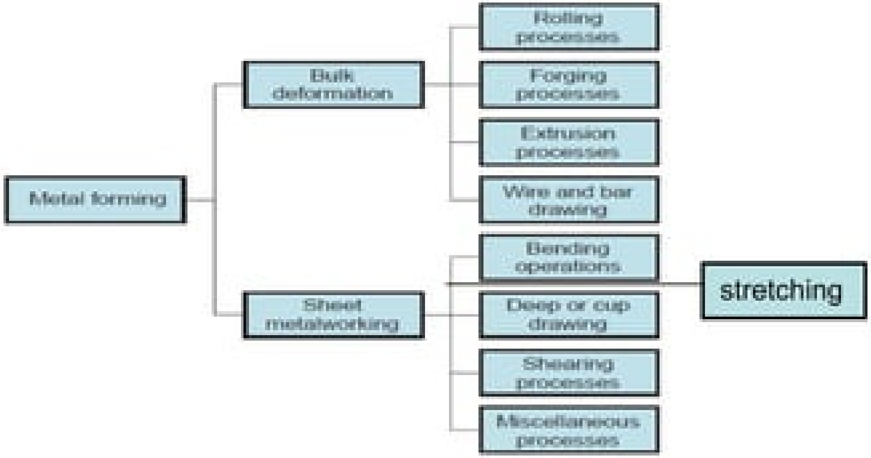
Metal forming processes

Metal forming: Large set of manufacturing processes in which the material is deformed plastically to take the shape of the die geometry. The tools used for such deformation are called die, punch etc. depending on the type of process.

Plastic deformation: Stresses beyond yield strength of the workpiece material is required.

Categories: Bulk metal forming, Sheet metal forming



Metal forming

Bulk deformation

Rolling processes

Forging processes

Extrusion processes

Wire and bar drawing

Sheet metalworking

Bending operations

Deep or cup drawing

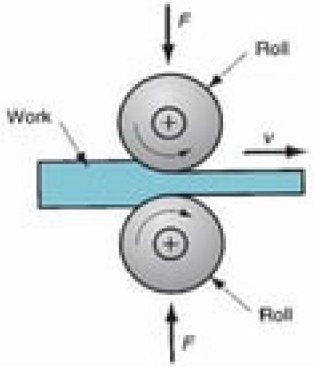
Shearing processes

Miscellaneous processes

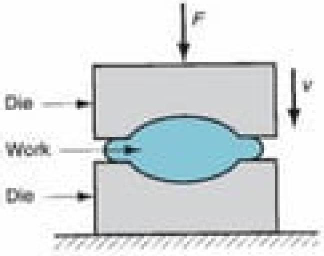
stretching

General classification of metal forming processes

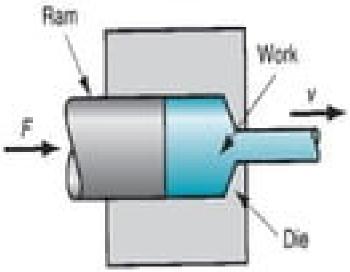
Classification of basic bulk forming processes



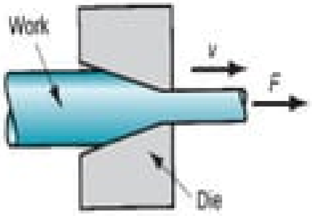
Rolling



Forging



Extrusion



Wire drawing

Bulk forming: It is a severe deformation process resulting in massive shape change. The surface area-to-volume of the work is relatively small. Mostly done in hot working conditions.

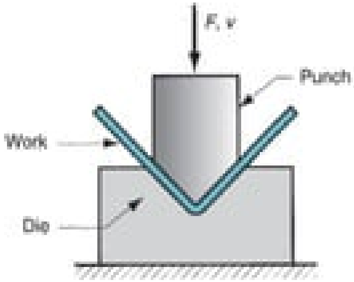
Rolling: In this process, the workpiece in the form of slab or plate is compressed between two rotating rolls in the thickness direction, so that the thickness is reduced. The rotating rolls draw the slab into the gap and compresses it. The final product is in the form of sheet.

Forging: The workpiece is compressed between two dies containing shaped contours. The die shapes are imparted into the final part.

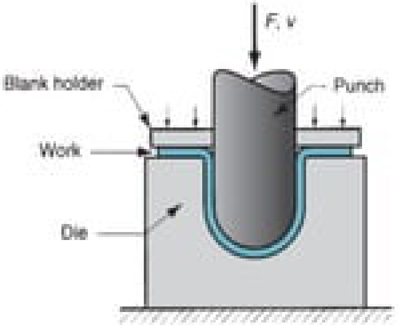
Extrusion: In this, the workpiece is compressed or pushed into the die opening to take the shape of the die hole as its cross section.

Wire or rod drawing: similar to extrusion, except that the workpiece is pulled through the die opening to take the cross-section.

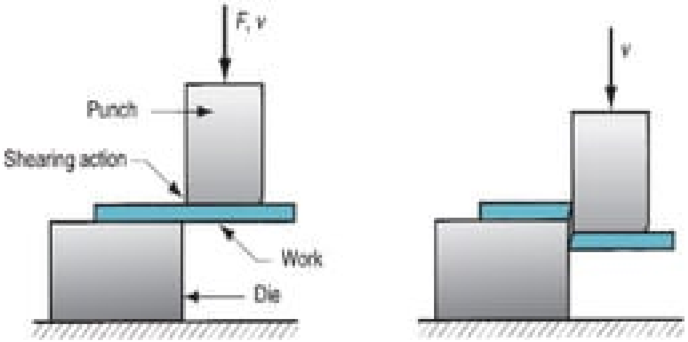
Classification of basic sheet forming processes



Bending



Deep drawing



shearing

Sheet forming: Sheet metal forming involves forming and cutting operations performed on metal sheets, strips, and coils. The surface area-to-volume ratio of the starting metal is relatively high. Tools include punch, die that are used to deform the sheets.

Bending: In this, the sheet material is strained by punch to give a bend shape (angle shape) usually in a straight axis.

Deep (or cup) drawing: In this operation, forming of a flat metal sheet into a hollow or concave shape like a cup, is performed by stretching the metal in some regions. A blank-holder is used to clamp the blank on the die, while the punch pushes into the sheet metal. The sheet is drawn into the die hole taking the shape of the cavity.

Shearing: This is nothing but cutting of sheets by shearing action.

Cold working, warm working, hot working

Cold working: Generally done at room temperature or slightly above RT.

Advantages compared to hot forming:
(1) closer tolerances can be achieved; (2) good surface finish; (3) because of strain hardening, higher strength and hardness is seen in part; (4) grain flow during deformation provides the opportunity for desirable directional properties; (5) since no heating of the work is involved, furnace, fuel, electricity costs are minimized, (6) Machining requirements are minimum resulting in possibility of near net shaped forming.
Disadvantages: (1) higher forces and power are required; (2) strain hardening of the work metal limit the amount of forming that can be done, (3) sometimes cold forming-annealing-cold forming cycle should be followed, (4) the work piece is not ductile enough to be cold worked.

Warm working: In this case, forming is performed at temperatures just above room temperature but below the recrystallization temperature. The working temperature is taken to be 0.3 T_m where T_m is the melting point of the workpiece.
Advantages: (1) enhanced plastic deformation properties, (2) lower forces required, (3) intricate work geometries possible, (4) annealing stages can be reduced.

Hot working: Involves deformation above recrystallization temperature, between $0.5T_m$ to $0.75T_m$.

Advantages: (1) significant plastic deformation can be given to the sample, (2) significant change in workpiece shape, (3) lower forces are required, (4) materials with premature failure can be hot formed, (5) absence of strengthening due to work hardening.

Disadvantages: (1) shorter tool life, (2) poor surface finish, (3) lower dimensional accuracy, (4) sample surface oxidation

Bulk forming processes

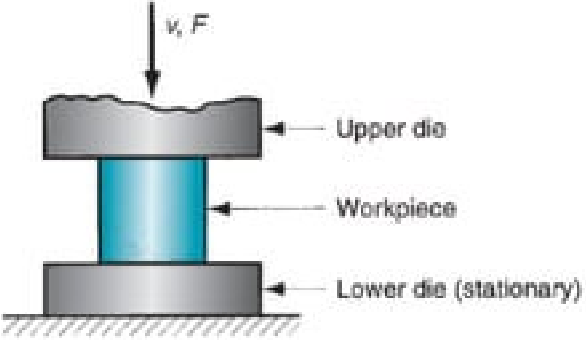
Forging

- 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:

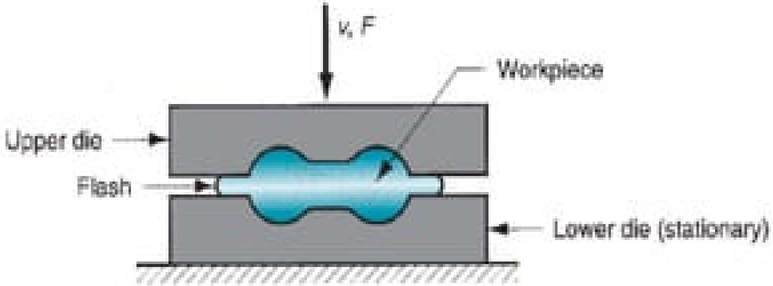
  impact load => forging hammer; gradual pressure => forging press
- Category based on type of forming:

  Open die forging, impression die forging, flashless forging

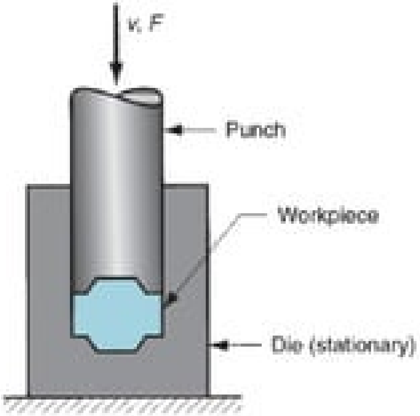


Open die forging

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.



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.

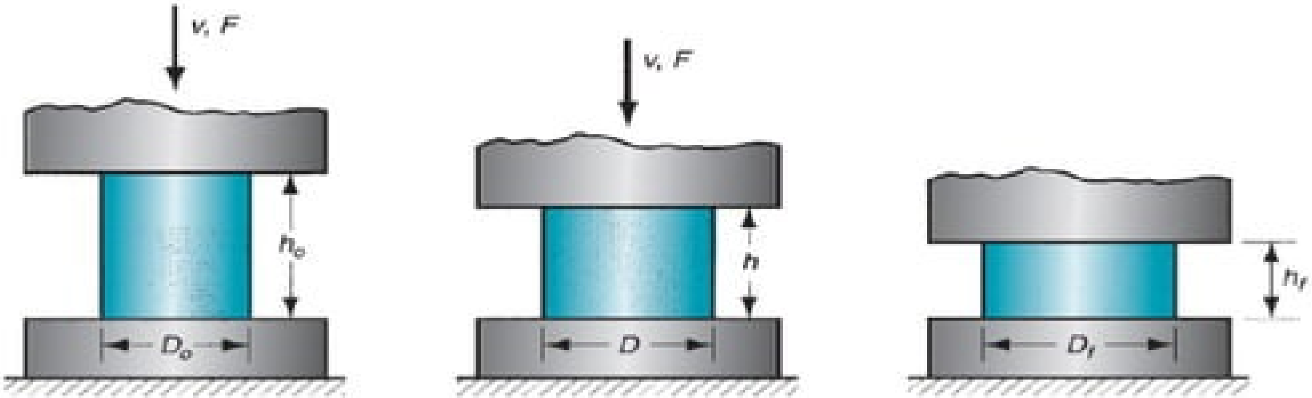
In flashless forging, the work piece is fully restricted within the die and no flash is produced. The amount of initial work piece used must be controlled accurately so that it matches the volume of the die cavity.

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.

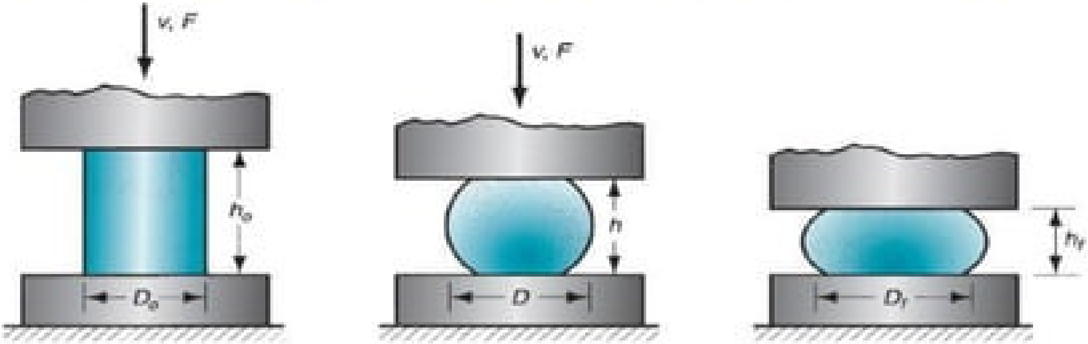
In ideal condition, $\varepsilon = \ln (h_o/h)$. h will be equal to h_f at the end of compression, ε will be maximum for the whole forming. Also $F = \sigma_f A$ is used to find the force required for forging, where σ_f is the flow stress corresponding to ε at that stage of forming.



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

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.



