Forging

• It is a deformation process in which the work piece is compressed between two dies, using either impact load or hydraulic load (or gradual load) to deform it.

• It is used to make a variety of high-strength components for automotive, aerospace, and other applications. The components include engine crankshafts, connecting rods, gears, aircraft structural components, jet engine turbine parts etc.

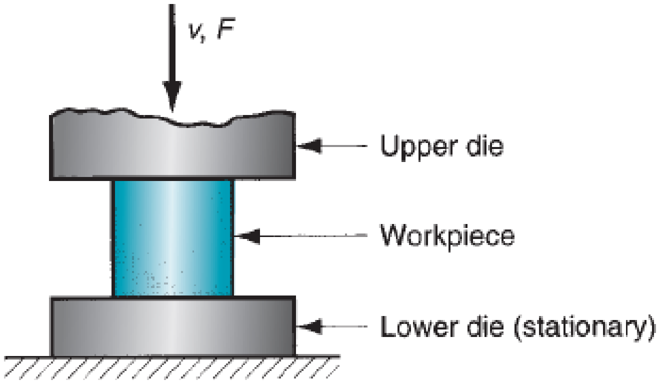
• Category based on temperature : cold, warm, hot forging

• Category based on presses:

impact load => forging hammer; gradual pressure => forging press

• Category based on type of forming:

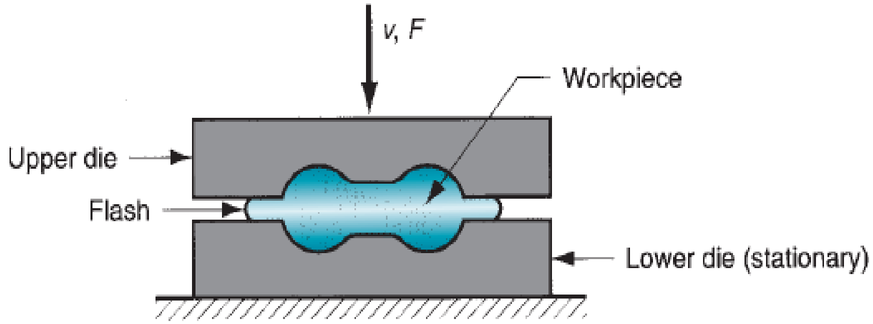
Open die forging, impression die forging, flashless forging



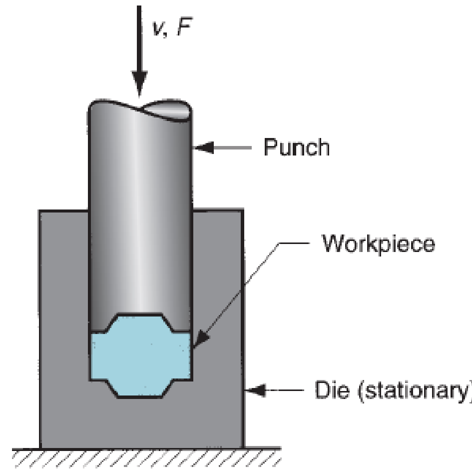
Open die forging

In open die forging, the work piece is compressed between two flat platens or dies, thus allowing the metal to flow without any restriction in the sideward direction relative to the die surfaces.

M.P. Groover, *Fundamental of modern manufacturing Materials, Processes and systems*, 4ed



impression die forging



flashless forging

In impression die forging, the die surfaces contain a shape that is given to the work piece during compression, thus restricting the metal flow significantly. There is some extra deformed material outside the die impression which is called as flash. This will be trimmed off later.

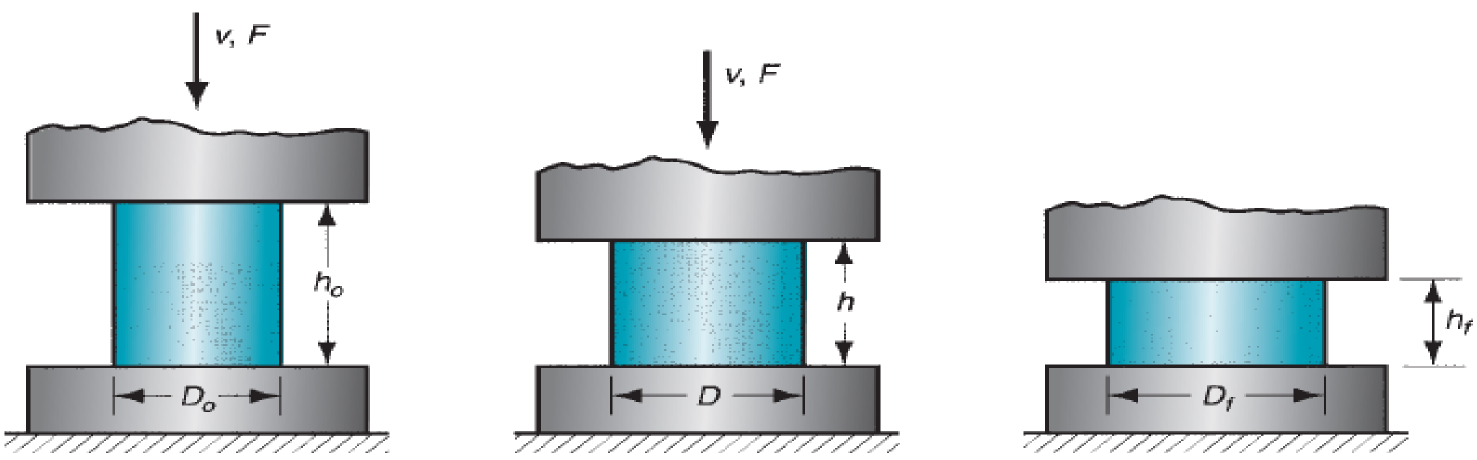
In flashless forging, the work piece is fully restricted within the die and no flash is produced. The amount of initial work piece used must be controlled accurately so that it matches the volume of the die cavity.

Open die forging

A simplest example of open die forging is compression of billet between two flat die halves which is like compression test. This also known as upsetting or upset forging. Basically height decreases and diameter increases.

Under ideal conditions, where there is no friction between the billet and die surfaces, homogeneous deformation occurs. In this, the diameter increases uniformly throughout its height.

In ideal condition, $\varepsilon = \ln (h_o/h)$. h will be equal to h_f at the end of compression, ε will be maximum for the whole forming. Also $F = \sigma_f A$ is used to find the force required for forging, where σ_f is the flow stress corresponding to ε at that stage of forming.

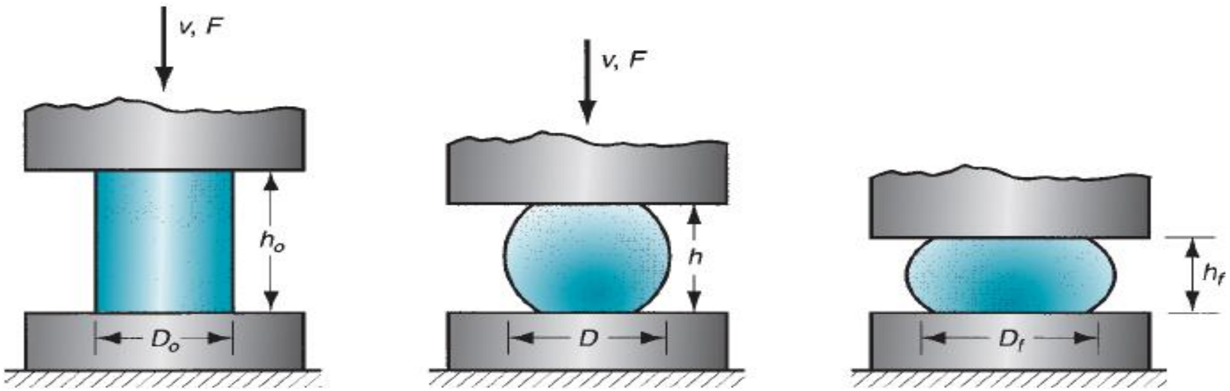


Start of compression **Partial compression** **Completed compression**

M.P. Groover, *Fundamental of modern manufacturing Materials, Processes and systems*, 4ed

In actual forging operation, the deformation will not be homogeneous as bulging occurs because of the presence of friction at the die-billet interface. This friction opposes the movement of billet at the surface. This is called barreling effect.

The barreling effect will be significant as the diameter-to-height (*D/h*) ratio of the workpart increases, due to the greater contact area at the billet–die interface. Temperature will also affect the barreling phenomenon.



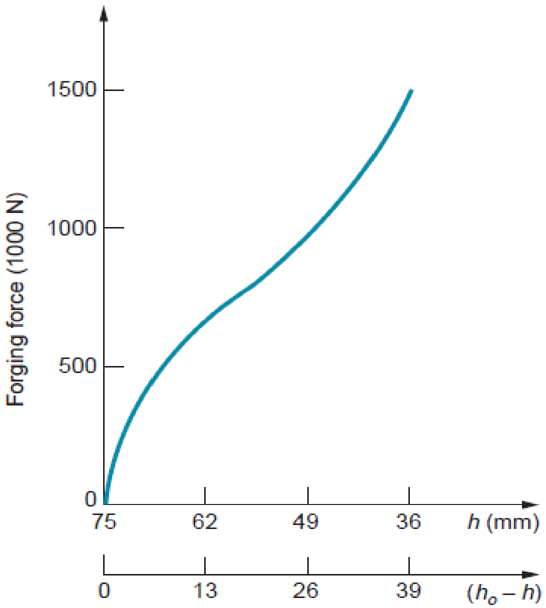
Start of compression | **Partial compression** | **Completed compression**

In actual forging, the accurate force evaluation is done by using, $F = K_f \sigma_f A$ by considering the effect of friction and *D/h* ratio. Here,

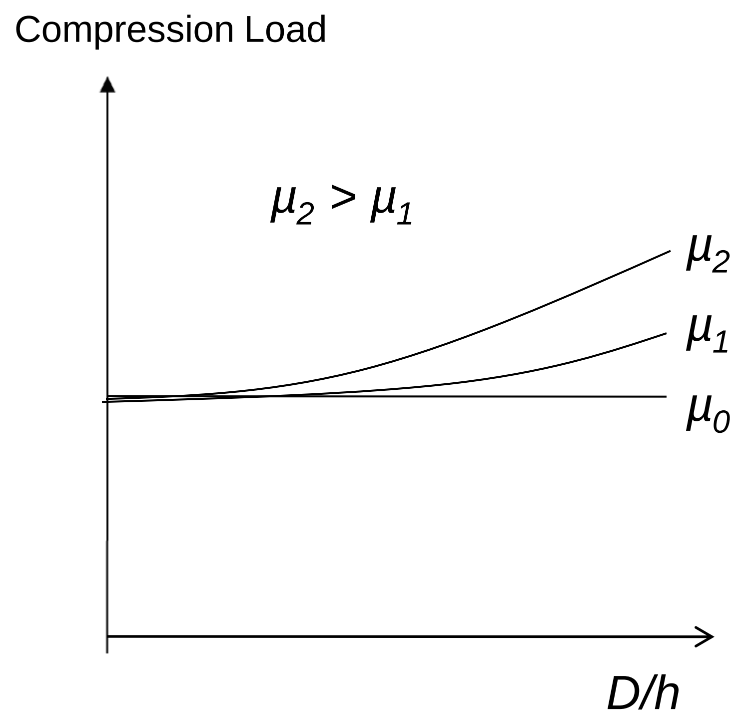
$$K_f = 1 + \frac{0.4 \mu D}{h}$$

Where K_f = forging shape factor, μ = coefficient of friction, D = work piece diameter, h = work piece height

