ram stroke** (and the remaining billet length).
- The higher values in direct extrusion result from friction at the container wall.
- Shape of initial pressure build-up depends on **die angle** (higher the angle, steeper the build-up).
- The increase in pressure at the end of stroke is related to **butt formation** (a small portion of billet that cannot be forced through die opening).
- **Ram force (F)** and **ram power (W)** can be calculated in a similar way of forging:

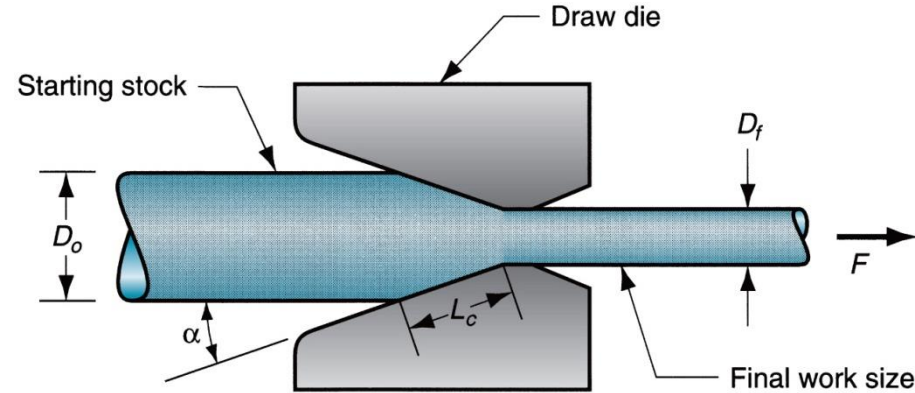
$$F = \sigma_0 A_0 \ln \left(\frac{A_0}{A_f} \right)$$

$$W = \sigma_0 V \ln \left(\frac{h_f}{h_0} \right)$$





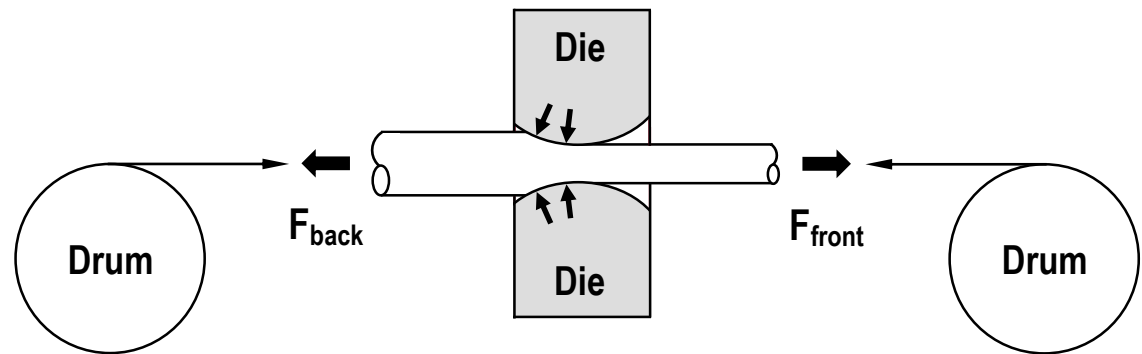
- It involves **pulling the metal through a die** by means of a tensile force applied to the exit side.
- The end is grasped by tongs on a draw bench and pulled through.
- There may be few successive drawing dies on continuous drawing.



α : die angle (half angle) L_c : contact length

- **Drawing load** can be obtained as (assuming that *there is no friction*):

$$F = \sigma_0 A_f \ln \left(\frac{A_0}{A_f} \right)$$



- **The number of dies** varies from 4 to 12, and **the maximum possible reduction per pass** is 0.63.
- In practice, draw reductions per pass are well below the theoretical limit. Reductions of 0.5 for single-draft bar drawing and 0.3 for multiple-draft wire drawing seem to be the upper limits.