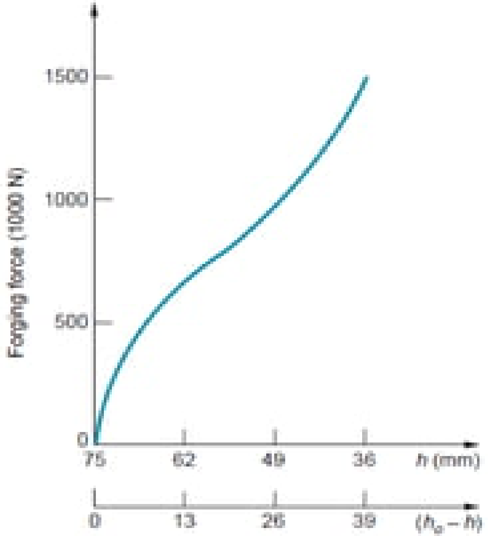
Start of compression

Partial compression

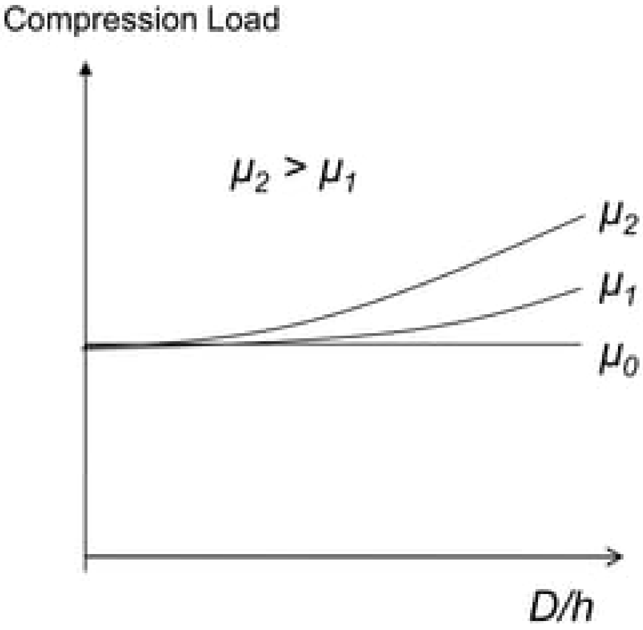
Completed compression

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

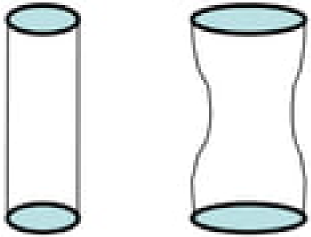
Typical load-stroke curve in open die forging



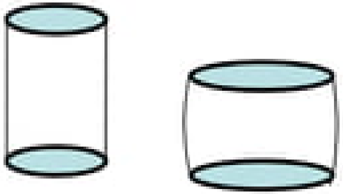
Effect of *D/h* ratio on load:



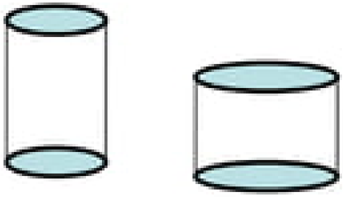
Effect of *h/D* ratio on barreling:



Long cylinder: *h/D* >2



Cylinder having *h/D* < 2 w



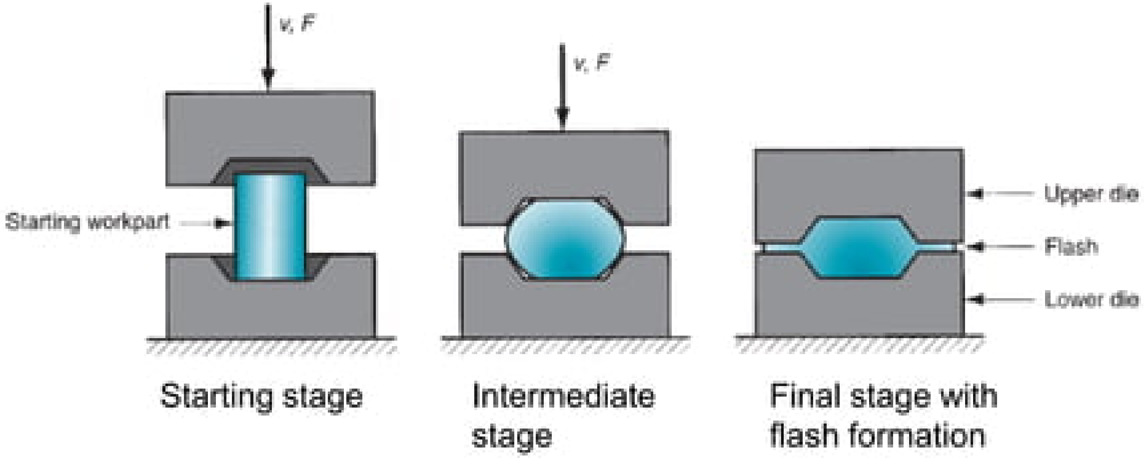
Frictionless compression

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.

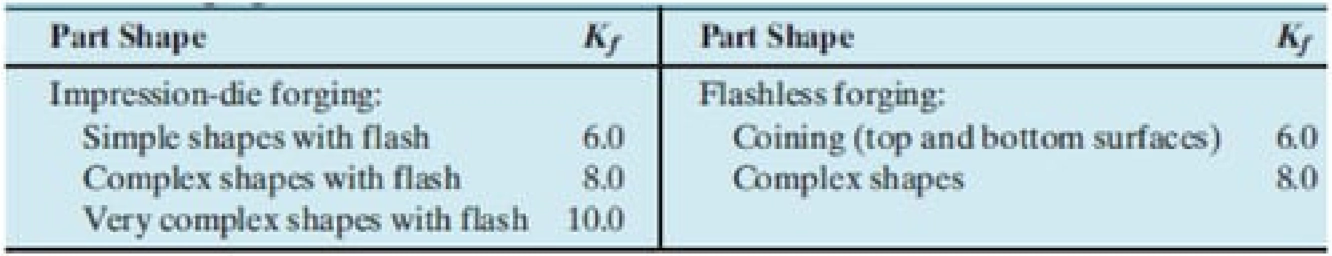


The formula used for open die forging earlier can be used for closed die forging, i.e.,

$F = K_f \sigma_f A$

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		

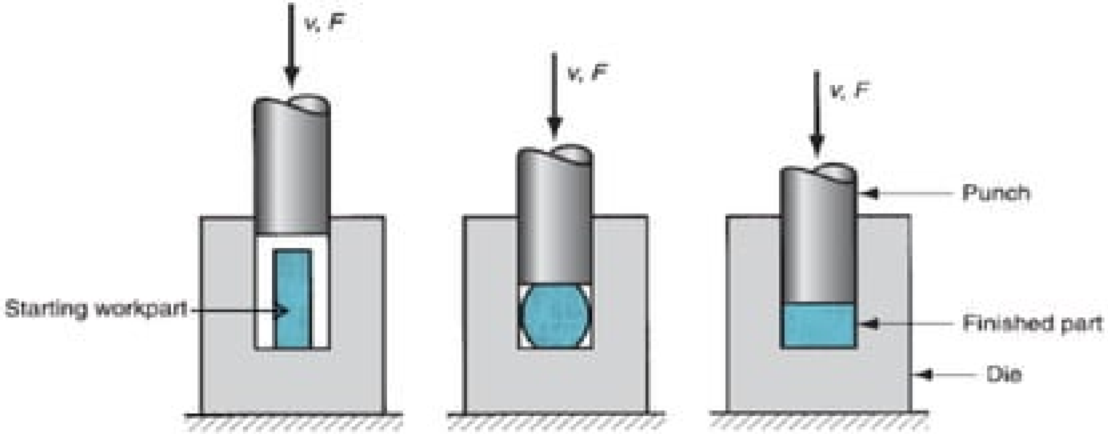
The above equation is applied to find the maximum force during the operation, since this is the load that will determine the required capacity of the press used in the forging operation.

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:

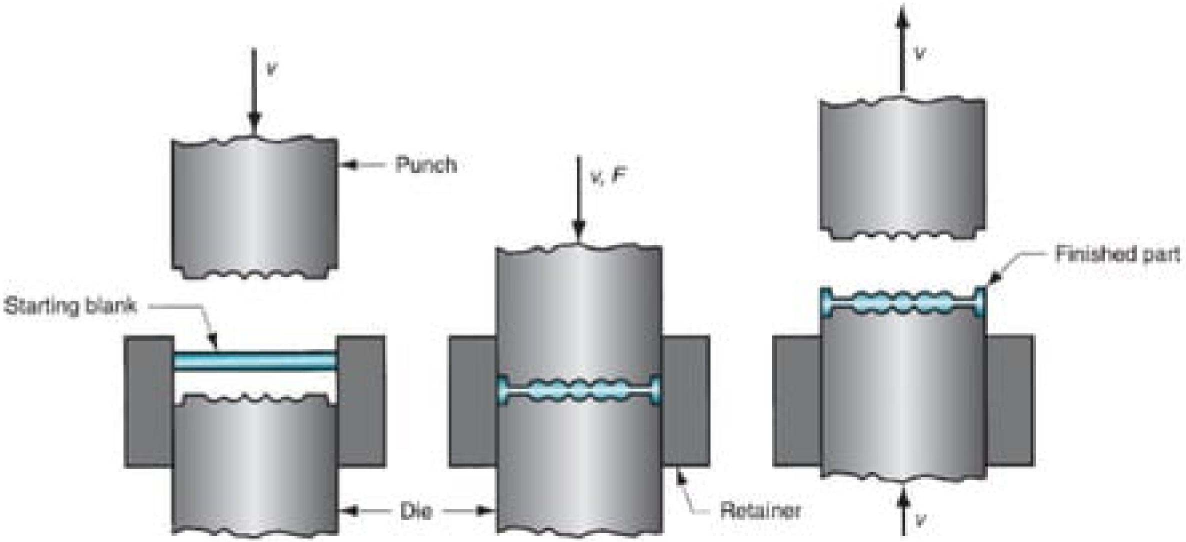


In flashless forging, most important is that the work piece volume must equal the space in the die cavity within a very close tolerance.
If the starting billet size is too large, excessive pressures will cause damage to the die and press.
If the billet size is too small, the cavity will not be filled.

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.

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:

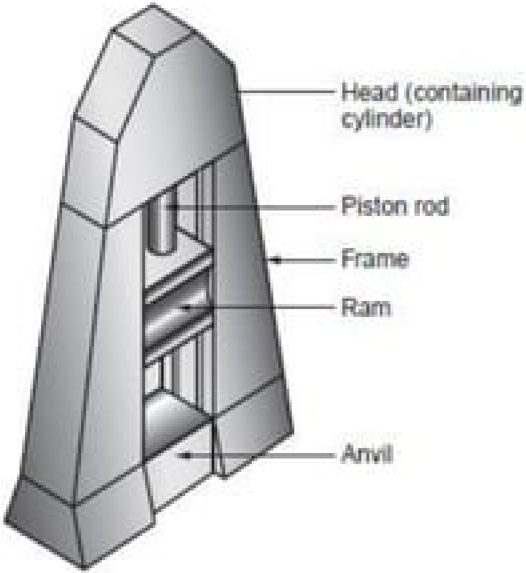
Hammers operate by applying an impact loading on the work piece. This is also called as drop hammer, owing to the means of delivering impact energy.

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 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.



Drop hammers

Presses:

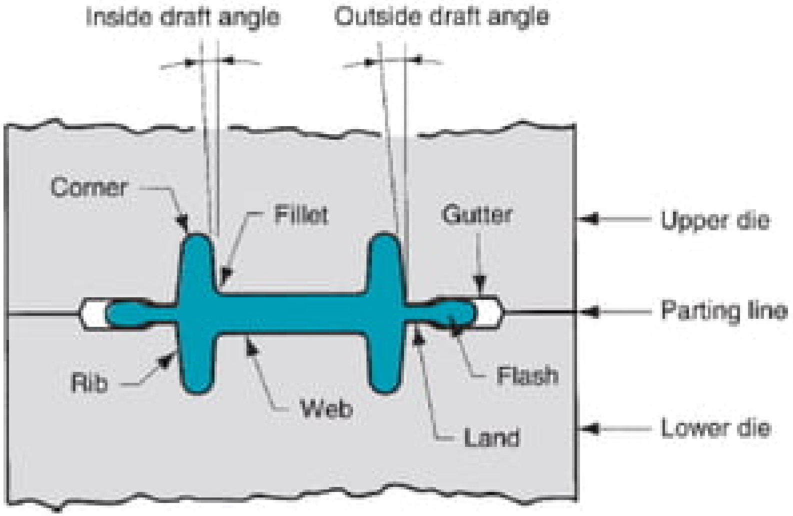
The force is given to the forging billet gradually, and not like impact force.

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:



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.

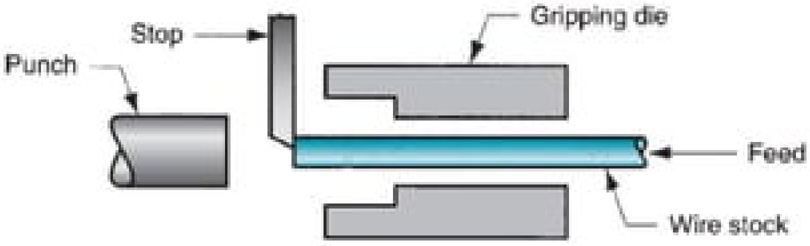
Flash: The pressure build up because of flash formation is controlled proper design of gutter and flash land.

Other forging operations

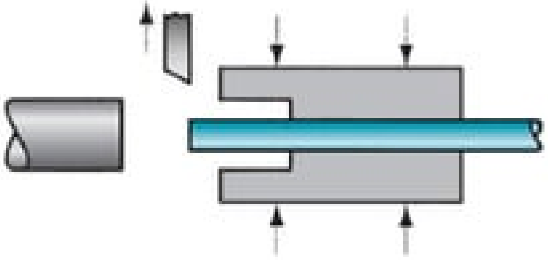
Upset forging:

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.

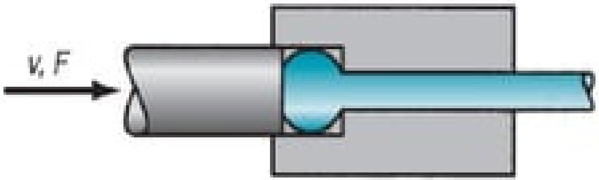
Upset forging is widely used in the fastener industries to form heads on nails, bolts, and similar products.



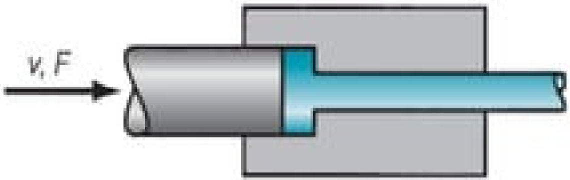
Feeding of work piece



Gripping of work piece and retracting of stop



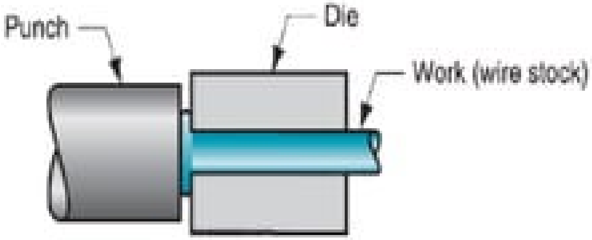
Forward movement of punch and upsetting



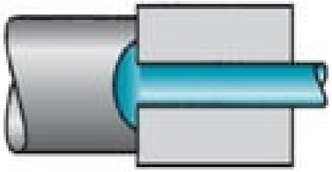
Forging operation completes

Heading:

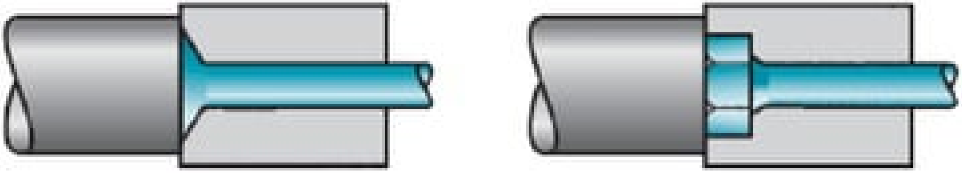
The following figure shows variety of heading operations with different die profiles.