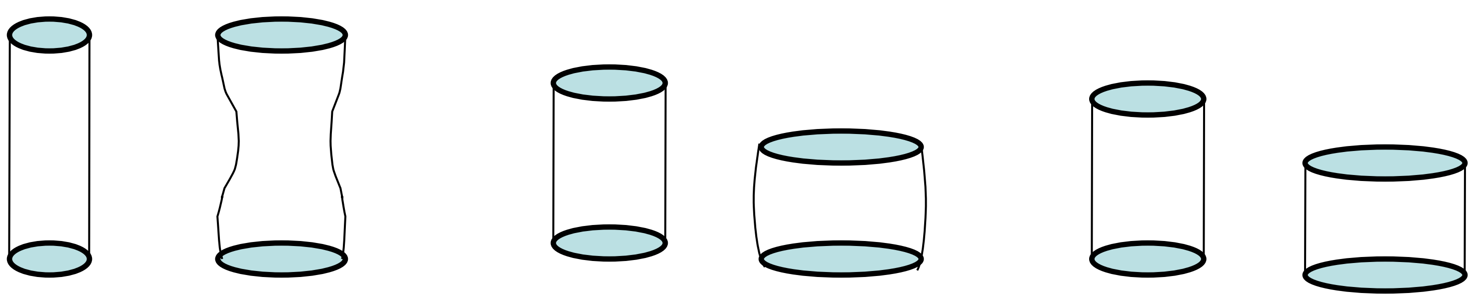
Typical load-stroke curve in open die forging



Effect of *D/h* ratio on load:



Effect of *h/D* ratio on barreling:



Long cylinder: *h/D* >2

Cylinder having *h/D* < 2 with friction

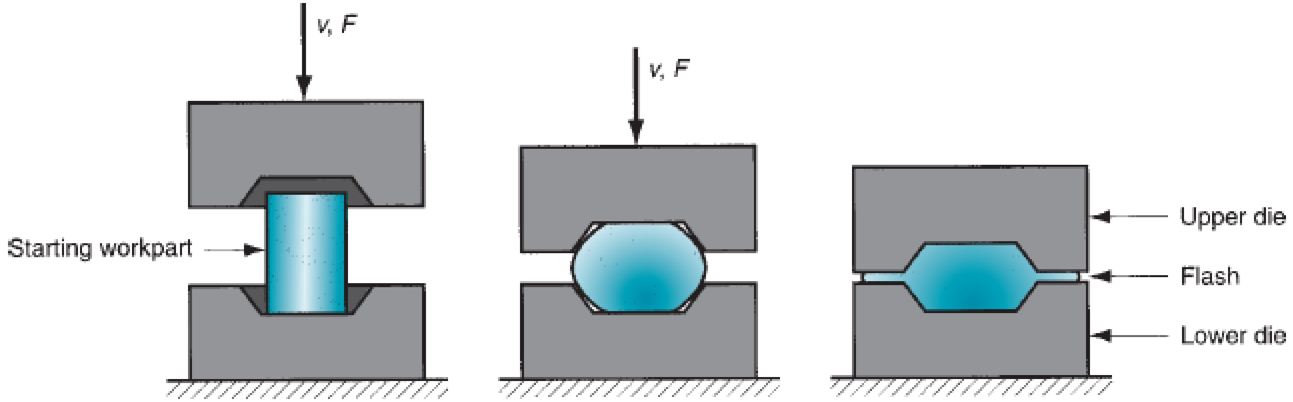
Frictionless compression

Closed die forging

Closed die forging called as impression die forging is performed in dies which has the impression that will be imparted to the work piece through forming.

In the intermediate stage, the initial billet deforms partially giving a bulged shape. During the die full closure, impression is fully filled with deformed billet and further moves out of the impression to form flash.

In multi stage operation, separate die cavities are required for shape change. In the initial stages, uniform distribution of properties and microstructure are seen. In the final stage, actual shape modification is observed. When drop forging is used, several blows of the hammer may be required for each step.



Starting stage

Intermediate stage

Final stage with flash formation

M.P. Groover, *Fundamental of modern manufacturing Materials, Processes and systems*, 4ed

The formula used for open die forging earlier can be used for closed die forging, i.e.,

$F = K_f \sigma_f A$

Where F is maximum force in the operation; A is projected area of the part including flash, σ_f is flow stress of the material, K_f is forging shape factor.

Now selecting the proper value of flow stress is difficult because the strain varies throughout the work piece for complex shapes and hence the strength varies. Sometimes an average strength is used. K_f is used for taking care of different shapes of parts. Table shows the typical values of K_f used for force calculation. In hot working, appropriate flow stress at that temperature is used.

Part Shape	K_f	Part Shape	K_f
Impression-die forging:		Flashless forging:	
Simple shapes with flash	6.0	Coining (top and bottom surfaces)	6.0
Complex shapes with flash	8.0	Complex shapes	8.0
Very complex shapes with flash	10.0		

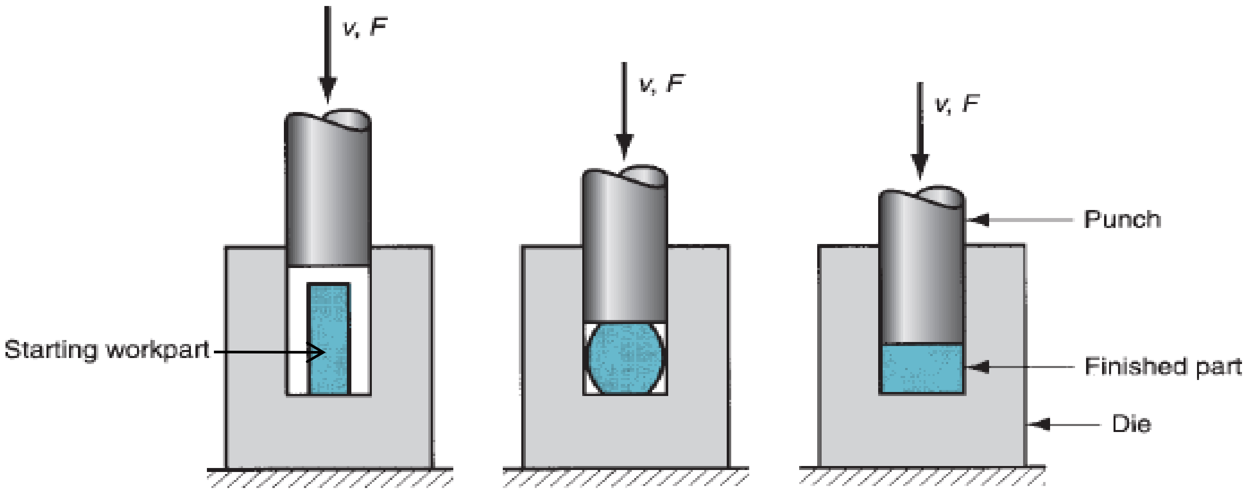
The above equation is applied to find the maximum force during the operation, since this is the load that will determine the required capacity of the press used in the forging operation.

Impression die forging is not capable of making close tolerance objects. Machining is generally required to achieve the accuracies needed. The basic geometry of the part is obtained from the forging process, with subsequent machining done on those portions of the part that require precision finishing like holes, threads etc.

In order to improve the efficiency of closed die forging, precision forging was developed that can produce forgings with thin sections, more complex geometries, closer tolerances, and elimination of machining allowances. In precision forging operations, sometimes machining is fully eliminated which is called near-net shape forging.

Flashless forging

The three stages of flashless forging is shown below:



In flashless forging, most important is that the work piece volume must equal the space in the die cavity within a very close tolerance.

If the starting billet size is too large, excessive pressures will cause damage to the die and press.

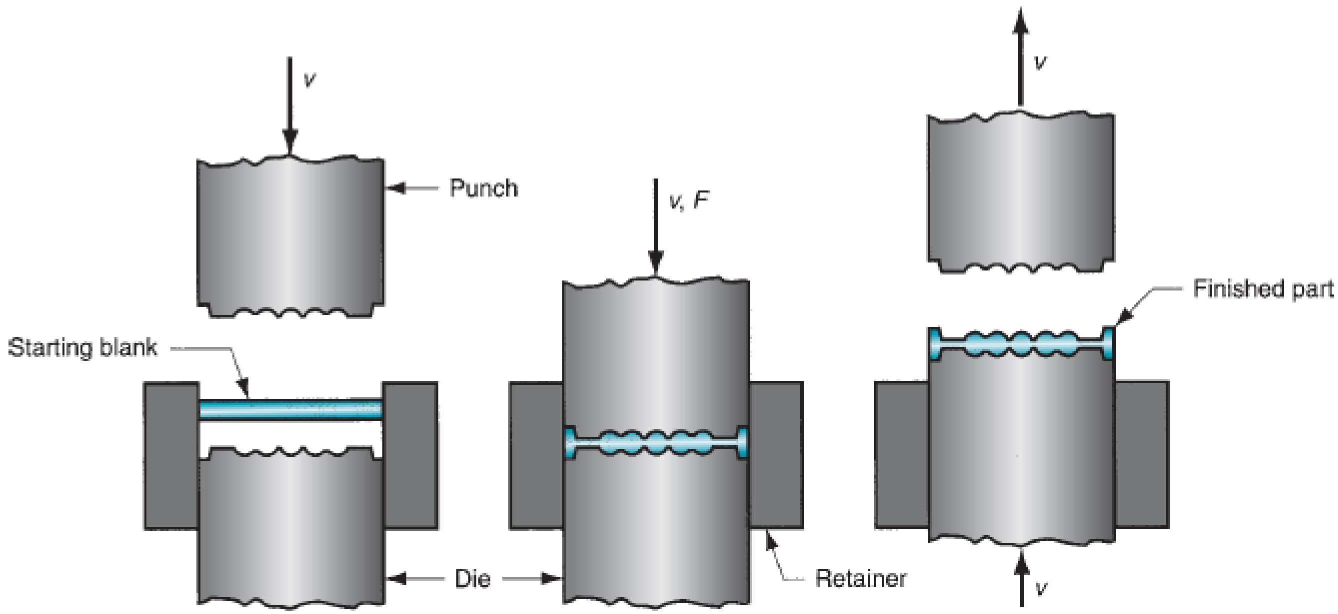
If the billet size is too small, the cavity will not be filled.

Because of the demands, this process is suitable to make simple and symmetrical part geometries, and to work materials such as Al, Mg and their alloys.

M.P. Groover, *Fundamental of modern manufacturing Materials, Processes and systems*, 4ed

Coining is a simple application of closed die forging in which fine details in the die impression are impressed into the top or/and bottom surfaces of the work piece.

Though there is little flow of metal in coining, the pressures required to reproduce the surface details in the die cavity are at par with other impression forging operations.



Starting of cycle

Fully compressed

Ram pressure removed and ejection of part

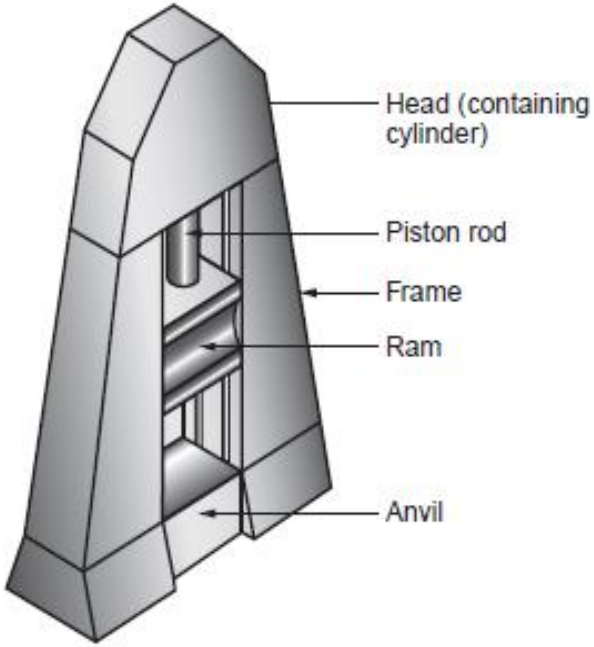
Making of coin

Forging hammers, presses and dies

Hammers:

Hammers operate by applying an impact loading on the work piece. This is also called as drop hammer, owing to the means of delivering impact energy.