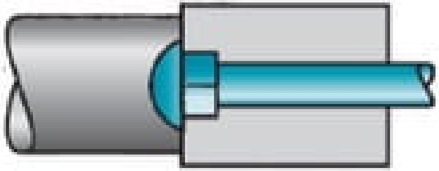
Heading a die using open die forging



Round head formed by punch only



Head formed inside die only



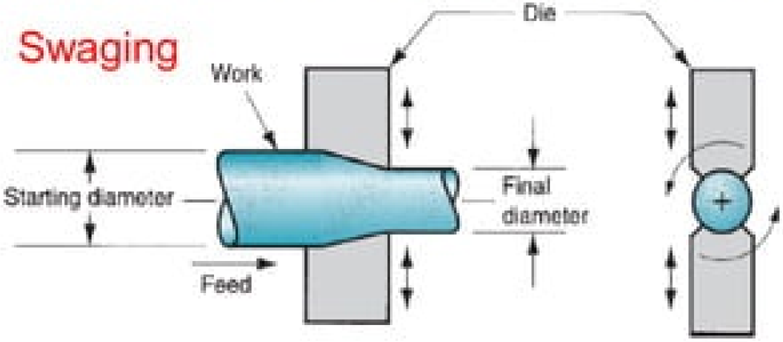
Bolt head formed by both die and punch

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:

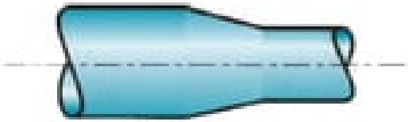
Swaging is used to reduce the diameter of a tube or a rod at the end of the work piece to create a tapered section. In general, this process is conducted by means of rotating dies that hammer a workpiece in radial direction inward to taper it as the piece is fed into the dies. A mandrel is required to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

Swaging

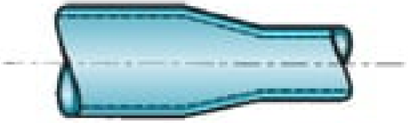


Radial forging:

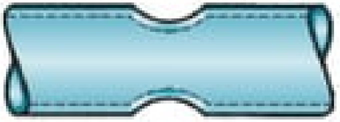
This operation is same as swaging, except that in radial forging, the dies do not rotate around the work piece, instead, the work is rotated as it feeds into the hammering dies.



Diameter reduction of solid work



Tube tapering



Swaging to form a groove on the tube

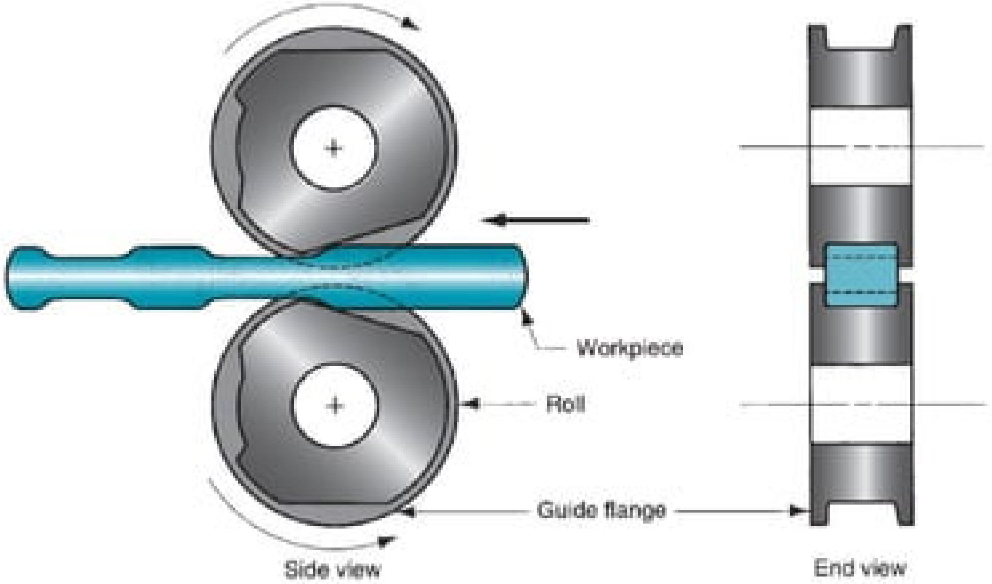
Swaging with different die profiles

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.

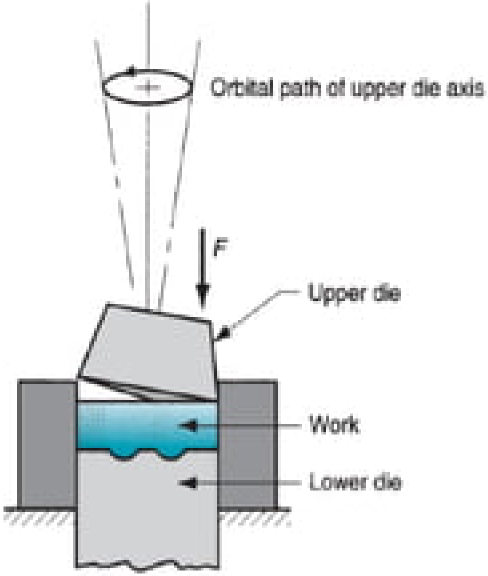
Depending on the amount of deformation, the rolls rotate partially. Roll-forged parts are generally stronger and possess desired grain structure compared to machining that might be used to produce the same part.

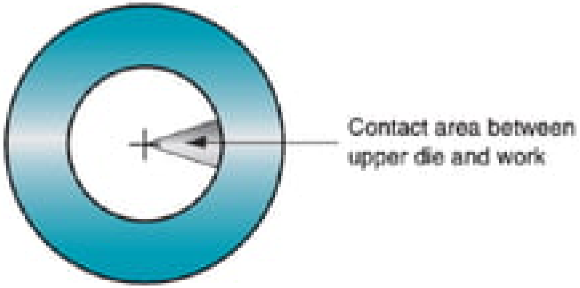


Orbital forging:

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 :

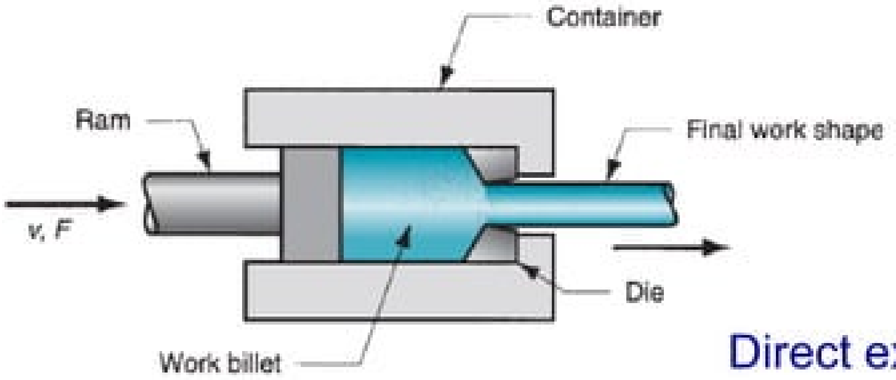
- Variety of shapes are possible, especially using hot extrusion
- Grain structure and strength properties are enhanced in cold and warm extrusion
- Close tolerances are possible, mainly in cold extrusion

Types of extrusion:

Direct or forward extrusion, Indirect or backward extrusion

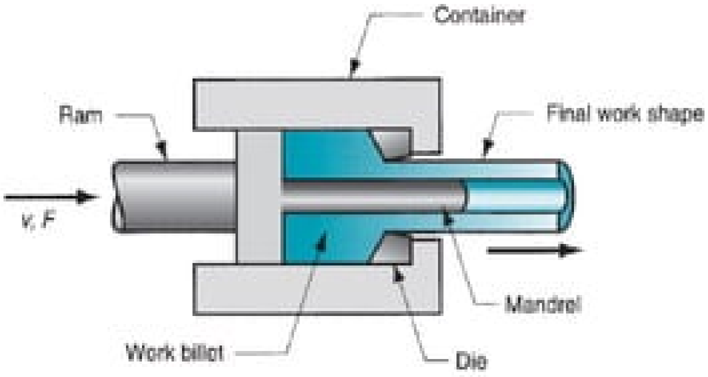
Direct extrusion: - A metal billet is first loaded into a container having die holes. A ram compresses the material, forcing it to flow through the die holes.

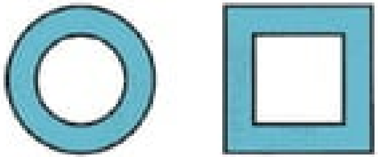
- Some extra portion of the billet will be present at the end of the process that cannot be extruded and is called *butt*. It is separated from the product by cutting it just beyond the exit.



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.



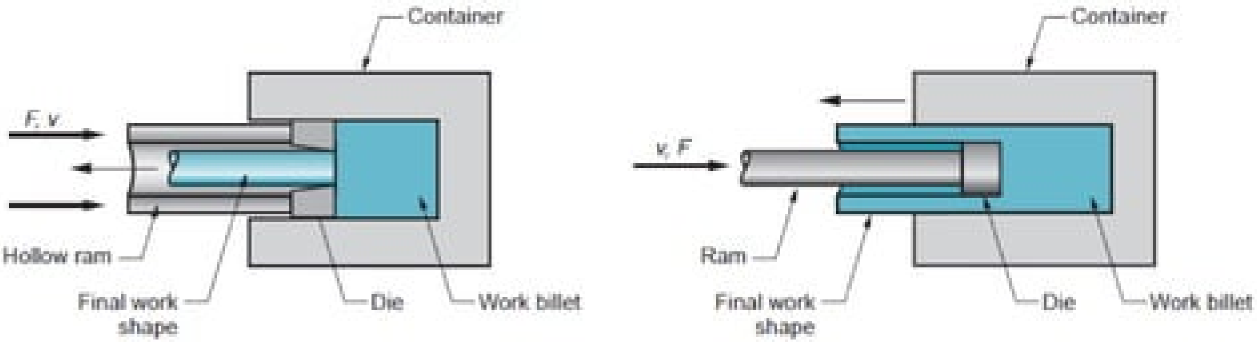


Making hollow shapes using direct extrusion

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.

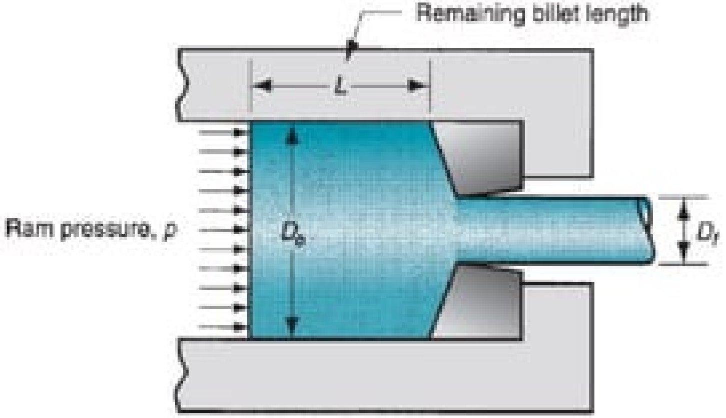
Indirect extrusion: - In this type, the die is mounted to the ram and not on the container. As the ram compresses the metal, it flows through the die hole on the ram side which is in opposite direction to the movement of ram.

- 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,

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

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.

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

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 sliding friction condition. Assuming sticking friction at the interface, we can write:

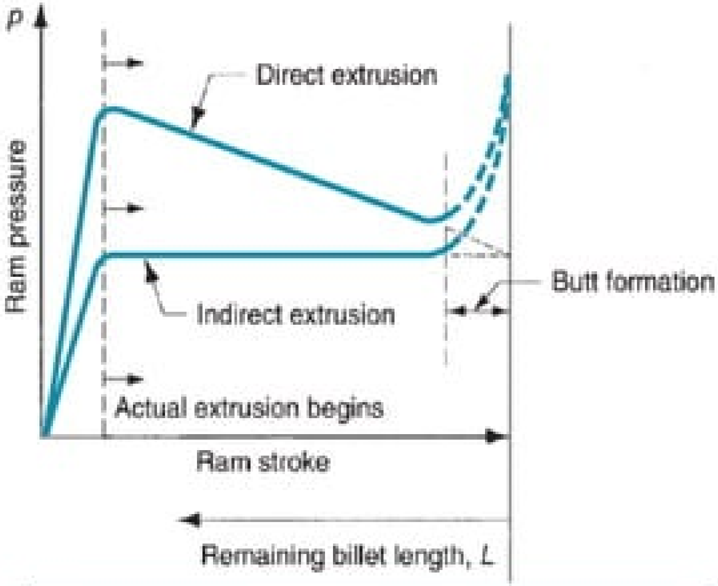
$$K \pi D_0 L = \frac{p_f \pi D_0^2}{4}$$

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.

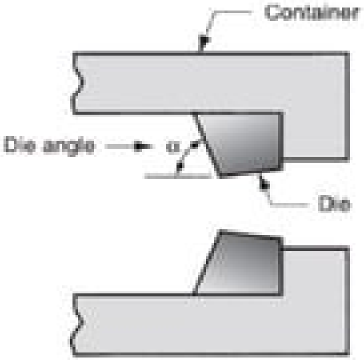


The shape of the initial pressure build up depends on die angle. Higher die angles cause steeper pressure buildups.

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.

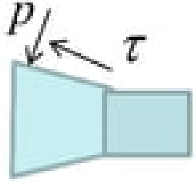


Ram pressure variation with stroke for direct and indirect extrusion is shown in Figure.

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:

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

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

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

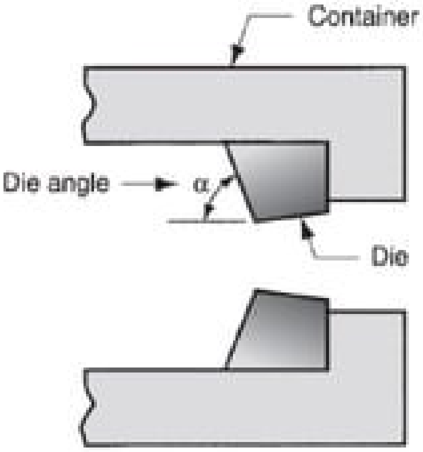
Extrusion dies

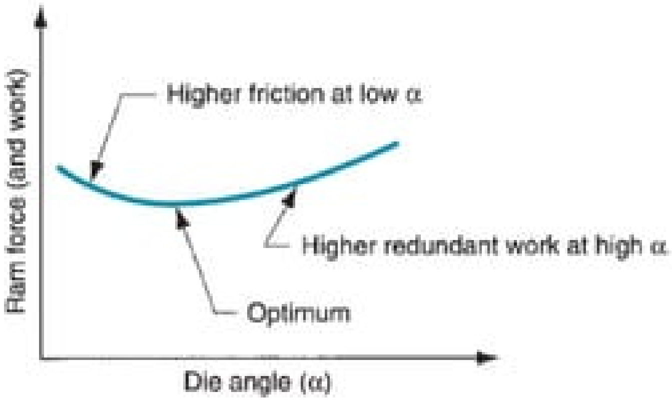
- Two important factors in an extrusion die are: die angle, orifice shape.

- 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.