When the upper die strikes the work piece, the impact energy applied causes the part to take the form of the die cavity. Sometimes, several blows of the hammer are required to achieve the desired change in shape.



Drop hammers

Drop hammers are classified as:
Gravity drop hammers, power drop hammers.

Gravity drop hammers - achieve their energy by the falling weight of a heavy ram. The force of the blow is dependent on the height of the drop and the weight of the ram.

Power drop hammers - accelerate the ram by pressurized air or steam.

Presses:

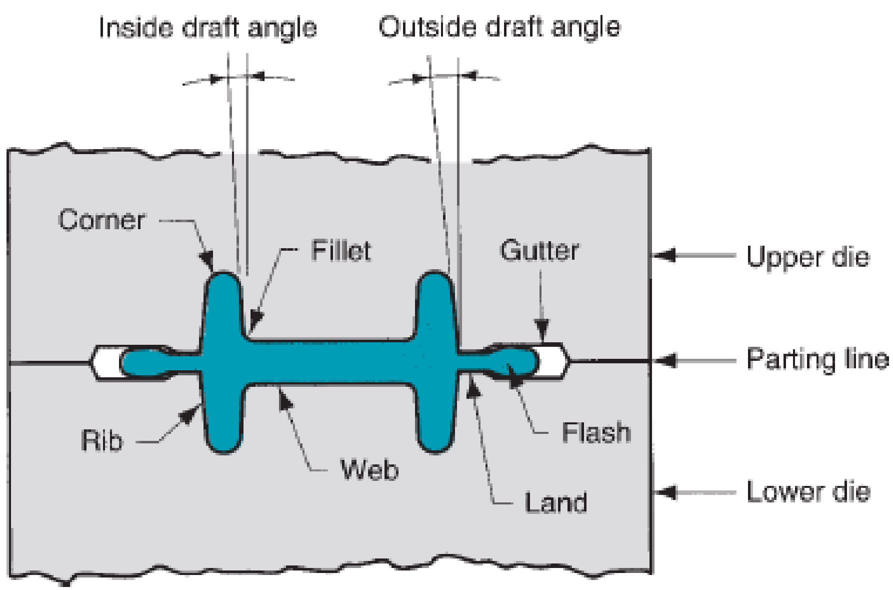
The force is given to the forging billet gradually, and not like impact force.

Mechanical presses: In these presses, the rotating motion of a drive motor is converted into the translation motion of the ram. They operate by means of eccentrics, cranks, or knuckle joints. Mechanical presses typically achieve very high forces at the bottom of the forging stroke.

Hydraulic presses : hydraulically driven piston is used to actuate the ram.

Screw presses : apply force by a screw mechanism that drives the vertical ram. Both screw drive and hydraulic drive operate at relatively low ram speeds.

Forging dies:



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Parting line: The parting line divides the upper die from the lower die. In other words, it is the plane where the two die halves meet. The selection of parting line affects grain flow in the part, required load, and flash formation.

Draft: It is the amount of taper given on the sides of the part required to remove it from the die.

Draft angles: It is meant for easy removal of part after operation is completed. 3° for Al and Mg parts; 5° to 7° for steel parts.

Webs and ribs: They are thin portions of the forging that is parallel and perpendicular to the parting line. More difficulty is witnessed in forming the part as they become thinner.

Fillet and corner radii: Small radii limits the metal flow and increase stresses on die surfaces during forging.

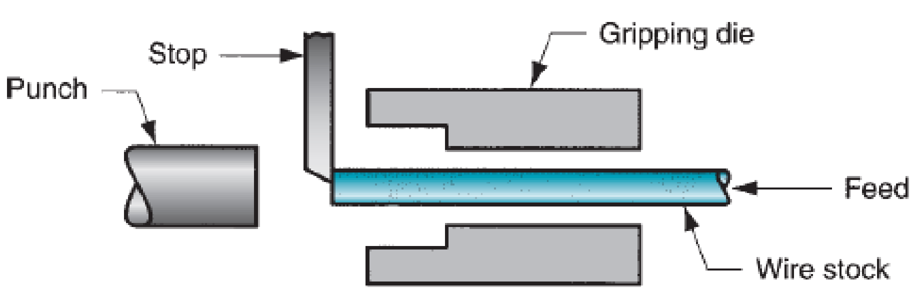
Flash: The pressure build up because of flash formation is controlled proper design of gutter and flash land.

Other forging operations

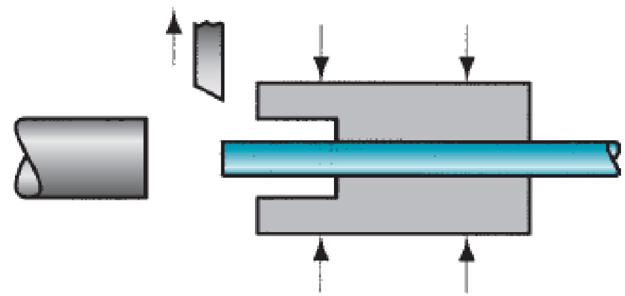
Upset forging:

It is a deformation operation in which a cylindrical work piece is increased in diameter with reduction in length. In industry practice, it is done as closed die forging.

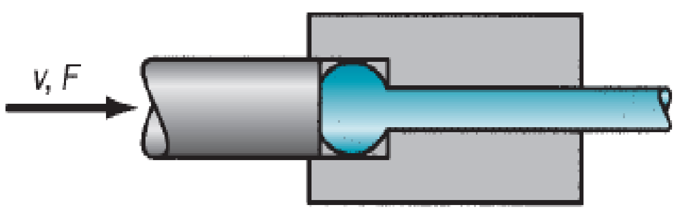
Upset forging is widely used in the fastener industries to form heads on nails, bolts, and similar products.



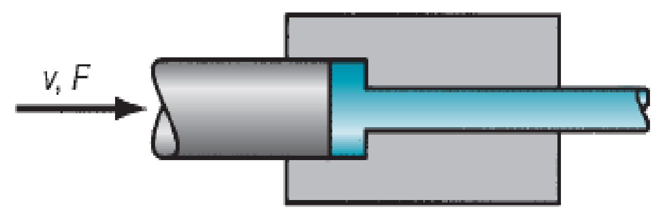
Feeding of work piece



Gripping of work piece and retracting of stop



Forward movement of punch and upsetting



Forging operation completes

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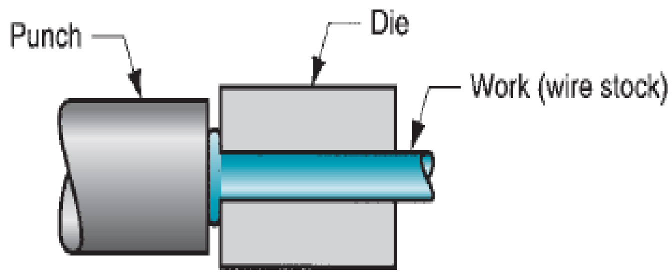
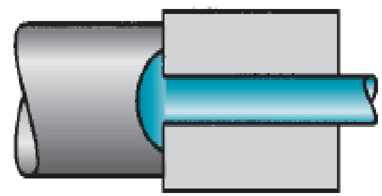
Heading:

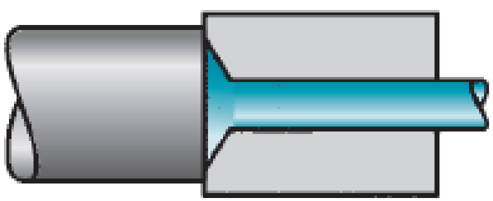
The following figure shows variety of heading operations with different die profiles.

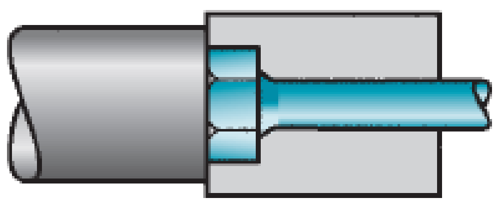


Heading a die using open die forging

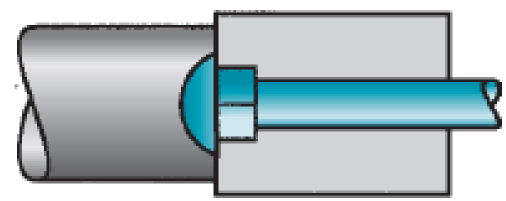


Round head formed by punch only





Head formed inside die only



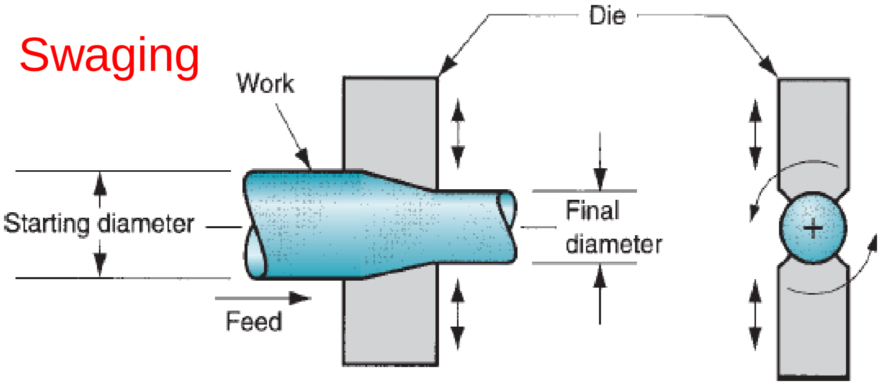
Bolt head formed by both die and punch

Long bar stock (work piece) is fed into the machines by horizontal slides, the end of the stock is upset forged, and the piece is cut to appropriate length to make the desired product. The maximum length that can be upset in a single blow is three times the diameter of the initial wire stock.

Swaging:

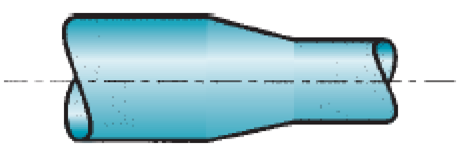
Swaging is used to reduce the diameter of a tube or a rod at the end of the work piece to create a tapered section. In general, this process is conducted by means of rotating dies that hammer a workpiece in radial direction inward to taper it as the piece is fed into the dies. A mandrel is required to control the shape and size of the internal diameter of tubular parts during swaging.

Swaging

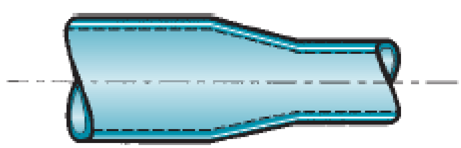


Radial forging:

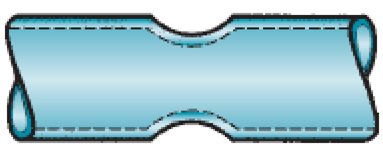
This operation is same as swaging, except that in radial forging, the dies do not rotate around the work piece, instead, the work is rotated as it feeds into the hammering dies.



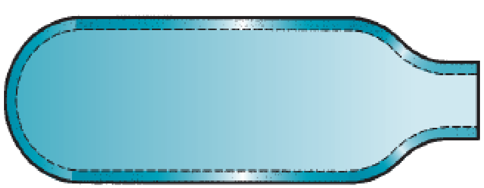
Diameter reduction of solid work



Tube tapering



Swaging to form a groove on the tube



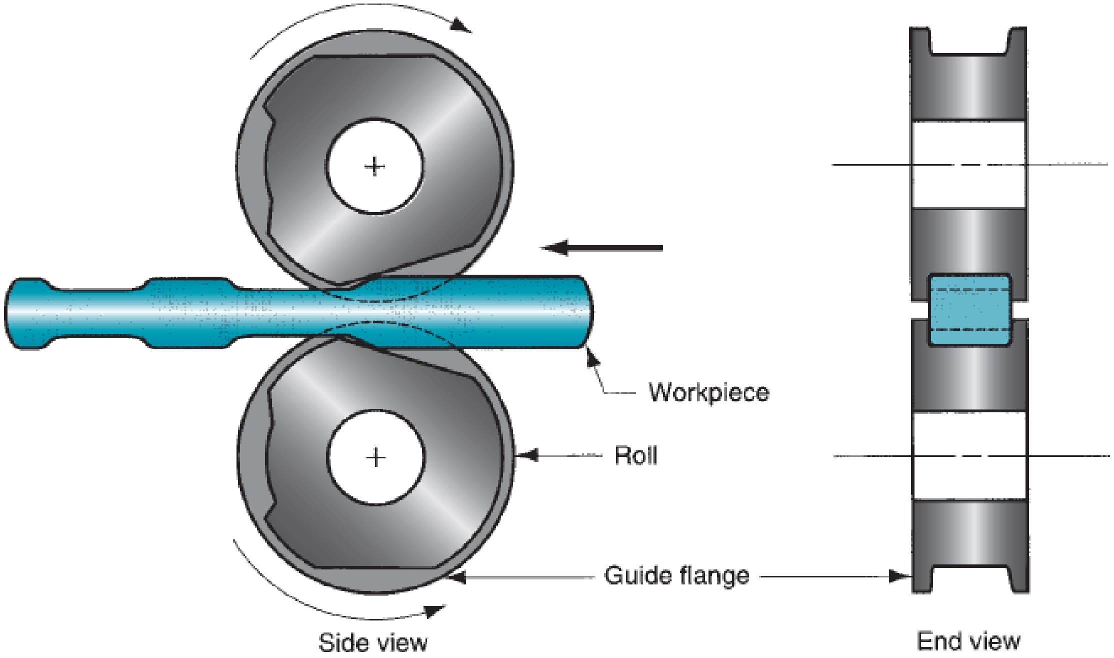
Swaging with different die profiles

Swaging the edge of a cylinder

Roll forging:

It is a forming process used to reduce the cross section of a cylindrical or rectangular rod by passing it through a set of opposing rolls that have matching grooves w.r.t. the desired shape of the final part. It combines both rolling and forging, but classified as forging operation.

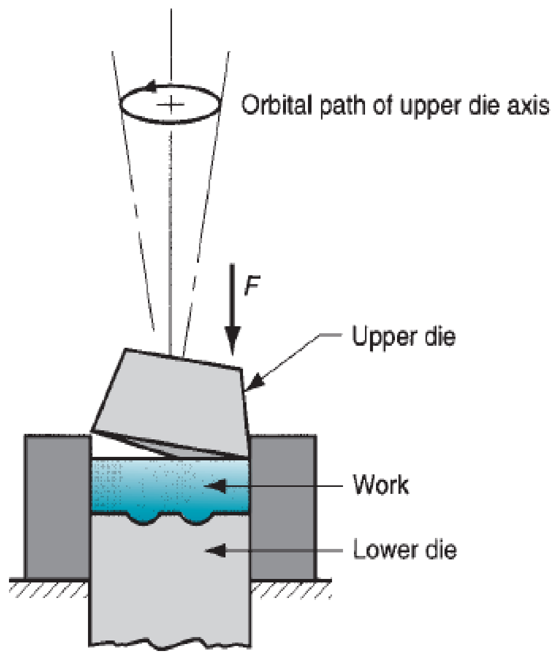
Depending on the amount of deformation, the rolls rotate partially. Roll-forged parts are generally stronger and possess desired grain structure compared to machining that might be used to produce the same part.

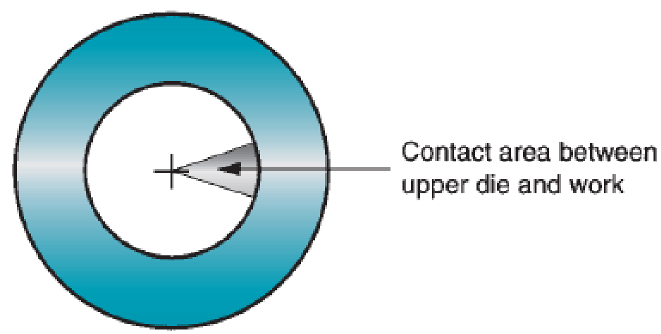


Orbital forging:

In this process, forming is imparted to the workpiece by means of a cone-shaped upper die that is simultaneously rolled and pressed into the work. The work is supported on a lower die.

Because of the inclined axis of cone, only a small area of the work surface is compressed at any stage of forming. As the upper die revolves, the area under compression also revolves. Because of partial deformation contact at any stage of forming, there is a substantial reduction in press load requirement.





Isothermal forging:

It is a hot-forging operation in which the work is maintained at some elevated temperature during forming. The forging dies are also maintained at the same elevated temperature. By avoiding chill of the work in contact with the cold die surfaces, the metal flows more readily and the force requirement is reduced.

The process is expensive than conventional forging and is usually meant for difficult-to-forge metals, like Ti, superalloys, and for complex part shapes. The process is done in vacuum or inert atmosphere to avoid rapid oxidation of the die material.

Extrusion

Extrusion is a bulk forming process in which the work metal is forced or compressed to flow through a die hole to produce a desired cross-sectional shape. Example: squeezing toothpaste from a toothpaste tube.

Advantages :

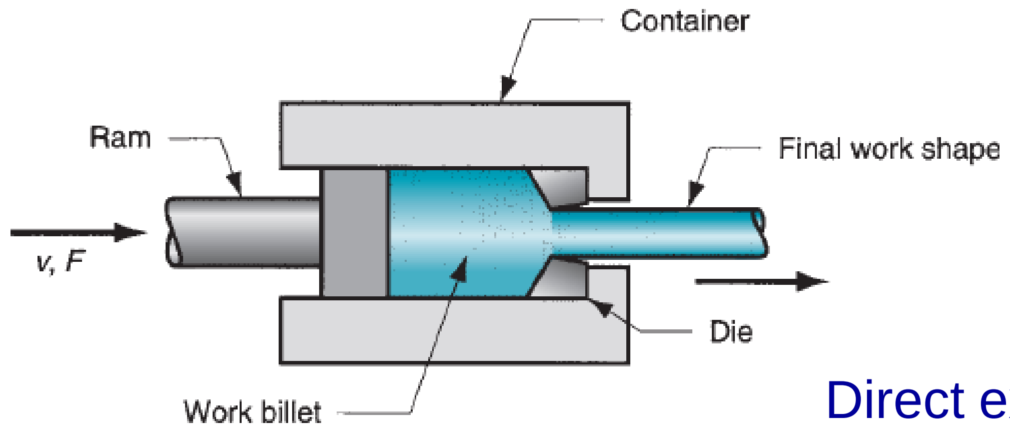
- Variety of shapes are possible, especially using hot extrusion
- Grain structure and strength properties are enhanced in cold and warm extrusion
- Close tolerances are possible, mainly in cold extrusion

Types of extrusion:

Direct or forward extrusion, Indirect or backward extrusion

Direct extrusion: - A metal billet is first loaded into a container having die holes. A ram compresses the material, forcing it to flow through the die holes.

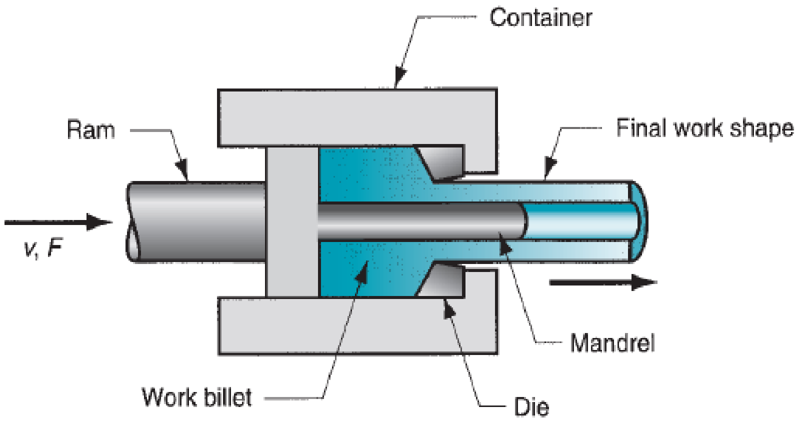
- Some extra portion of the billet will be present at the end of the process that cannot be extruded and is called *butt*. It is separated from the product by cutting it just beyond the exit of the die.

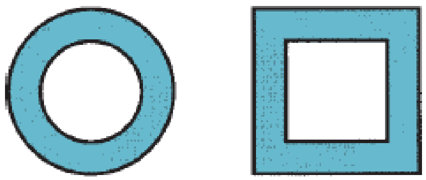


Direct extrusion

- In direct extrusion, a significant amount of friction exists between the billet surface and the container walls, as the billet is forced to slide toward the die opening. Because of the presence of friction, a substantial increase in the ram force is required.
- In hot direct extrusion, the friction problem is increased by the presence of oxide layer on the surface of the billet. This oxide layer can cause defects in the extruded product.
- In order to address these problems, a dummy block is used between the ram and the work billet. The diameter of the dummy block is kept slightly smaller than the billet diameter, so that a thin layer of billet containing the oxide layer is left in the container, leaving the final product free of oxides.

M.P. Groover, *Fundamental of modern manufacturing Materials, Processes and systems*, 4ed



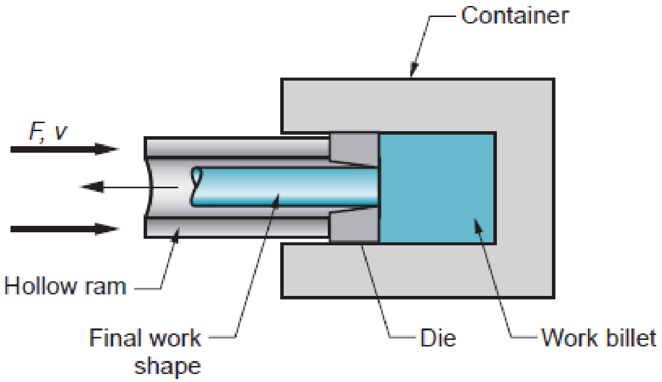


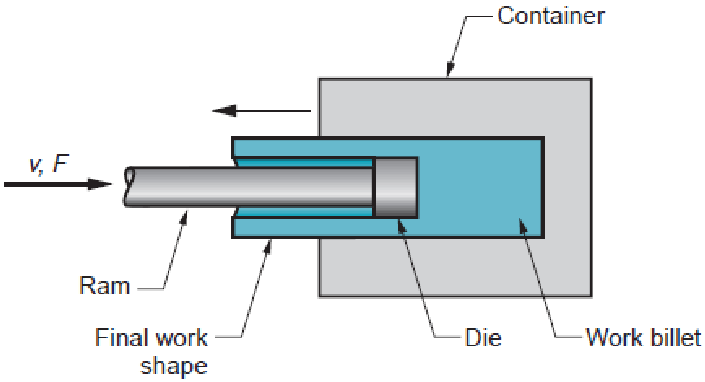
Making hollow shapes using direct extrusion

Hollow sections like tubes can be made using direct extrusion setup shown in above figure. The starting billet is prepared with a hole parallel to its axis. As the billet is compressed, the material will flow through the gap between the mandrel and the die opening.