Die materials

For hot extrusion - tool and alloy steels.

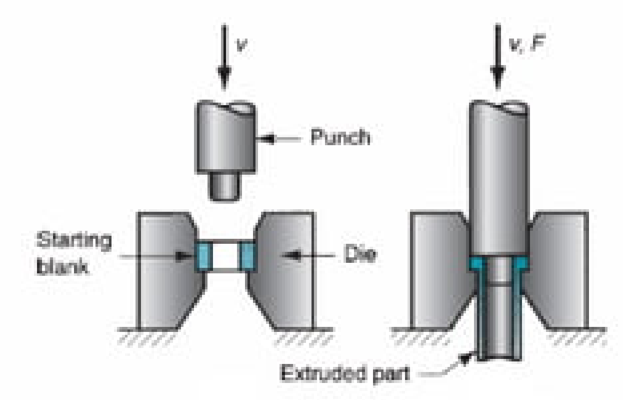
Important properties of die materials are high wear resistance, high thermal conductivity to remove heat from the process.

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

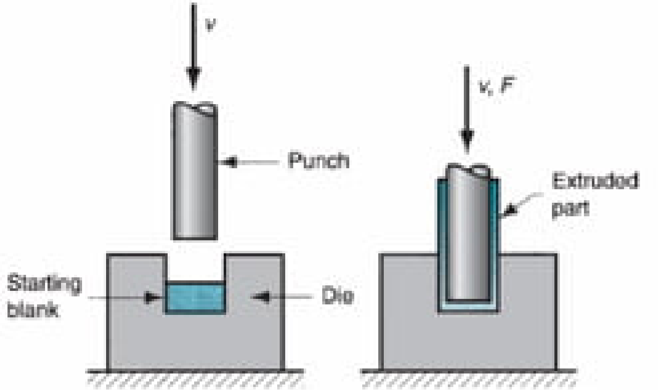
Other extrusion processes

Impact extrusion:

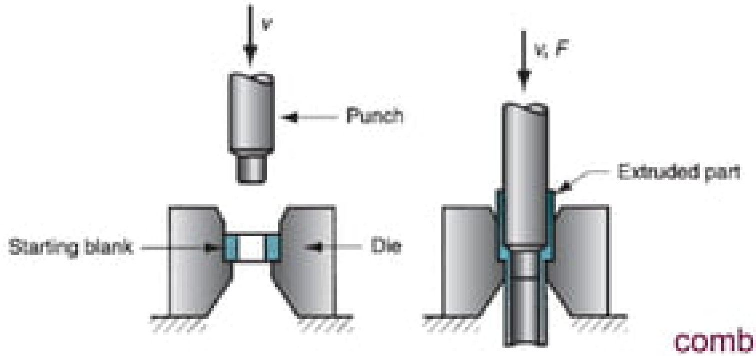
- It is performed at higher speeds and shorter strokes. The billet is extruded through the die by impact pressure and not just by applying pressure.
- But impacting can be carried out as forward extrusion, backward extrusion, or combination of these.



forward extrusion



Backward extrusion

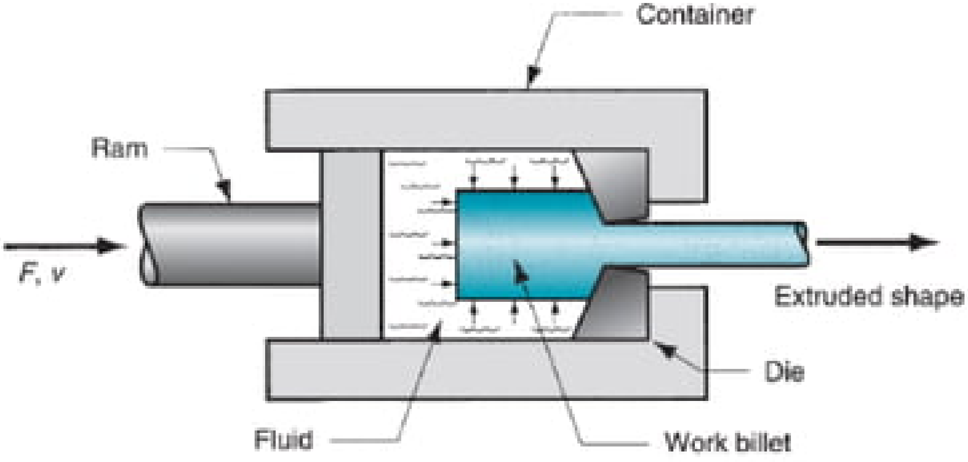


combined extrusion

- 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

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.

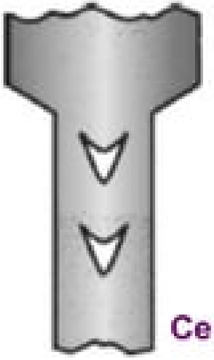
This process is also applicable for ductile metals, and here high reduction ratios are possible.

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

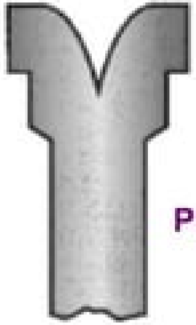
Centerburst:

- 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.



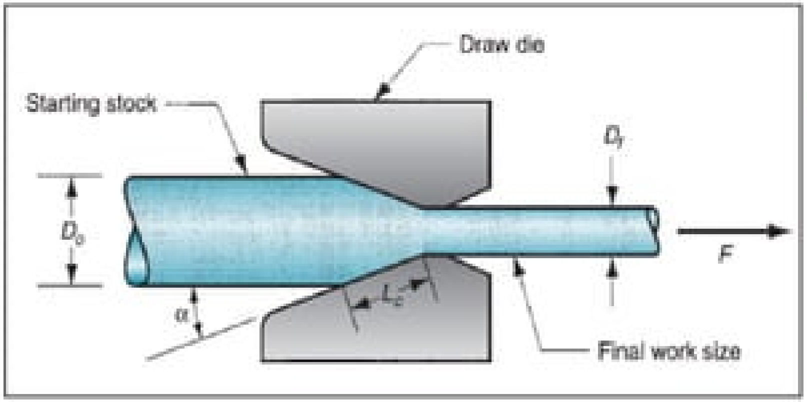
Piping

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

Wire, rod, bar drawing

- In this bulk forming process, a wire, rod, bar are pulled through a die hole reducing their cross-section area.



Wire, rod, bar drawing

Difference between wire drawing and rod drawing:

Initial stock size:

- The basic difference between bar drawing and wire drawing is the stock size that is used for forming. Bar drawing is meant for large diameter bar and rod, while wire drawing is meant for small diameter stock. Wire sizes of the order of 0.03 mm are produced in wire drawing.

Operating stages:

- Bar drawing is generally done as a single stage operation, in which stock is pulled through one die opening. The inlet bars are straight and not in the form of coil, which limits the length of the work that can be drawn. This necessitates a batch type operation.

- In contrast, wire is drawn from coils consisting of several hundred meters of wire and is drawn through a series of dies. The number of dies varies between 4 and 12. This is termed as ‘continuous drawing’ because of the long production runs that are achieved with the wire coils. The segments can be butt-welded to the next to make the operation truly continuous.

Simple analysis of wire drawing

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

$$\varepsilon = \ln(\frac{A_0}{A_f}) = \ln(\frac{1}{1-r})$$

Here $r = (A_0 - A_f) / A_0$

Under ideal deformation, the stress required in wire drawing is given by,

$$\sigma_d = \bar{Y}_f \ln(\frac{A_0}{A_f})$$

Here $\bar{Y}_f = \frac{K\varepsilon^n}{1+n}$, $\bar{Y}_f$ is the average flow stress corresponding to ε mentioned in above equation.

In order to consider the effect of die angle and friction coefficient on the drawing stress, Schey has proposed another equation as shown below:

$$\sigma_d = \bar{Y}_f \left(1 + \frac{\mu}{\tan\alpha}\right) \phi \ln(\frac{A_0}{A_f})$$

Here ϕ is a term that accounts for inhomogeneous deformation which is found by the following eqn. for round cross-section.

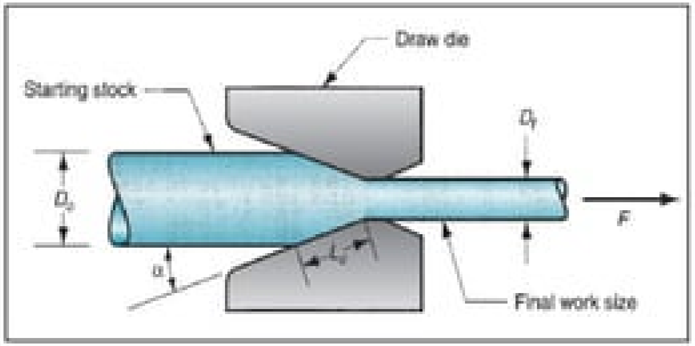
$$\phi = 0.88 + 0.12\frac{D}{L_c}$$

Here D is the average diameter of the workpiece, L_C is the contact length of the work with die given by,

$$D = \frac{D_0 + D_f}{2}; L_C = \frac{D_0 - D_f}{2\sin\alpha}$$

Finally the drawing force is given by, $F = A_f\sigma_d$

The power required for drawing is given by multiplying drawing force with exit velocity of the workpiece



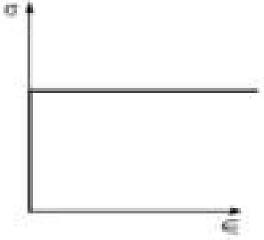
Wire is drawn through a draw die with entrance angle 15°. Starting diameter is 2.5 mm and final diameter 2 mm. The coefficient of friction at the work–die interface is 0.07. The metal has a strength coefficient K = 205 MPa and a strain-hardening exponent n = 0.2. Determine the draw stress and draw force in this operation.

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

Maximum reduction per pass

Increase in reduction, increase the draw stress. If the reduction is large enough, draw stress will exceed the yield strength of the material. Then the wire will just elongate rather than new material being drawn into the die hole. To have a successful wire drawing operation, drawing stress should be less than yield strength of the drawn metal.

Assume a perfectly plastic material ($n = 0$), no friction and redundant work, then,



$$\sigma_d = \bar{Y}_f \ln(\frac{A_0}{A_f}) = Y \ln(\frac{A_0}{A_f}) = Y \ln(\frac{1}{1-r}) = Y$$

which means that

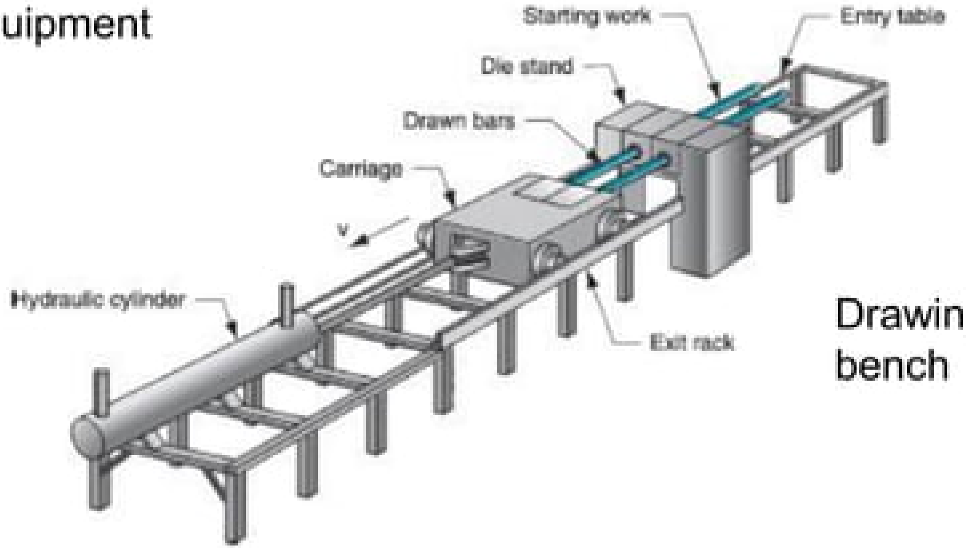
$$\ln(\frac{A_0}{A_f}) = \ln(\frac{1}{1-r}) = 1$$

This gives a condition that the maximum possible reduction, r_{max} is

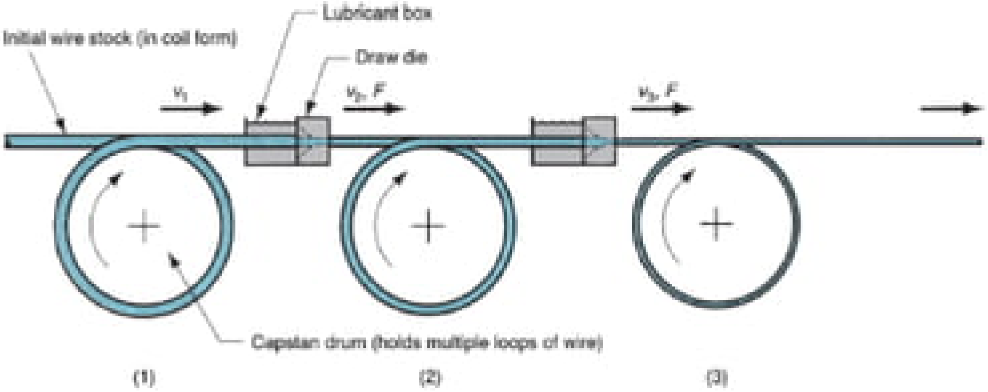
r_{max} = 0.632 (theoretical maximum limit)

This analysis ignores the effects of friction and redundant work, which would further reduce the maximum value, and strain hardening, which would increase the maximum reduction because of the stronger wire than the starting metal. **Reductions of 0.5-0.3 per pass seem to be possible in industrial operations.**

Drawing equipment

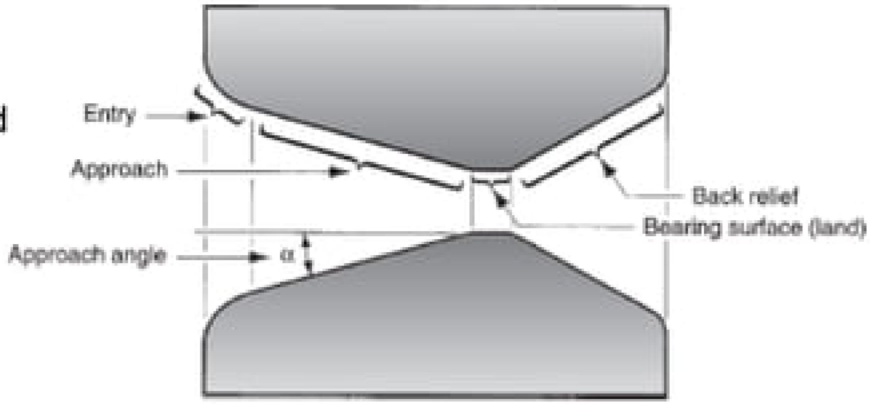


Drawing bar by draw bench



Continuous drawing of wire

Drawing dies



The entry region is generally a bell-shaped mouth that does not contact the work-piece. Its function is to contain and push the lubricant into the die and prevent wearing of work and die surfaces

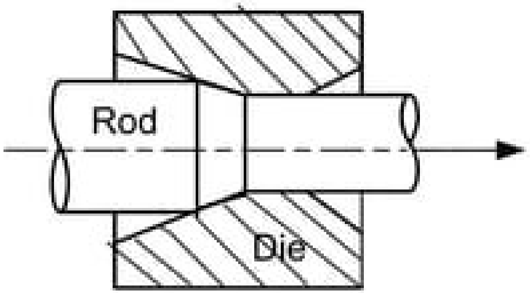
The approach region is where the drawing operation occurs. It is cone-shaped with an angle (half-angle) normally ranging from 6° to 20°.