Indirect extrusion: - In this type, the die is mounted to the ram and not on the container. As the ram compresses the metal, it flows through the die hole on the ram side which is in opposite direction to the movement of ram.

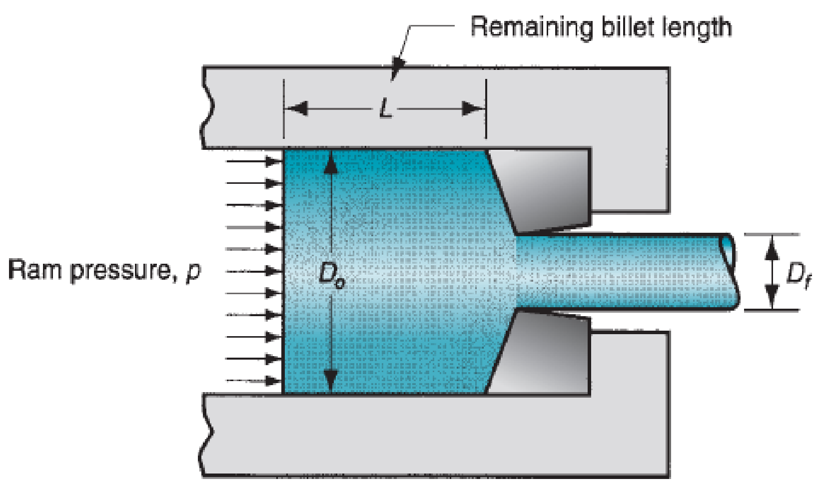
- Since there is no relative motion between the billet and the container, there is no friction at the interface, and hence the ram force is lower than in direct extrusion.
- Limitations: lower rigidity of the hollow ram, difficulty in supporting the extruded product at the exit





Indirect extrusion: solid billet and hollow billet

Simple analysis of extrusion



Pressure distribution and billet dimensions in direct extrusion

Assuming the initial billet and extrudate are in round cross-section. An important parameter, extrusion ratio (r_e), is defined as below:

$$r_e = \frac{A_0}{A_f}$$

A_0 - CSA of the initial billet

A_f - CSA of the extruded section

True strain in extrusion under ideal deformation (no friction and redundant work) is given by,

$$\varepsilon = \ln(r_e) = \ln(\frac{A_0}{A_f})$$

Under ideal deformation, the ram pressure required to extrude the billet through die hole is given by,

$$\boxed{p = \bar{Y}_f \ln(r_e) = \bar{Y}_f \ln(\frac{A_0}{A_f})}$$ where $$\bar{Y}_f = \frac{K\varepsilon^n}{1+n}$$

Note: The average flow stress is found out by integrating the flow curve equation between zero and the final strain defining the range of forming

Where Y_f is average flow stress, and ε is maximum strain value during the extrusion process.

The actual pressure for extrusion will be greater than in ideal case, because of the friction between billet and die and billet and container wall.

There are various equations used to evaluate the actual true strain and associated ram pressure during extrusion. The following relation proposed by Johnson is of great interest.

$$\varepsilon_x = a + b \ln r_e = a + b\varepsilon \quad \Longrightarrow \quad \boxed{p = \bar{Y}_f \varepsilon_x}$$

Where ε_x is extrusion strain; *a* and *b* are empirical constants for a given die angle. Typical values are: *a* = 0.8, *b* = 1.2 - 1.5.

In direct extrusion, assuming that friction exists at the interface, we can find the actual extrusion pressure as follows:

billet-container friction force = additional ram force to overcome that friction

$$\mu p_e \pi D_0 L = \frac{p_f \pi D_0^{\ 2}}{4}$$

Where p_f is additional pressure required to overcome friction, p_e is pressure against the container wall

The above eqn. assume <u>sliding friction</u> condition. Assuming <u>sticking friction</u> at the interface, we can write:

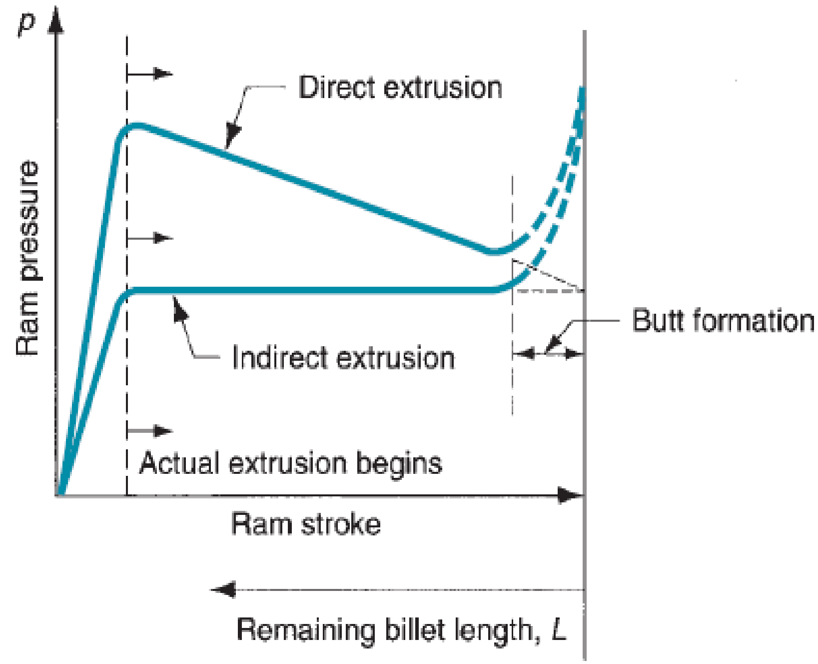
$$K \pi D_0 L = \frac{p_f \pi D_0^{\ 2}}{4}$$

Where K is shear yield strength & m = 1

The above eqn. gives, $p_f = \dfrac{4KL}{D_0}$

Assuming, $K = \dfrac{\bar{Y}_f}{2}$ we get, $\boxed{p_f = \bar{Y}_f \dfrac{2L}{D_0}}$

This is the additional pressure required to overcome friction during extrusion.

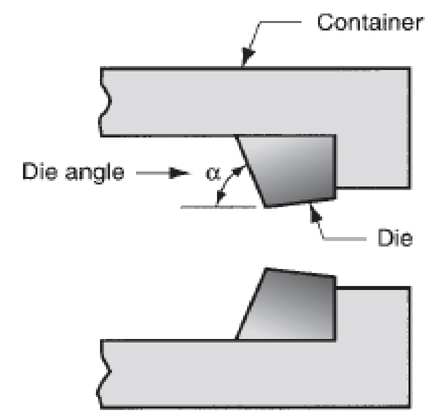


The shape of the initial pressure build up depends on die angle. Higher die angles cause steeper pressure buildups.

Now the actual ram pressure required for direct extrusion is given by,

$$\boxed{p = \bar{Y}_f \left(\varepsilon_x + \frac{2L}{D_0} \right)}$$

L is the billet length remaining to be extruded, and D_0 is the initial diameter of the billet. Here *p* is reduced as the remaining billet length decreases during the extrusion process.



Ram pressure variation with stroke for direct and indirect extrusion is shown in Figure.

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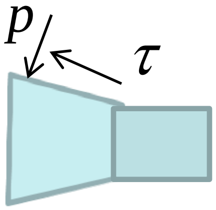
Sliding friction

The Coulomb friction stress (τ) between two surfaces is proportional to normal pressure (*p*).
The constant of proportionality is called friction coefficient (*μ*). This is assumed constant, but not mandatory. This condition exists when the forming tools are well lubricated and forming done at room temperature.

$$\tau = \mu p$$



Sticking friction

In this condition, a layer of material contacting the die-surface may stick onto the die and plastic flow may occur just under the surface layer. In this case, the friction stress (τ) is equal to shear yield strength (*K*), assuming friction factor '*m*' equal to 1.

This condition exists in hot forging, when no lubrication is used, in higher friction conditions. Mostly a part of contacting surface may be in slipping and another part in sticking condition.

$$\tau = mK$$

A billet 75 mm long and 25 mm in diameter is to be extruded in a direct extrusion operation with extrusion ratio r_e = 4.0. The extrudate has a round cross section. The die angle (half angle) is 90°. The work metal has a strength coefficient of 415 MPa, and strain-hardening exponent of 0.18. Use the Johnson formula with a = 0.8 and b=1.5 to estimate extrusion strain. Find the pressure applied to the end of the billet as the ram moves forward.

Empirical formulae for extrusion pressure

Hot extrusion of Al alloys:

For extrusion of pure Al, Al-Zn alloy, Al-Zn-Mg alloy in the temperature range of 50-500°C.

$$p_e/\sigma_0 = 0.52 + 1.32\ln R$$ for values of R from 1 to 100

$$p_e/\sigma_0 = -13 + 4.78\ln R$$ for values of R from 100 to 1000

Here *R = 1/(1-r)* where '*r*' is the relative reduction in area

Cold extrusion of steel:

$$p_e = 0.262F(A_r)^{0.787}(2\alpha)^{0.375}\frac{N}{mm^2}$$

Where A_r = percent reduction in area = $\frac{A_1 - A_2}{A_1}\times 100$

$$\mathrm{F} = \frac{\text{Yield strength of steel}}{\text{Yield strength of lead}}$$

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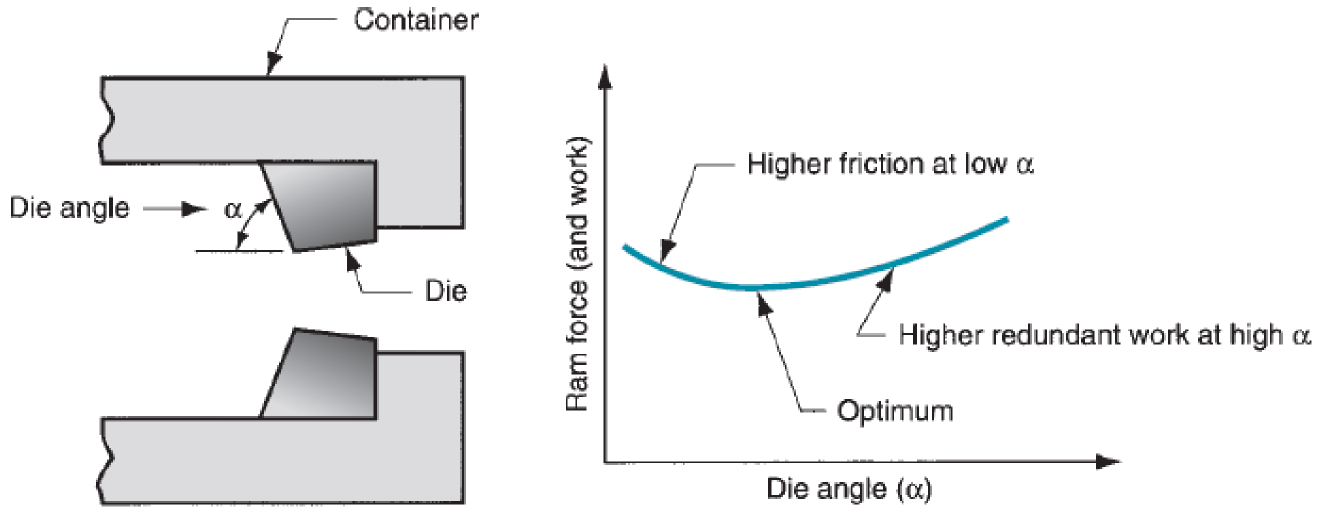
Extrusion dies

- Two important factors in an extrusion die are: die angle, orifice shape.

- For low die angles, surface area of the die is large, resulting in increased friction at the die-billet interface. Higher friction results in higher ram force.

- For a large die angle, more turbulence in the metal flow is caused during reduction, increasing the ram force required.

- The effect of die angle on ram force is a U-shaped function, shown in Figure. So, an optimum die angle exists. The optimum angle depends on various factors like work material, billet temperature, and lubrication.



- The extrusion pressure eqns. derived earlier are for a circular die orifice.

- The shape of the die orifice affects the ram pressure required to perform an extrusion operation, as it determines the amount of squeezing of metal billet.

-The effect of the die orifice shape can be assessed by the die shape factor, defined as the ratio of the pressure required to extrude a cross section of a given shape relative to the extrusion pressure for a circular cross section of the same area.

$$k_x = 0.98 + 0.02\left(\frac{c_x}{c_c}\right)^{2.25}$$

Where k_x is the die shape factor in extrusion; C_x is the perimeter of the extruded cross section, and C_c is the perimeter of a circle of the same area as the actual extruded shape.

$\frac{c_x}{c_c}$ varies from 1 to 6.

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Die materials

For hot extrusion - tool and alloy steels.

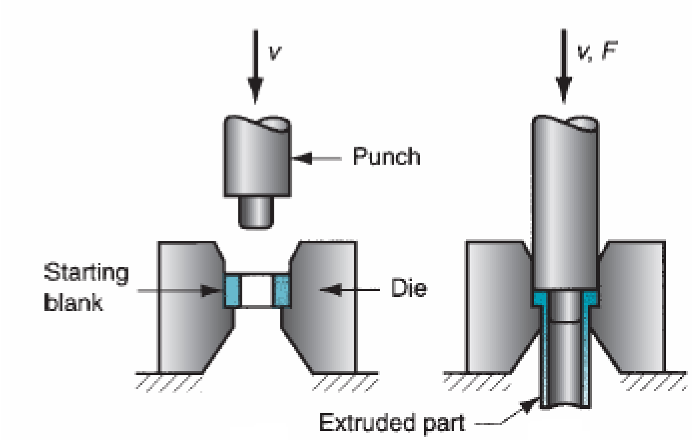
Important properties of die materials are high wear resistance, high thermal conductivity to remove heat from the process.

For cold extrusion - tool steels and cemented carbides.
Carbides are used when high production rates, long die life, and good dimensional control are expected.

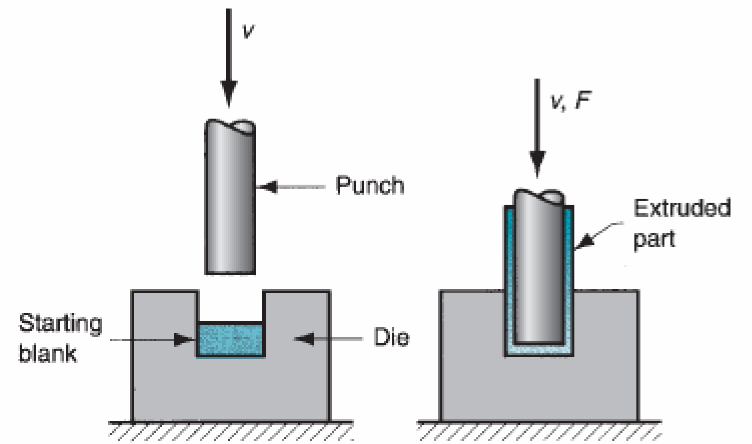
Other extrusion processes

Impact extrusion:

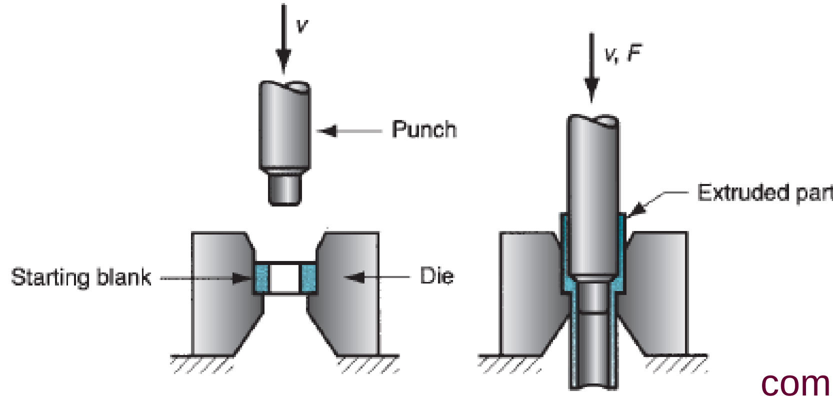
- It is performed at higher speeds and shorter strokes. The billet is extruded through the die by impact pressure and not just by applying pressure.
- But impacting can be carried out as forward extrusion, backward extrusion, or combination of these.



forward extrusion



Backward extrusion

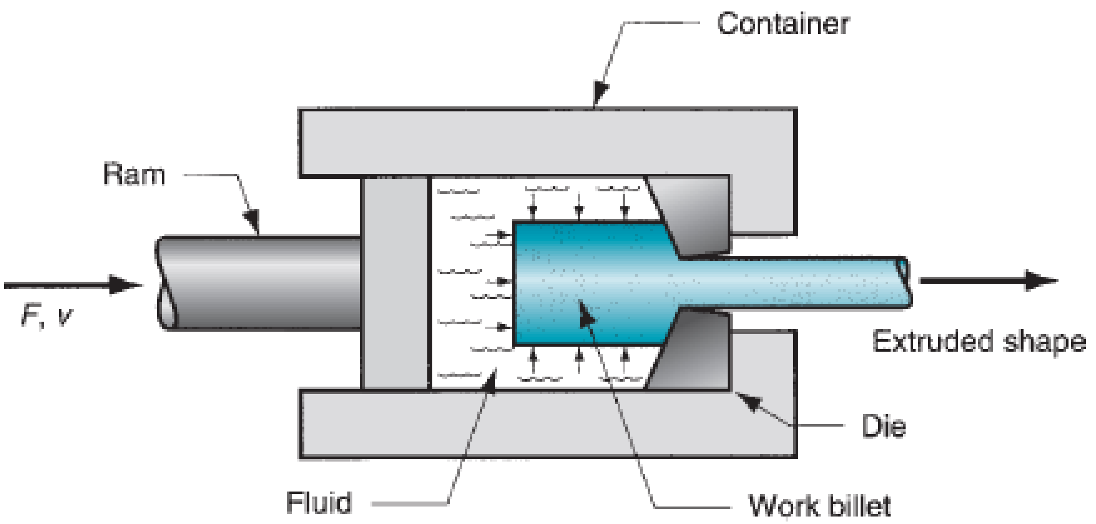


combined extrusion

- Impact extrusion is carried out as cold forming. Very thin walls are possible by backward impact extrusion method. Eg: making tooth paste tubes, battery cases.

- Advantages of IE: large reductions and high production rates

Hydrostatic extrusion:



Hydrostatic extrusion

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In hydrostatic extrusion, the billet is surrounded with fluid inside the container and the fluid is pressurized by the forward motion of the ram.

There is no friction inside the container because of the fluid, and friction is minimized at the die opening. If used at high temperatures, special fluids and procedures must be followed.

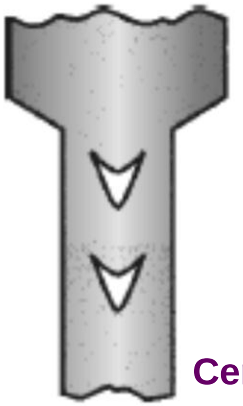
Hydrostatic pressure on the work and no friction situation increases the material's ductility. Hence this process can be used on metals that would be too brittle for conventional extrusion methods.

This process is also applicable for ductile metals, and here high reduction ratios are possible.

The preparation of starting work billet is important. The billet must be formed with a taper at one end to fit tightly into the die entry angle, so that it acts as a seal to prevent fluid leakage through die hole under pressure.

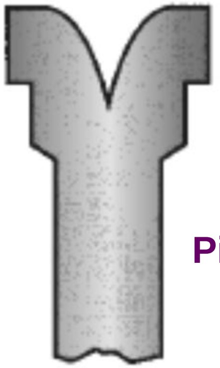
Defects during extrusion

Centerburst:
- This is an internal crack that develops as a result of tensile stresses along the center axis of the workpiece during extrusion. A large material motion at the outer regions pulls the material along the center of the work. Beyond a critical limit, bursting occurs.
- Conditions that promote this defect are: higher die angles, low extrusion ratios, and impurities in the work metal. This is also called as Chevron cracking.



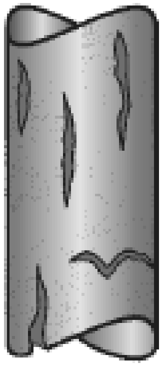
Centerburst

Piping: It is the formation of a sink hole in the end of the billet. This is minimized by the usage of a dummy block whose diameter is slightly less than that of the billet.



Piping

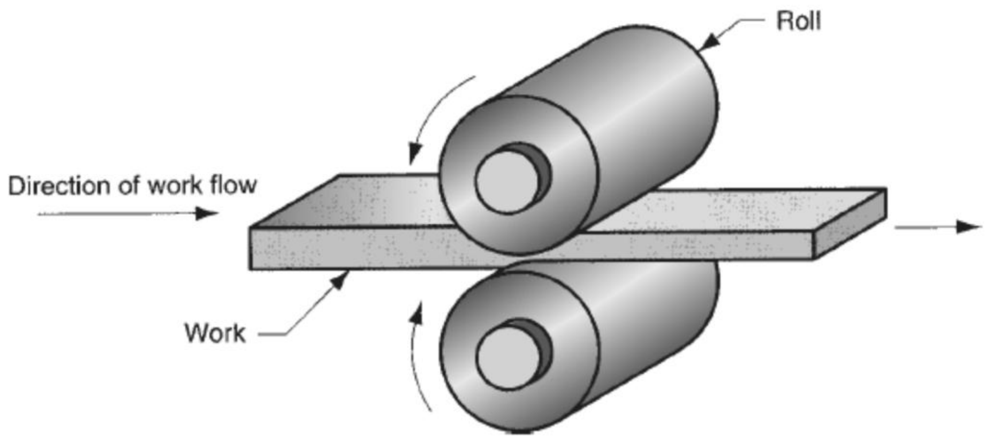
Surface cracking: This defect results from high workpiece temperatures that cause cracks to develop at the surface. They also occur at higher extrusion speeds, leading to high strain rates and heat generation. Higher friction at the surface and surface chilling of high temperature billets in hot extrusion also cause this defect.



Surface cracking

Rolling

Rolling is a metal forming process in which the thickness of the work is reduced by compressive forces exerted by two rolls rotating in opposite direction. Flat rolling is shown in figure. Similarly shape rolling is also possible like a square cross section is formed into a shape such as an I-beam, L-beam.



Flat rolling

Important terminologies:

Bloom: It has a square cross section 150 mm x 150 mm or more.