The bearing surface or land, determines the size of the final drawn work-piece.

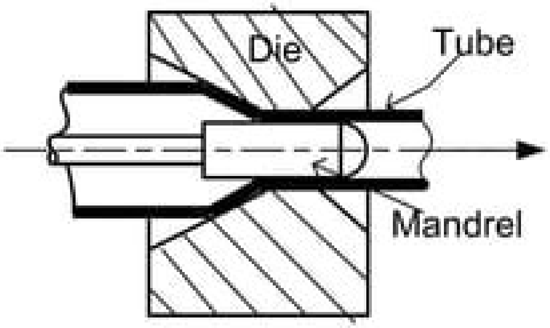
Finally, the back relief is the exit zone. It is provided with a back relief angle (half-angle) of about 25-30°.

Tube drawing

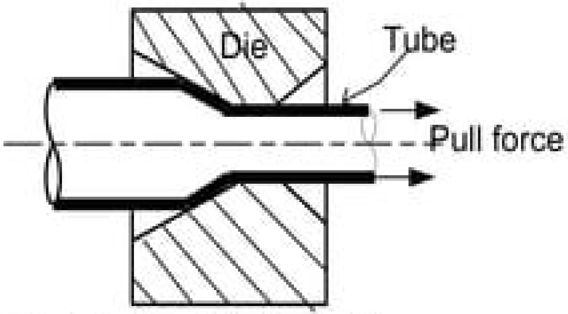
This operation is used to reduce the diameter or wall thickness of the seamless tubes and pipes. Tube drawing can be done either with or without mandrel. **The simplest method uses no mandrel and is used for diameter reduction called as tube sinking.** But inside diameter and wall thickness cannot be controlled. So mandrel is required.



(a) Rod drawing

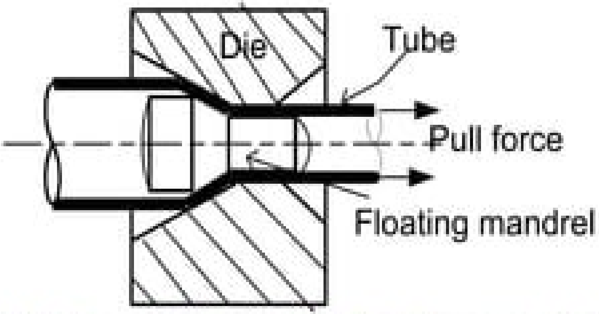


(c) Tube drawing with fixed mandrel



(b) Tube drawing without mandrel

(TUBE SINKING)



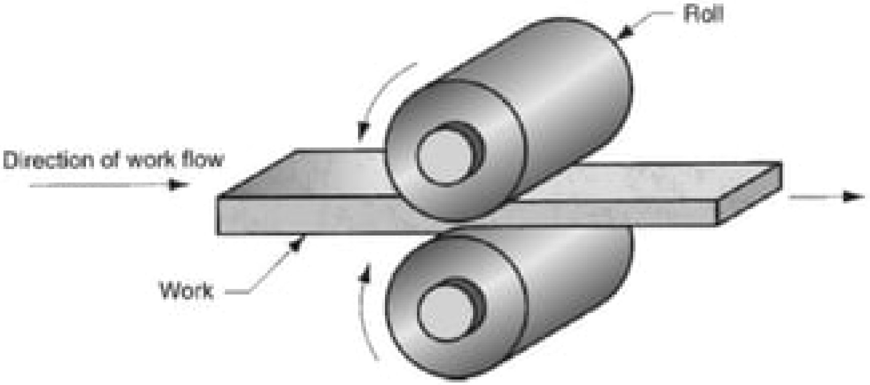
(d) Tube drawing with floating mandrel

Using a fixed mandrel: In this case, a mandrel is attached to a long support bar to control the inside diameter and wall thickness during the operation. The length of the support bar restricts the length of the tube that can be drawn.

Using a floating plug: As the name suggests the mandrel floats inside the tube and its shape is designed so that it finds a suitable position in the reduction zone of the die. There is no length restriction in this as seen with the fixed mandrel.

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.

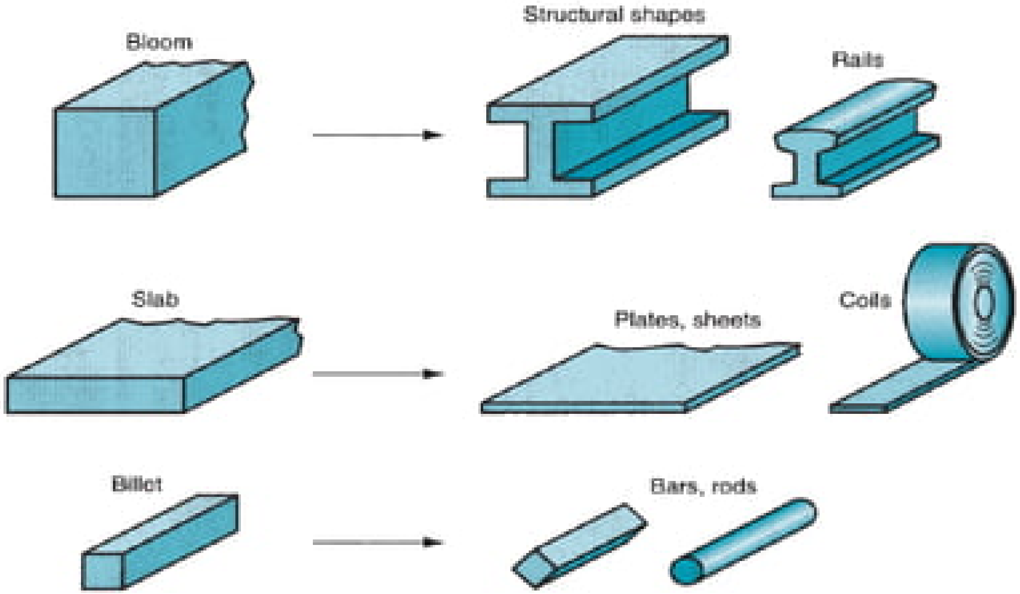
Slab: It is rolled from an ingot or a bloom and has a rectangular cross section of 250 mm width or more and thickness 40 mm or more.

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.



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.

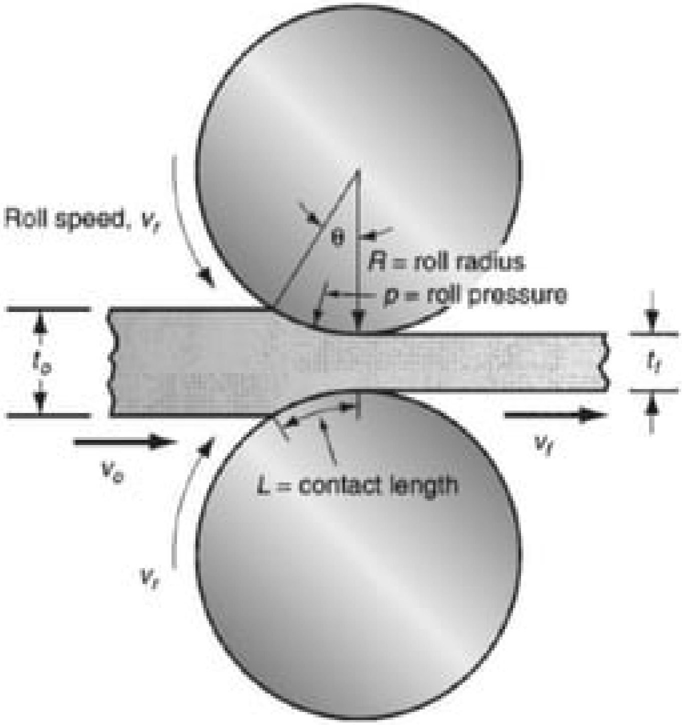
During rolling, the workpiece width increases which is termed as spreading. It will be large when we have low width to thickness ratio and low friction coefficient.

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

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.

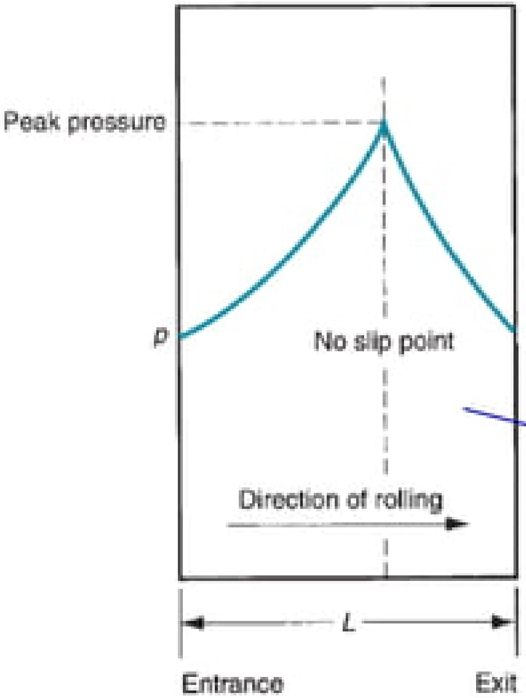
In cold rolling, the value is app. 0.1, in warm rolling, a typical value is around 0.2; and in hot rolling, it is around 0.4.

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

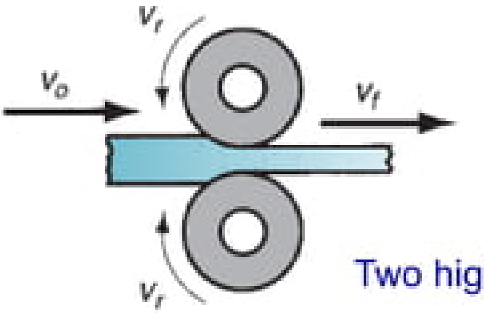
Two high rolling mill: This type of rolling mill consists of two rolls rotating in opposite directions.

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.

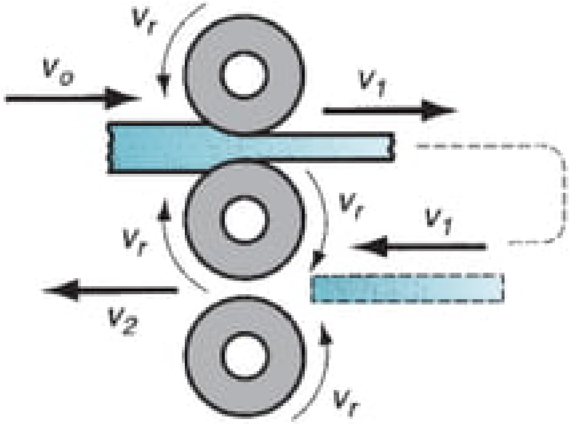


Two high rolling mill

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

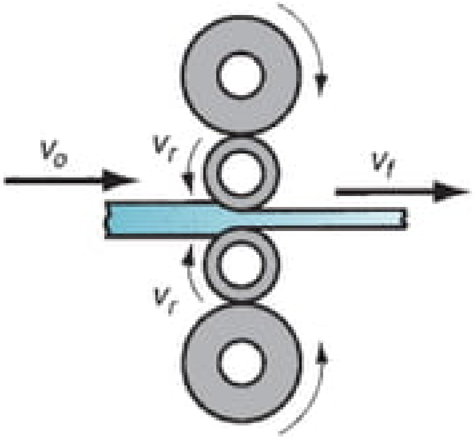


Three high rolling mill

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

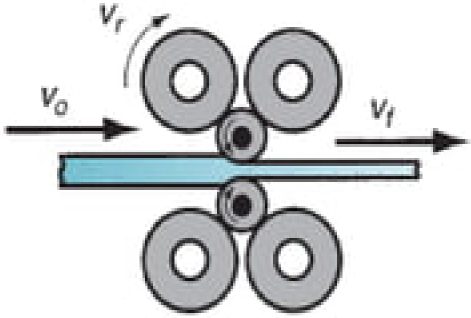
The small rolls will reduce the roll force required as the roll-sheet contact area will be reduced.

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

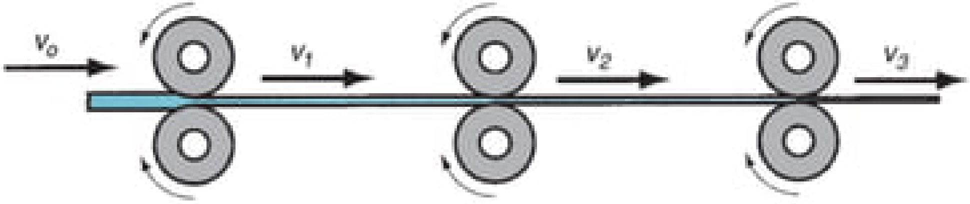


Cluster rolling mill

Tandem rolling mill:

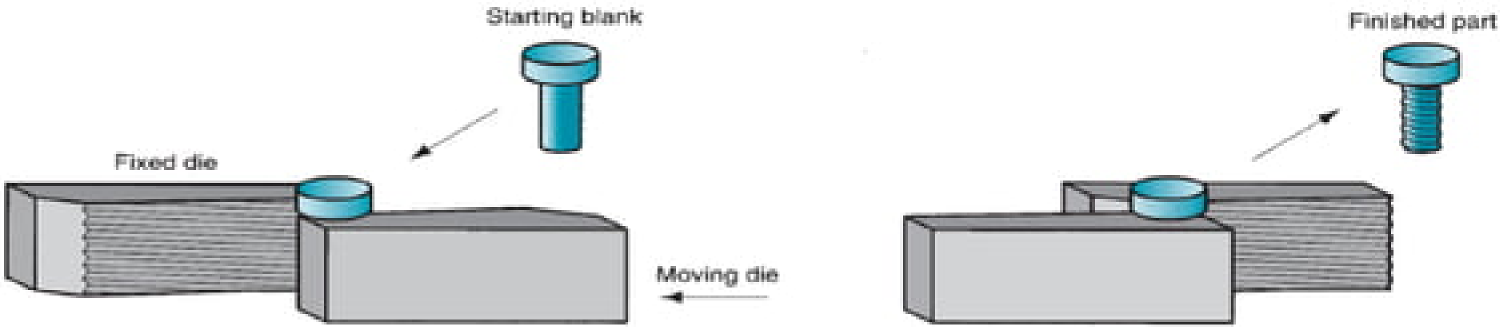
This consists of series of rolling stations of the order of 8 to 10. In each station, thickness reduction is given to the sheet. With each rolling station, the work velocity increases.