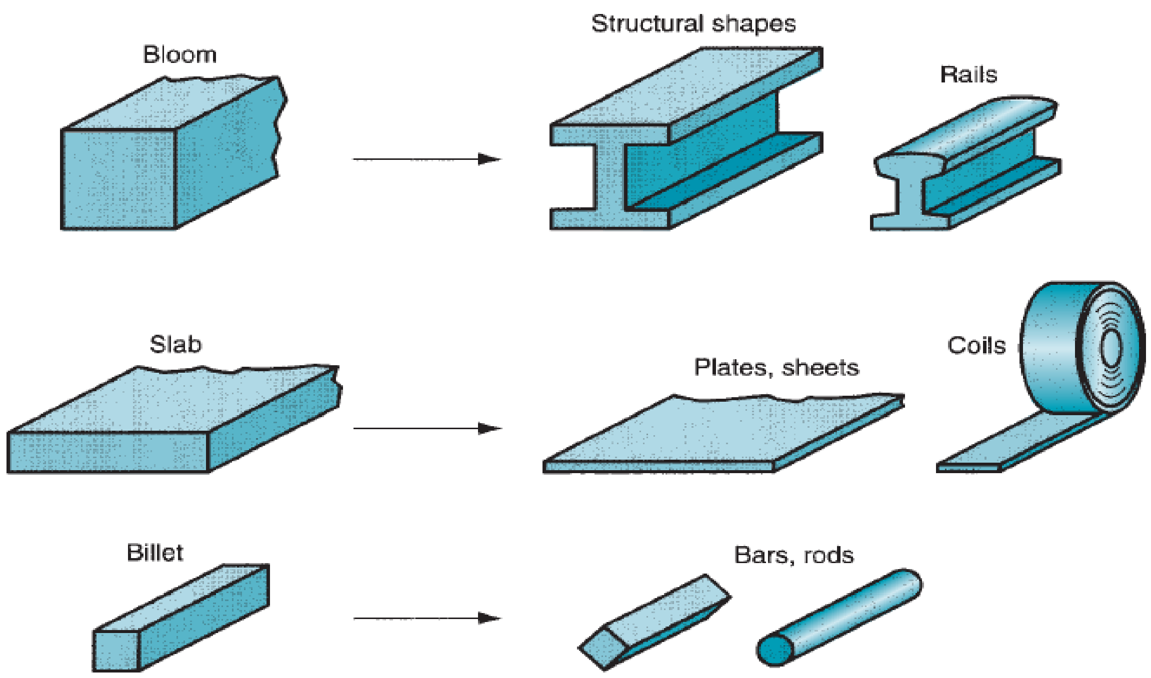
Slab: It is rolled from an ingot or a bloom and has a rectangular cross section of 250 mm width or more and thickness 40 mm or more.

Billet: It is rolled from a bloom and is square in cross-section with dimensions 40mm on a side or more.

Blooms are rolled into structural shapes like rails for railroad tracks.

Billets are rolled into bars, rods. They become raw materials for machining, wire drawing, forging, extrusion etc.

Slabs are rolled into plates, sheets, and strips. Hot rolled plates are generally used in shipbuilding, bridges, boilers, welded structures for various heavy machines, and many other products.



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The plates and sheets are further reduced in thickness by cold rolling to strengthen the metal and permits a tighter tolerance on thickness.

Important advantage is that the surface of the cold-rolled sheet does not contain scales and generally superior to the corresponding hot rolled product.

Later the cold-rolled sheets are used for stampings, exterior panels, and other parts used in automobile, aerospace and house hold appliance industries.

Simple analysis of flat strip rolling

The schematic of flat rolling is shown in previous slides. It involves rolling of sheets, plates having rectangular cross section in which the width is greater than the thickness.

In flat rolling, the plate thickness is reduced by squeezing between two rolls. The thickness reduction is quantified by draft which is given by,

$$d = t_0 - t_f$$

here t_0 and t_f are initial thickness and final thickness of the sheet used for rolling.

Draft is also defined as, $r = d / t_0$. Here r is reduction.

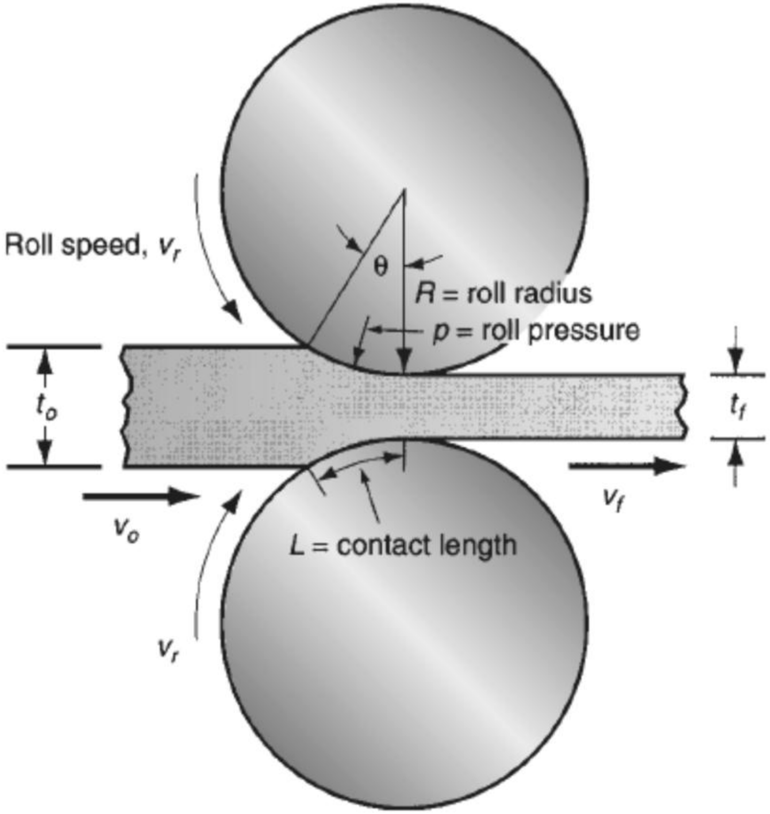
During rolling, the workpiece width increases which is termed as spreading. It will be large when we have low width to thickness ratio and low friction coefficient.

In strip rolling, $t_0 w_0 l_0 = t_f w_f l_f$ and hence $t_0 w_0 v_0 = t_f w_f v_f$

Here w_o and w_f are the initial and final work widths, l_0 and l_f are the initial and final work lengths. v_o and v_f are the entry and exit velocities of the work.

In strip rolling, the width will not change much after rolling. From the previous equation, it is observed that the exit velocity v_f is greater than entry velocity v_0. In fact, the velocity of the rolled sheet continuously increases from entry to exit.

The rolls contact the rolling sheet along an arc defined by angle θ. Each roll has radius R, and its has surface velocity v_r. This velocity is in between entry and exit velocity.



However, there is one point or zone along the contact arc where work velocity equals roll velocity. This is called the no-slip point, or neutral point.

On either side of the neutral point, slipping and friction occur between roll and sheet. The amount of slip between the rolls and the sheet can be quantified by forward slip, S,

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

v_f is the final velocity, v_r is the roll velocity

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The true strain during rolling is given by, $\varepsilon = \ln(\frac{t_0}{t_f})$

The true strain is used to find the average flow stress (Y_f) and further rolling power, force.

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

On the entry side of the neutral point, friction force is in one direction, and on the other side it is in the opposite direction, i.e., the friction force acts towards the neutral point. But the two forces are unequal.

The friction force on the entry side is greater, so that the net force pulls the sheet through the rolls. Otherwise, rolling would not be possible.

The limit to the maximum possible draft that can be accomplished in flat rolling is given by,

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

The equation indicates that if friction were zero, draft is zero, and it is not possible to accomplish the rolling operation.

The friction coefficient in rolling depends on lubrication, work material, and working temperature.

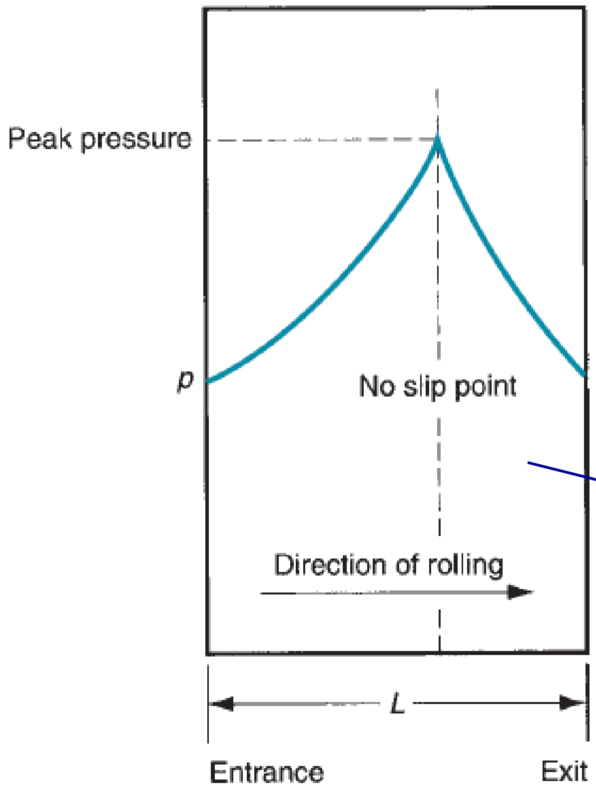
In cold rolling, the value is app. 0.1, in warm rolling, a typical value is around 0.2; and in hot rolling, it is around 0.4.

Hot rolling is characterized by sticking friction condition, in which the hot work surface adheres to the rolls over the contact region. This condition often occurs in the rolling of steels and high-temperature alloys.
When sticking occurs, the coefficient of friction can be as high as 0.7.

The roll force (*F*) is calculated by, $F = \bar{Y}_f wL$, *wL* is the contact area

The contact length (projected) is approximated by, $L = \sqrt{R(t_0 - t_f)}$

The rolling power required for two powered rolls is given by, $P = (2\pi N)FL$ (watts)



Area under the curve, rolling force, *F*,

$$F = w\int_0^L p\,dL$$

Typical variation in roll pressure along the contact length in flat rolling

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 0.12. Determine if the friction is sufficient to permit the rolling operation to be accomplished. If so, calculate the roll force, and horsepower (or rolling power).

Inference from equations: The strip rolling force and/or power of a given width and work material can be reduced by the following methods: (1) using hot rolling rather than cold rolling to reduce strength and strain hardening (*K* and *n*) of the work material; (2) reducing the draft in each rolling pass; (3) using a smaller roll radius ‘R’ to reduce force; and (4) using a lower rolling speed ‘N’ to reduce power.

Rolling mills

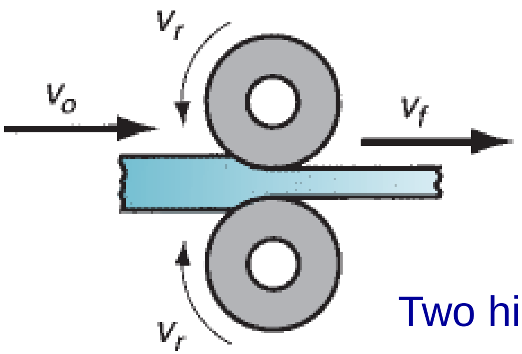
Two high rolling mill: This type of rolling mill consists of two rolls rotating in opposite directions.

Roll diameters: 0.6 to 1.4 m

Types: either reversing or non-reversing.

Non-reversing mill: rolls rotate only in one direction, and the slab always move from entry to exit side.

Reversing mill: direction of roll rotation is reversed, after each pass, so that the slab can be passed through in both the directions. This permits a continuous reductions to be made through the same pairs of rolls.