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

Thread rolling



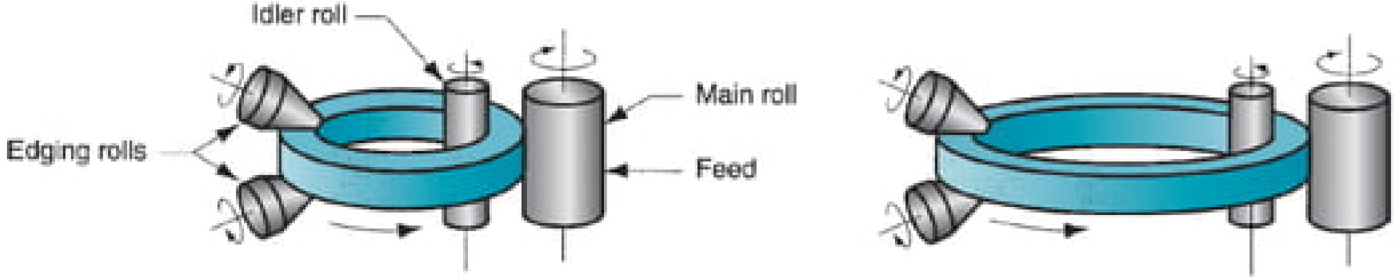
Thread rolling is used to create threads on cylindrical parts by rolling them between two dies as shown in figure.

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



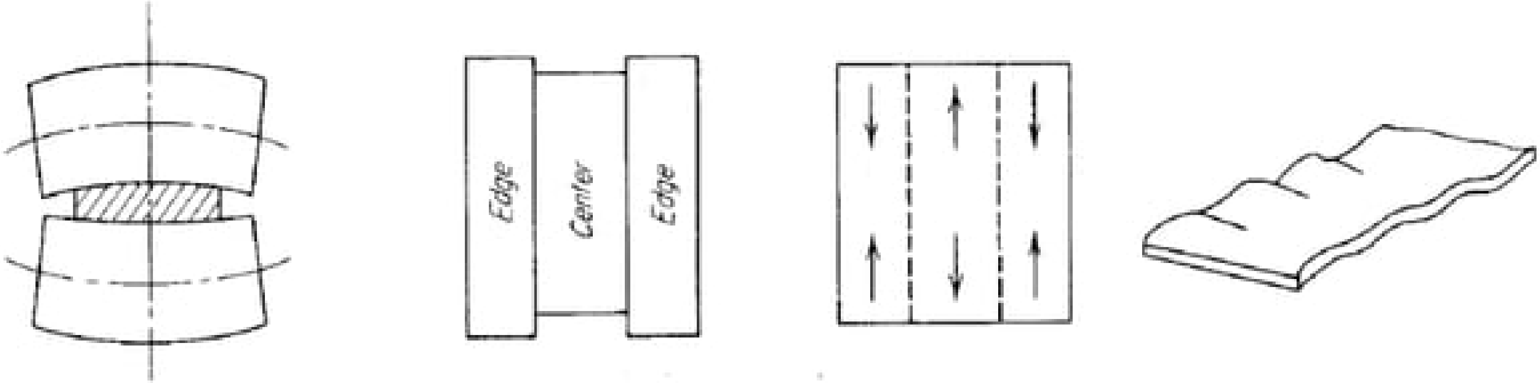
Start of process (thick walled, small diameter)

Completion of process (thin walled, large diameter)

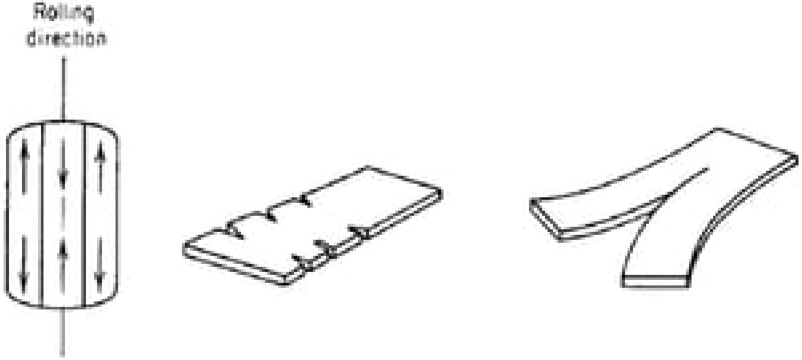
Ring rolling

Defects in strip rolling

Waviness



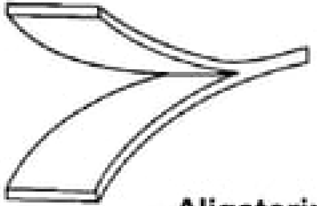
Cracking



Edge defect

Light reduction

Heavy reduction

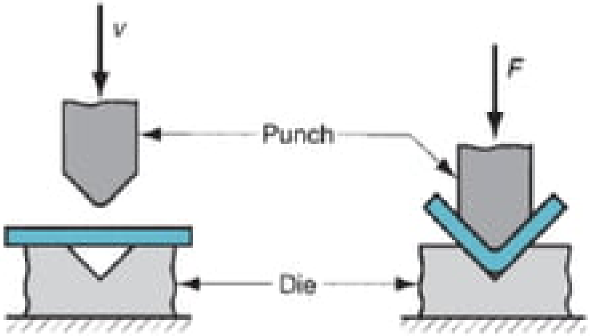


Aligatoring

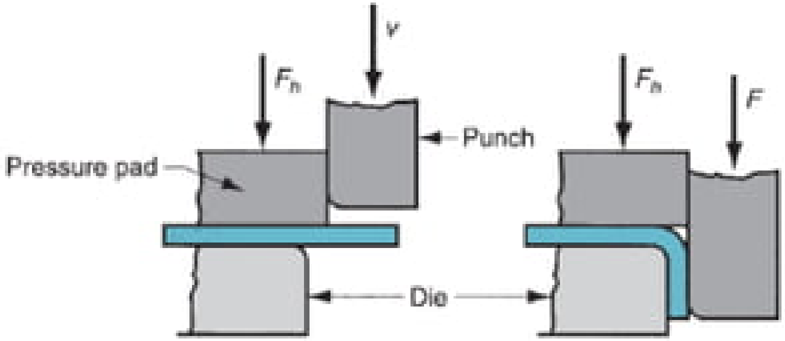
Sheet forming operations

Sheet forming:

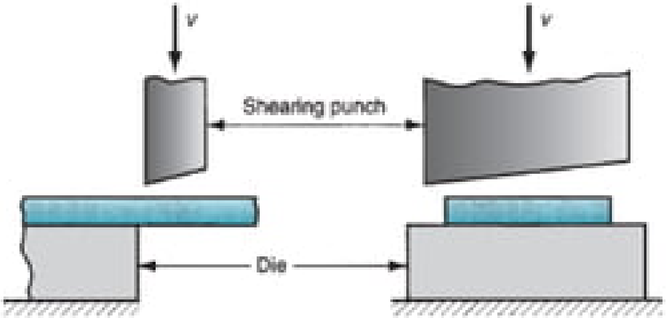
Involves plastic deformation of sheets like deep drawing, cutting, bending, hemming, flanging, curling, stretch forming/stretching, stamping etc.



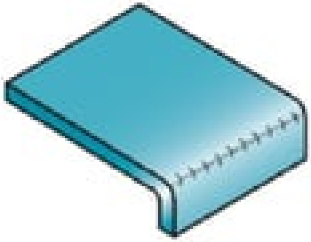
V-bending



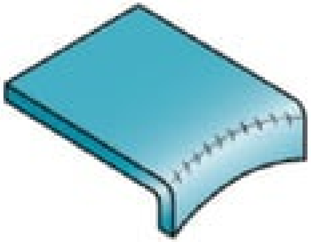
Edge bending



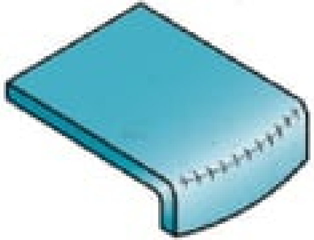
shearing



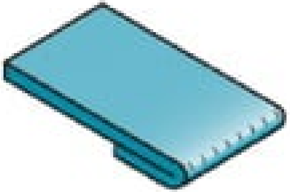
Straight flanging



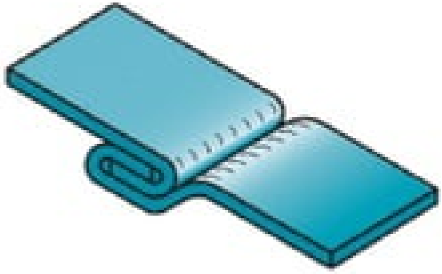
stretch flanging



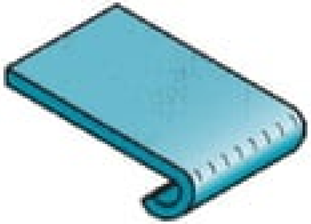
shrink flanging



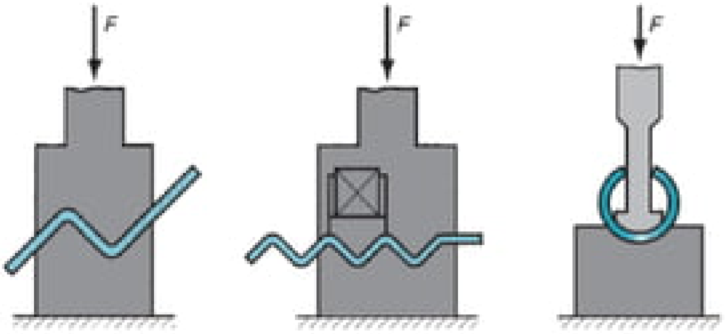
Hemming



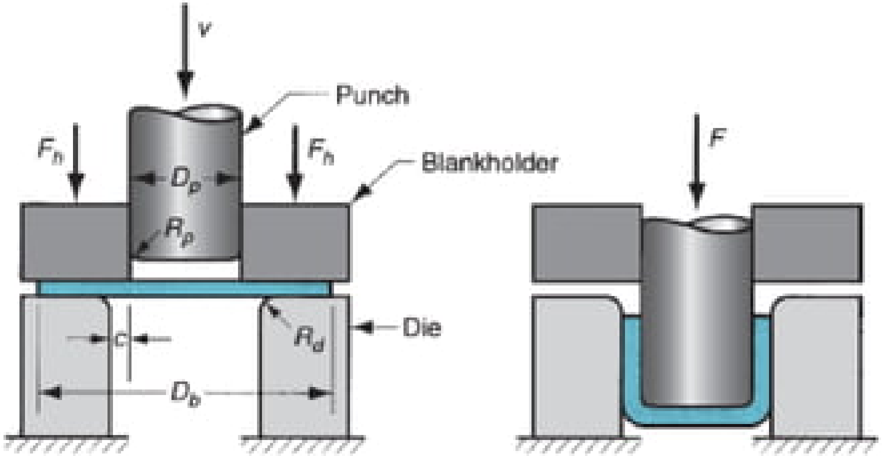
seaming



curling



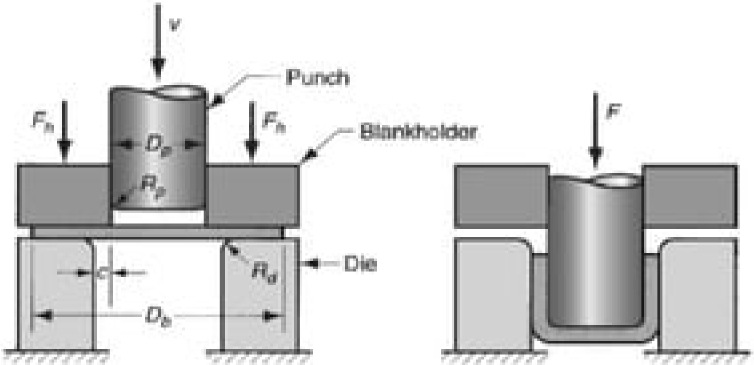
Other bending operations



Cup deep drawing

Cup deep drawing

It is a sheet forming operation, in which the sheet is placed over the die opening and is pushed by punch into the opening. The sheet is held flat on the die surface by using a blank holder.



c – clearance
D_b – blank diameter
D_p – punch diameter
R_d – die corner radius
R_p – punch corner radius
F – drawing force
F_h – holding force

The clearance '*c*' is defined to equal to 10% more than the sheet thickness '*t*'. If the clearance between the die and the punch is less than the sheet thickness, then ironing occurs.

$$c = 1.1t$$

Stages in deep drawing:

(i) As the punch pushes the sheet, it is subjected to a bending operation. Bending of sheet occurs over the punch corner and die corner. The outside perimeter of the blank moves slightly inwards toward the cup center.

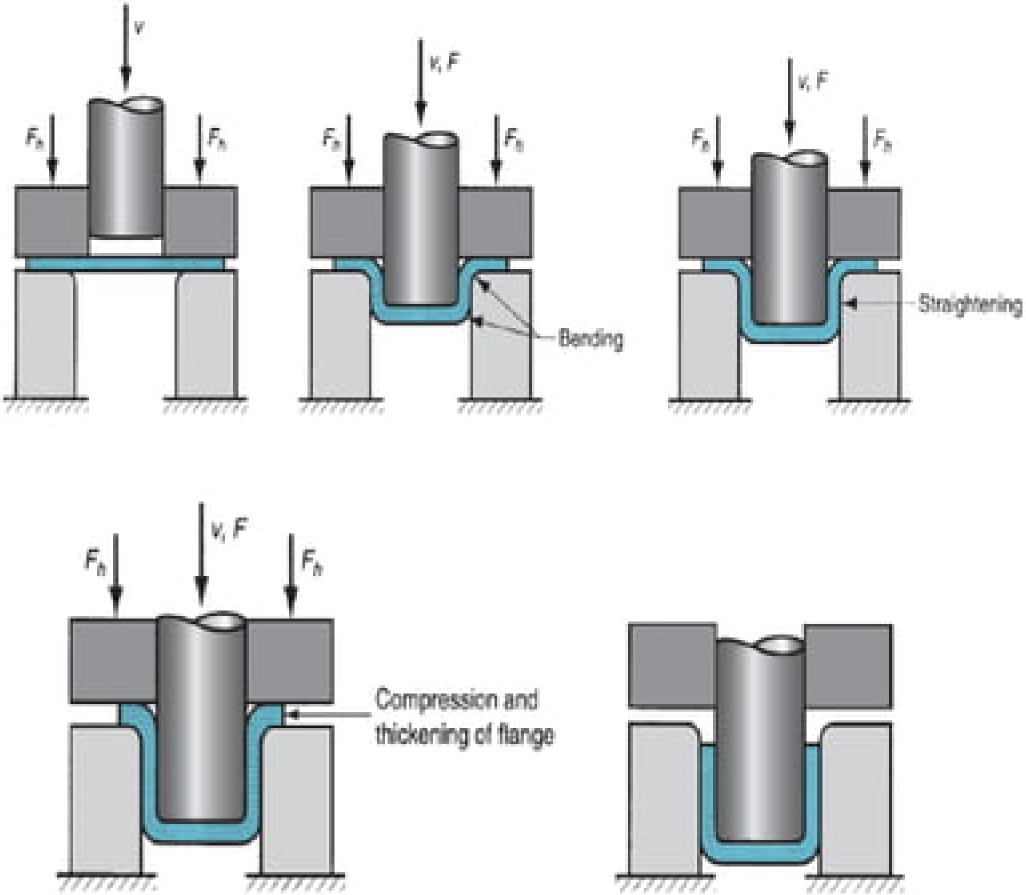
(ii) In this stage, the sheet region that was bent over the die corner will be straightened in the clearance region at this stage, so that it will become cup wall region. In order to compensate the presence of sheet in cup wall, more metal will be pulled from the sheet edge, i.e., more metal moves into the die opening.

(iii) Friction between the sheet and the die, blank holder surfaces restricts the movement of sheet into the die opening. The blank holding force also influences the movement. Lubricants or drawing compounds are generally used to reduce friction forces.

(iv) Other than friction, compression occurs at the edge of the sheet. Since the perimeter is reduced, the sheet is squeezed into the die opening. Because volume remains constant, with reduction in perimeter, thickening occurs at the edge.

In thin sheets, this is reflected in the form of wrinkling. This also occurs in case of low blank holding force. If BHF very small, wrinkling occurs. If it is high, it prevents the sheet from flowing properly toward the die hole, resulting in stretching and tearing of sheet.

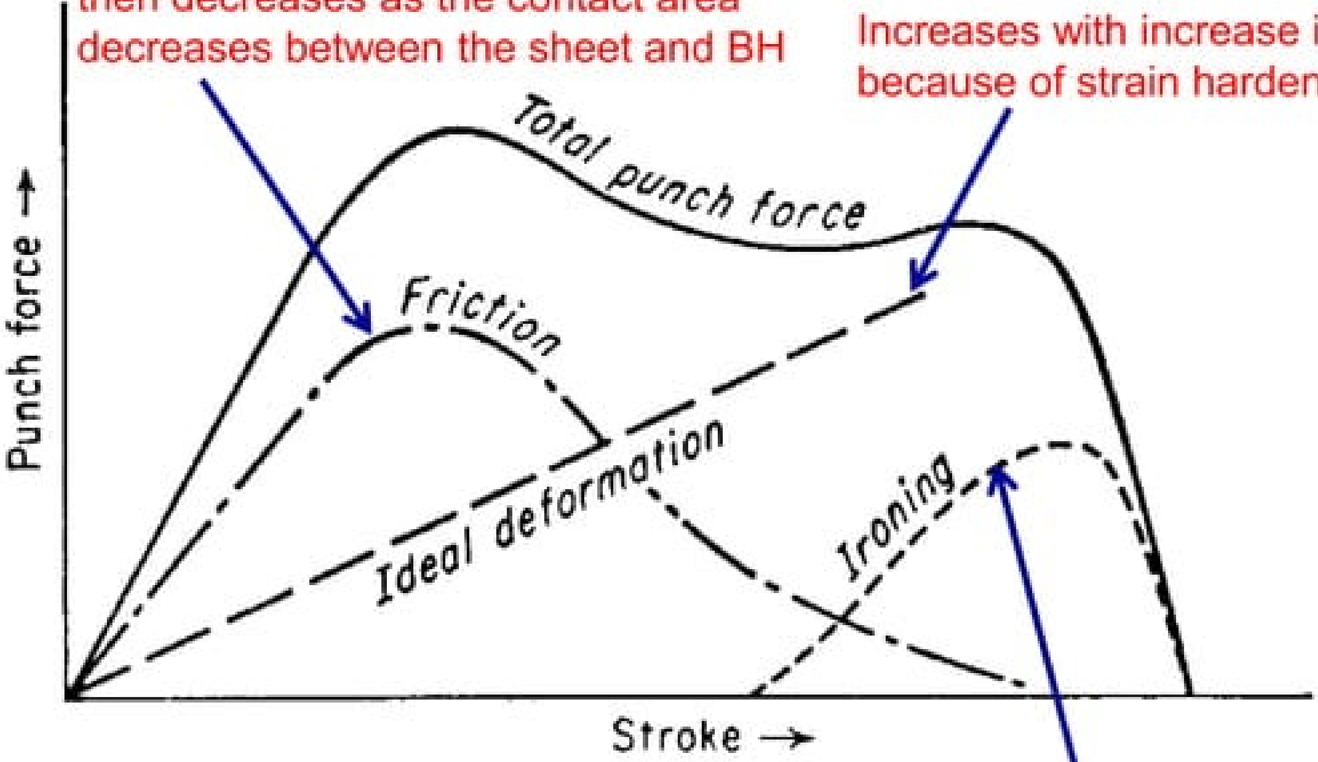
(v) The final cup part will have some thinning in side wall.



Stages in cup deep drawing

Friction force reaches peak early and then decreases as the contact area decreases between the sheet and BH

Increases with increase in strain because of strain hardening



Punch force-stroke for cup deep drawing: contribution from three important factors

Ironing occurs late in the process once the cup wall has reached the maximum thickness

Quantification of cup drawability

Drawing ratio: ratio of blank diameter, D_b, to punch diameter, D_p. The greater the ratio, the more severe the drawing operation.

$$DR = \frac{D_b}{D_p}$$

The limiting value for a given operation depends on punch and die corner radii, friction conditions, draw depth, and quality of the sheet metal like ductility, degree of directionality of strength properties in the metal.

Reduction, R, is defined as, $R = \frac{D_b - D_p}{D_b}$

Limiting values: $DR \leq 2$; $R \leq 0.5$

Thickness to diameter ratio, $t/D_b > 1\%$;

As the ratio decreases, tendency for wrinkling increases.

The maximum drawing force, *F* , can be estimated approximately by the following equation .

$$F = \pi D_p t \sigma_{UTS} \left(\frac{D_b}{D_p} - 0.7 \right)$$

Correction factor for friction

The holding force, F_h, is given by,

$$F_h = 0.015 \sigma_{ys} \pi \left\{ D_b^{\,2} - \left(D_p + 2.2t + 2R_d \right)^2 \right\}$$

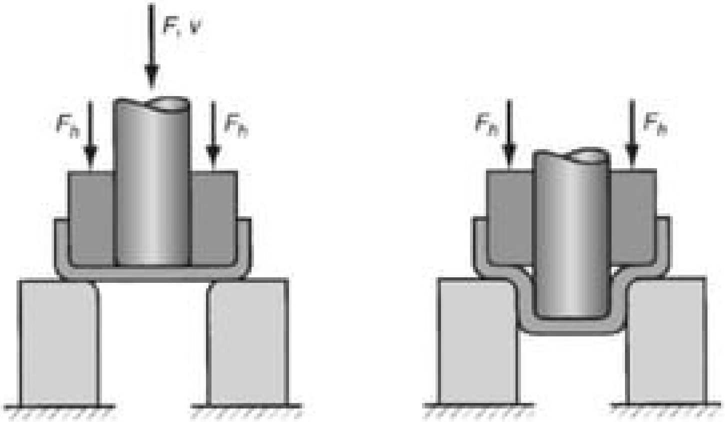
$$F_h = \frac{F}{3}$$ (approx. holding force is one-third of drawing force)

A cup drawing operation is performed in which the inside diameter = 80 mm and the height = 50 mm. The stock thickness = 3 mm, and the starting blank diameter = 150 mm. Punch and die radii = 4 mm. Tensile strength = 400 MPa and a yield strength = 180 MPa for this sheet metal. Determine: (a) drawing ratio, (b) reduction, (c) drawing force, and (d) blankholder force.

Redrawing

In many cases, the shape change involved in making that part will be severe (drawing ratio is very high). In such cases, complete forming of the part requires more than one deep drawing step.

Redrawing refers to any further drawing steps that is required to complete the drawing operation.

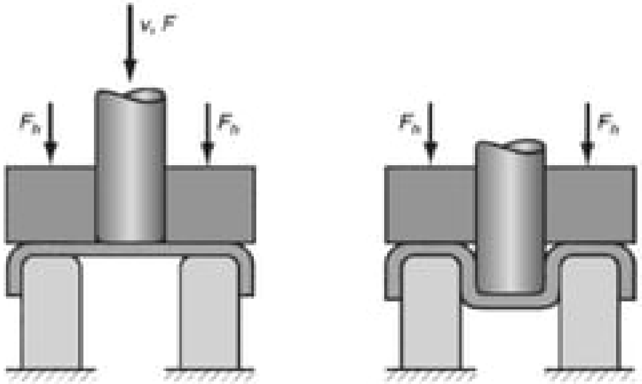


Redrawing

Guidelines for successful redrawing:

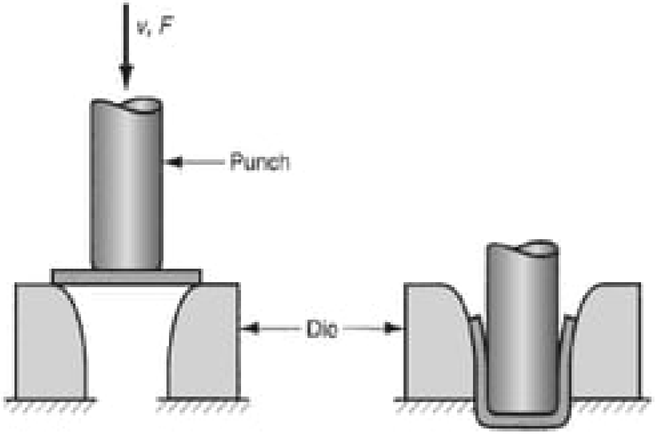
First draw: Maximum reduction of the starting blank - 40% to 45%
Second draw: 30%
Third draw : 16%

Reverse redrawing



In reverse redrawing, the sheet part will face down and drawing is completed in the direction of initial bend.

Drawing without blank holder



The main function of BH is to reduce wrinkling.
The tendency of wrinkling decreases with increase in thickness to blank diameter ratio (t/D_b). For a large t/D_b ratio, drawing without blank holder is possible.
The die used must have the funnel or cone shape to permit the material to be drawn properly into the die cavity.

Limiting value for drawing without BH:

$$D_b - D_p = 5t$$

Plastic anisotropy

The main cause of anisotropy of plastic properties is the preferred orientation of grains, i.e., tendency for grains to have certain orientations. This is cause mainly by mechanical forming of metals.

A useful parameter to quantify anisotropy is *R*, the plastic strain ratio, which is the ratio of true plastic strain in width direction to that in thickness direction. Higher R, large resistance to thinning.

$$R = \frac{\varepsilon_w}{\varepsilon_t}$$

For isotropic materials, *R* = 1; for anisotropic materials: *R* > 1 or *R* < 1

In many sheet forming operations like deep drawing, the materials exhibit some anisotropy in the sheet plane. So averaging is done to find a value quantifying all the variations in the sheet surface as given by the following equation. But this is practically impossible.

$$\overline{R} = \int_{\theta=0}^{\theta=360^\circ} R_\theta \, d\theta$$

(Average plastic strain ratio)

Usually the following equation is used by considering orthotropy is accurate.

$$\overline{R} = \frac{R_0 + 2R_{45} + R_{90}}{4}$$

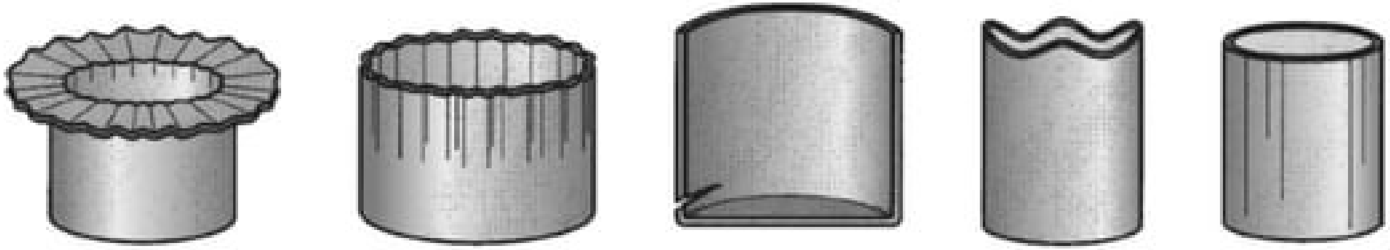
(normal anisotropy)

Another parameter that takes care of planar anisotropy is ΔR given by,

$$\Delta R = \frac{R_0 + R_{90} - 2R_{45}}{2}$$

This is a measure of how different the 45° directions are from the symmetry axes.

Defects in deep drawing



wrinkling in flange and cup wall **tearing** **earing** **surface scratches**

Wrinkling in flange and cup wall: This is like ups and downs or waviness that is developed on the flange. If the flange is drawn into the die hole, it will be retained in cup wall region.

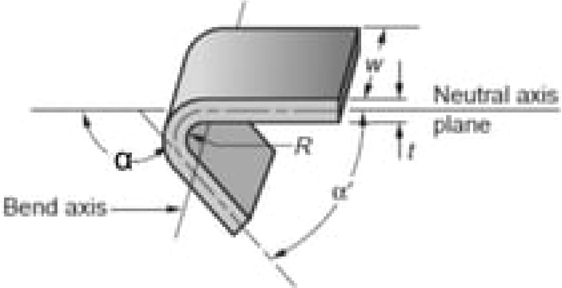
Tearing: It is a crack in the cup, near the base, happening due to high tensile stresses causing thinning and failure of the metal at this place. This can also occur due to sharp die corner.

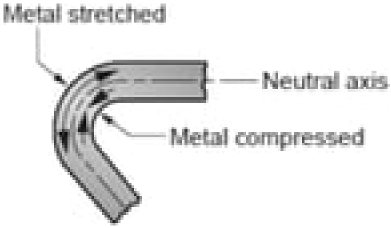
Earing: The height of the walls of drawn cups have peaks and valleys called as earing. There may be more than four ears. Earing results from planar anisotropy (ΔR), and ear height and angular position correlate well with the angular variation of R.

Surface scratches: Usage of rough punch, dies and poor lubrication cause scratches in a drawn cup.

Sheet bending

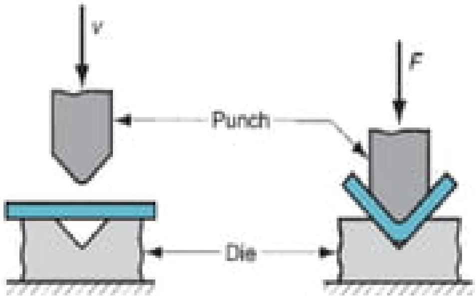
Sheet bending is defined as the straining of the metal around a straight axis as shown in figure. During bending operation, the metal on the inner side of the neutral plane is compressed, and the metal on the outer side of the neutral plane is stretched. Bending causes no change in the thickness of the sheet metal.