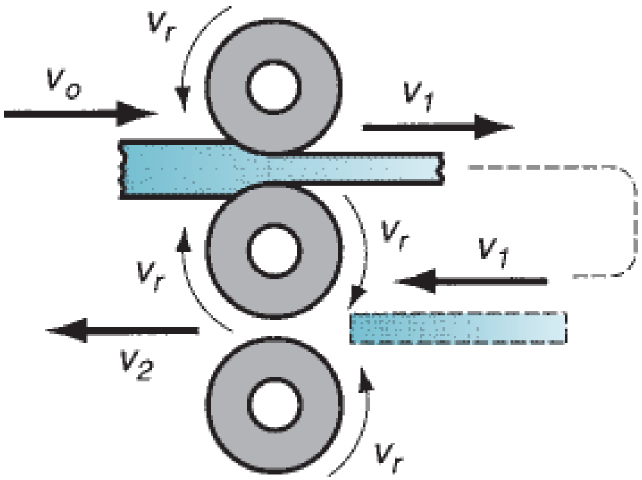


Two high rolling mill

Three high rolling mill: In this case, there are three rolls one above the other. At a time, for single pass, two rolls will be used. The roll direction will not be changed in this case.

The top two rolls will be used for first reduction and the sheet is shifted to the bottom two rolls and further reduction is done. This cycle is continued till actual reduction is attained.

Disadvantage: automated mechanism is required to shift the slab

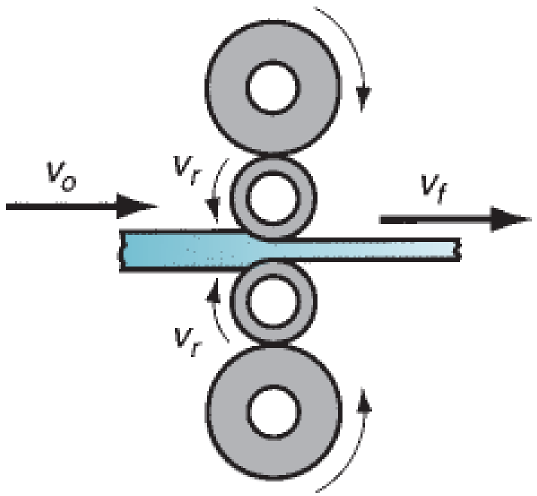


Three high rolling mill

Four high rolling mill: This consists of two small rolls for thickness reduction and two large backing rolls to support the small rolls.

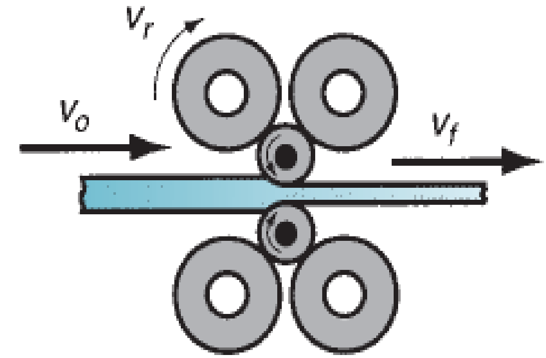
The small rolls will reduce the roll force required as the roll-sheet contact area will be reduced.

The large backing rolls are required to reduce the elastic deflection of small rolls when sheet passes between them.



Four high rolling mill

Cluster rolling mill: This uses smaller rolls for rolling

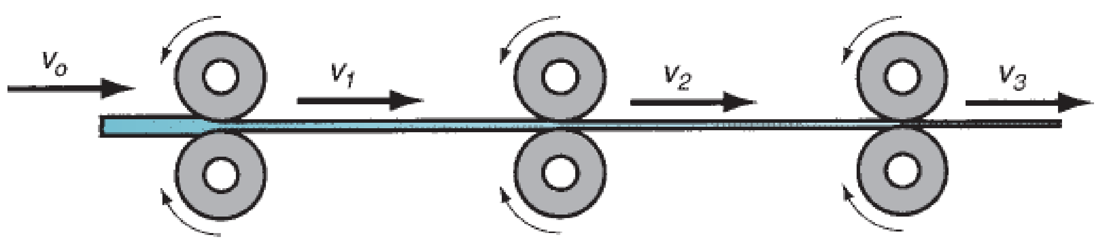


Cluster rolling mill

Tandem rolling mill:

This consists of series of rolling stations of the order of 8 to 10. In each station, thickness reduction is given to the sheet. With each rolling station, the work velocity increases.

This is fully used in industry practice, along with continuous casting operation. This results in reduction in floor space, shorter manufacturing lead time.



Tandem rolling mill

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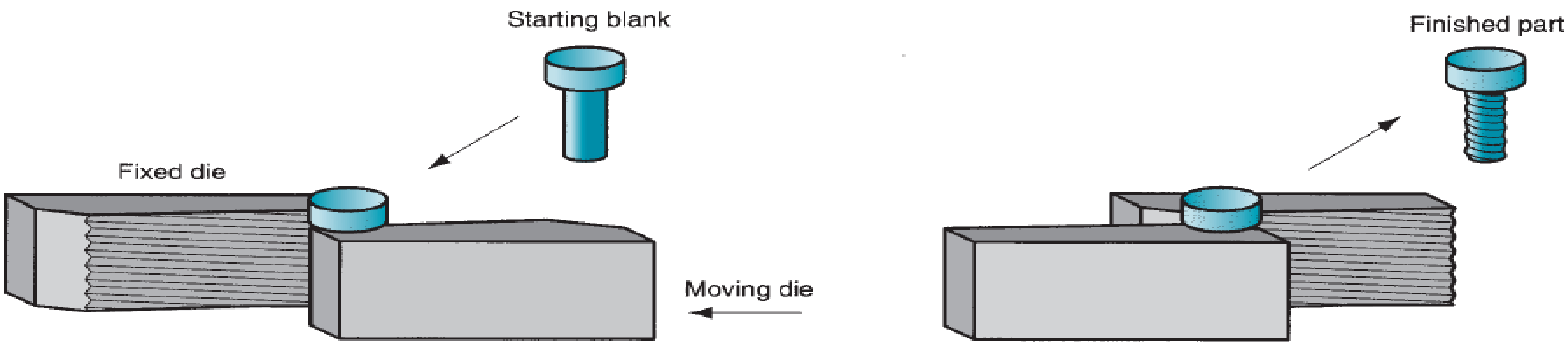
Thread rolling



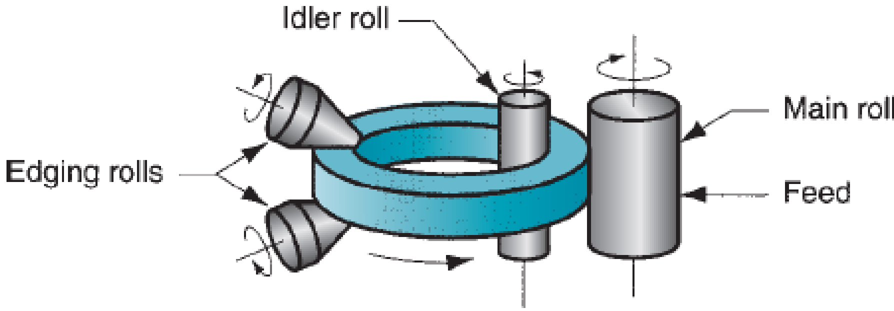
Thread rolling is used to create threads on cylindrical parts by rolling them between two dies as shown in figure.

It is used for mass production of external threaded parts like bolts and screws.

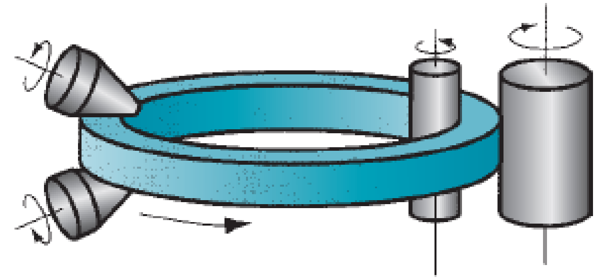
Ring rolling

Ring rolling is a forming process in which a thick walled ring part of smaller diameter is rolled into a thin walled ring of larger diameter.
As the thick walled ring is compressed, the deformed material elongates, making the diameter of the ring to be enlarged.

Application: ball and roller bearing races, steel tires for railroad wheels, rings for pipes, pressure vessels, and rotating machinery



Start of process (thick walled, small diameter)

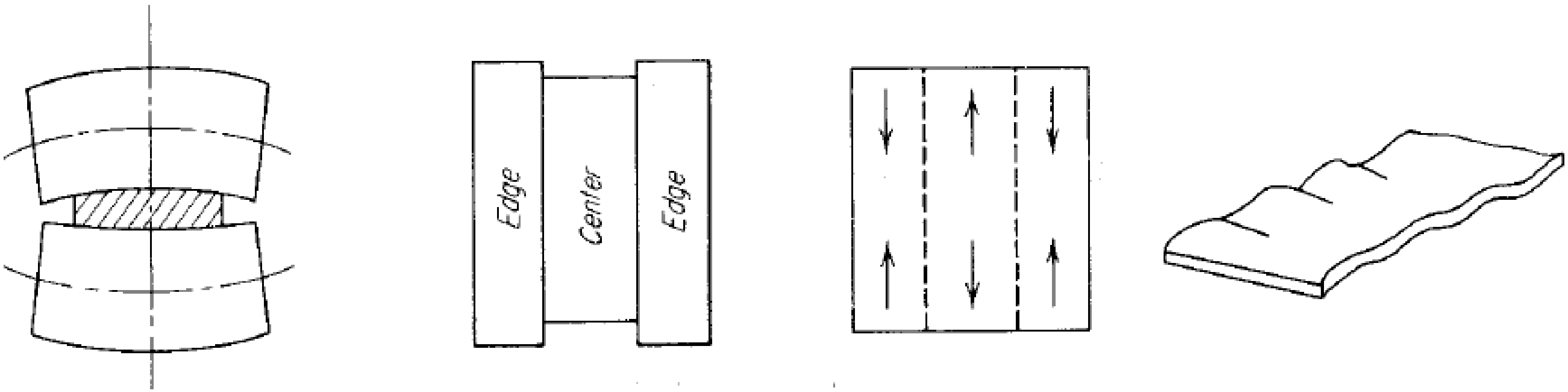


Completion of process (thin walled, large diameter)

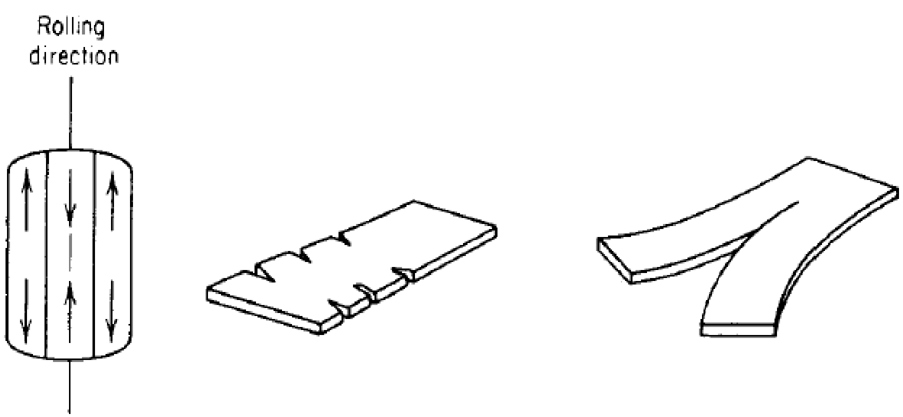
Ring rolling

Defects in strip rolling

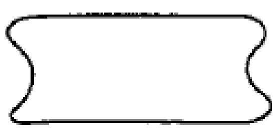
Waviness



Cracking

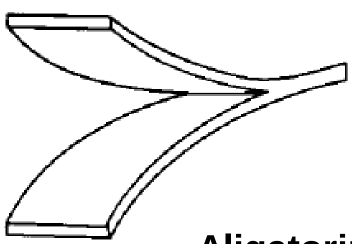


Edge defect



Light reduction

Heavy reduction



Aligatoring

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