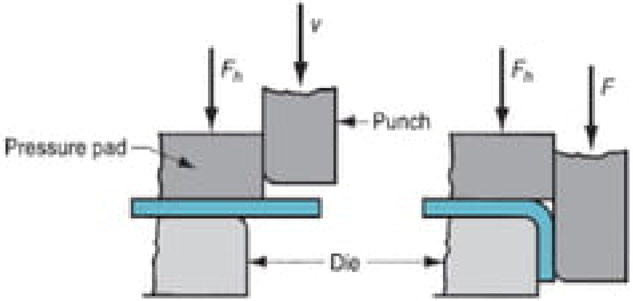




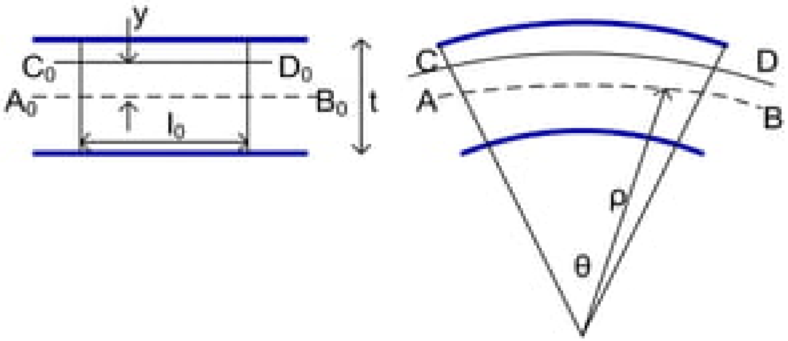
In V-bending, the sheet metal is bent between a V-shaped punch and die set up. The included angles range from very obtuse to very acute values.

In edge bending, cantilever loading of the sheet is seen. A pressure pad is used to apply a force to hold the sheet against the die, while the punch forces the sheet to yield and bend over the edge of the die.





Deformation during bending



For our analysis, it may be assumed that a plane normal section in the sheet will remain plane and normal and converge on the center of curvature as shown in Figure. The line A_0B_0 at the middle surface may change its length to AB, if the sheet is under stretching during bending. The original length l_o becomes, $l_s = \rho\theta$. A line C_0D_0 at a distance y from the middle surface will deform to a length,

$$l = \theta(\rho + y) = \rho\theta(1 + \frac{y}{\rho}) = l_s(1 + \frac{y}{\rho})$$

where ρ is the radius of curvature.

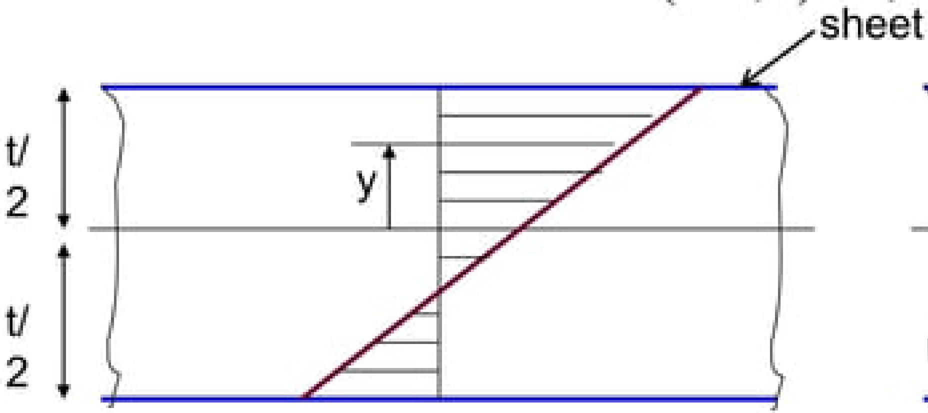
The axial strain of the fiber CD is,

$$\varepsilon_1 = \ln\frac{l}{l_0} = \ln\frac{l_s}{l_0} + \ln\left(1 + \frac{y}{\rho}\right) = \varepsilon_a + \varepsilon_b \qquad (1)$$

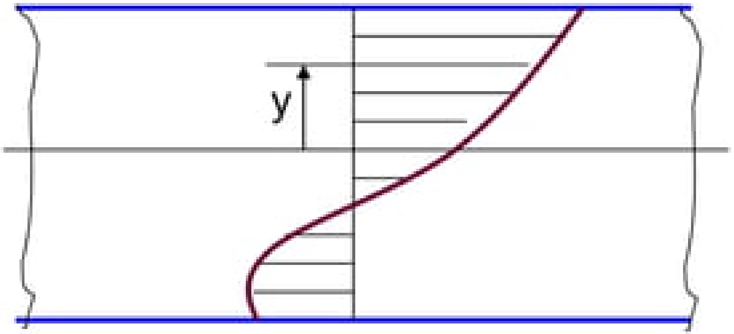
where 'ε_a' and 'ε_b' are the strains at the middle surface and bending strain respectively.

In the case of bending with radius of curvature larger compared to the thickness, the bending strain is approximated as,

$$\varepsilon_b = \ln\left(1+\frac{y}{\rho}\right) \approx \frac{y}{\rho}$$



Strain distribution in bending



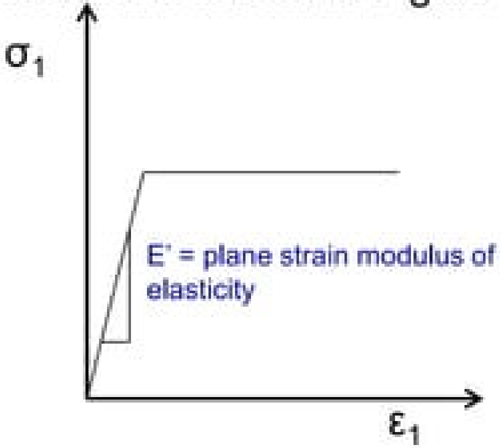
Typical stress distribution in bending

Choice of material model

For the strain distribution given by equation (1) for bending, the stress distribution on a section can be found out by knowing a stress-strain law.

Generally elastic-plastic strain hardening behavior is seen in sheet bending. But there are other assumptions also.

Elastic, perfectly plastic model: Strain hardening may not be important for a bend ratio (ρ/t) (radius of curvature/thickness) of about 50. For this case the stress-strain behavior is shown in Figure below.



Bending can be seen as plane strain deformation as strain along bend can be zero

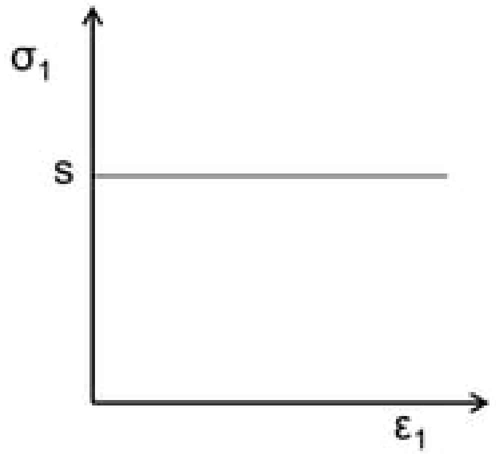
For elastic perfectly plastic model, for stress less than plane strain yield stress, S,

$$\boldsymbol{\sigma_1 = E' \varepsilon_1} \quad \text{where } E' = E/1-\gamma^2$$

For strains greater than yield strains, $\boldsymbol{\sigma_1 = S}$ *where* $S = \sigma_f (2/\sqrt{3})$

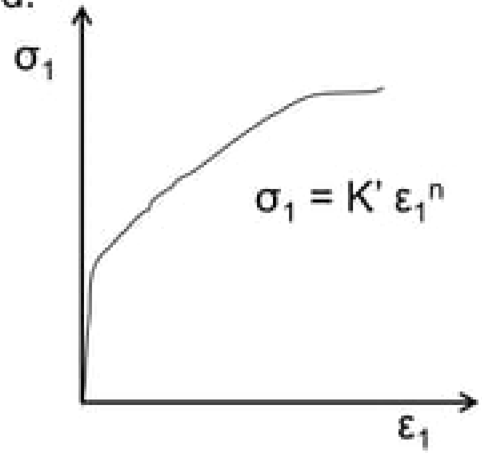
Rigid, perfectly plastic model: For smaller radius bends, where elastic springback is not considered, the elastic strains and strain hardening are neglected. So,

$$\sigma_1 = S$$



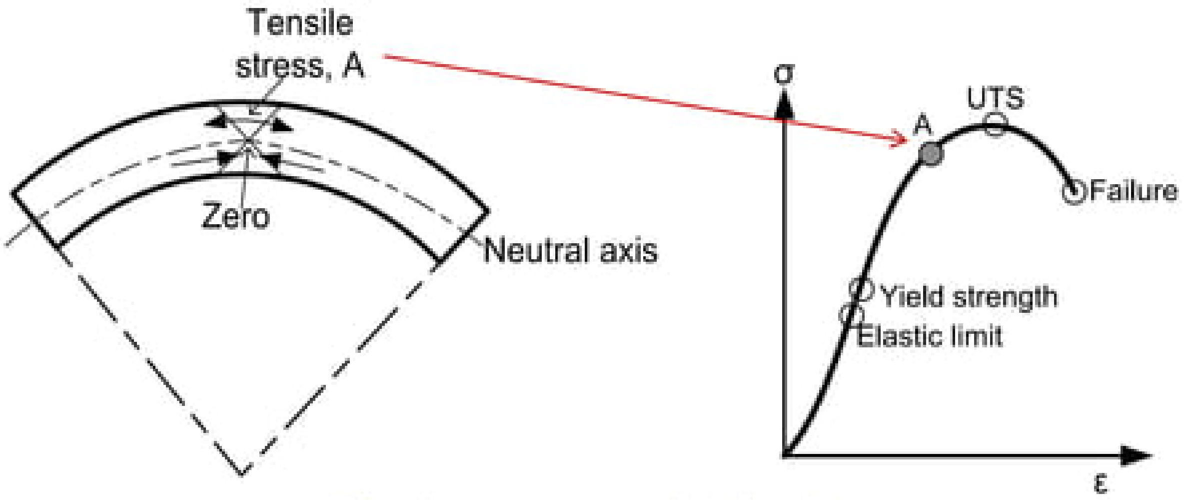
Strain hardening model: When the strains are large, elastic strains can be neglected, and the power hardening law can be followed.

$$\sigma_1 = K' \varepsilon_1^n$$



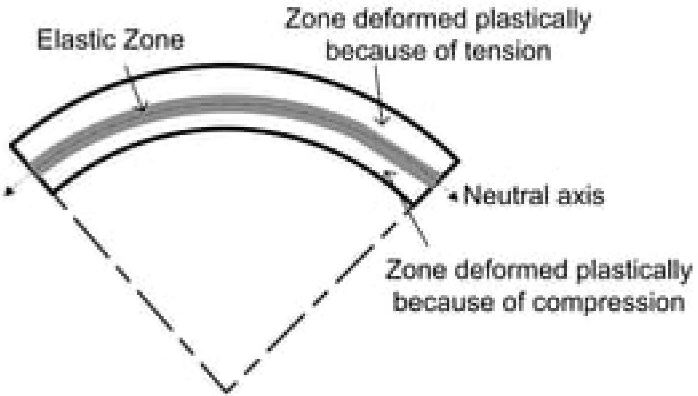
Spring back

- *Spring back* occurs because of the variation in bending stresses across the thickness, i.e., from inner surface to neutral axis to outer surface. The tensile stresses decrease and become zero at the neutral axis.
- Since the tensile stresses above neutral axis cause plastic deformation, the stress at any point (say '*A*') in the tensile stress zone should be less than the ultimate tensile strength in a typical tensile stress-strain behavior. The outer surface will crack, if the tensile stress is greater than ultimate stress during bending.
- The metal region closer to the neutral axis has been stressed to values below the elastic limit. This elastic deformation zone is a narrow band on both sides of the neutral axis, as shown in Fig. The metal region farther away from the axis has undergone plastic deformation, and obviously is beyond the yield strength.
- Upon load removal after first bending, the elastic band tries to return to the original flat condition but cannot, due to the restriction given by the plastic deformed regions. Some return occurs as the elastic and plastic zones reach an equilibrium condition and this return is named as *spring back*.

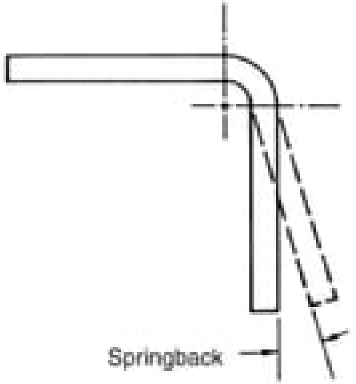


Changing stress patterns in a bend

ASM handbook, sheet metal forming



Elastic and plastic deformation zones during bending

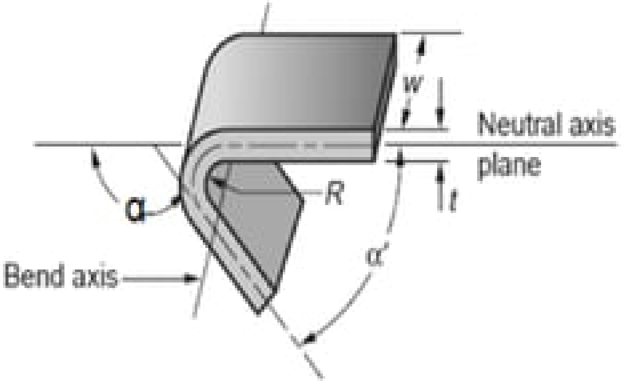


Springback

- Sprinback can be minimized by overbending, bottoming and stretch forming.
- In overbending, the punch angle and radius are made smaller than the specified angle on the final part so that the sheet metal springs back to the desired value.
- Bottoming involves squeezing the part at the end of the stroke, thus plastically deforming it in the bend region.

Spring back is defined by the equation:

$$SB = \frac{\alpha' - \alpha_{tool}}{\alpha_{tool}}$$

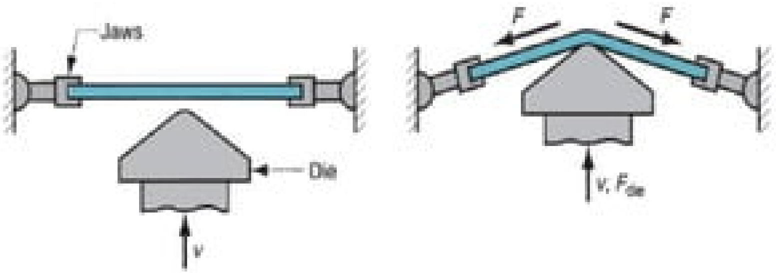


Stretching/stretch forming

- Stretch forming is a sheet metal forming process in which the sheet metal is intentionally stretched and simultaneously bent to have the shape change.

- The sheet is held by jaws or drawbeads at both the ends and then stretched by punch, such that the sheet is stressed above yield strength.

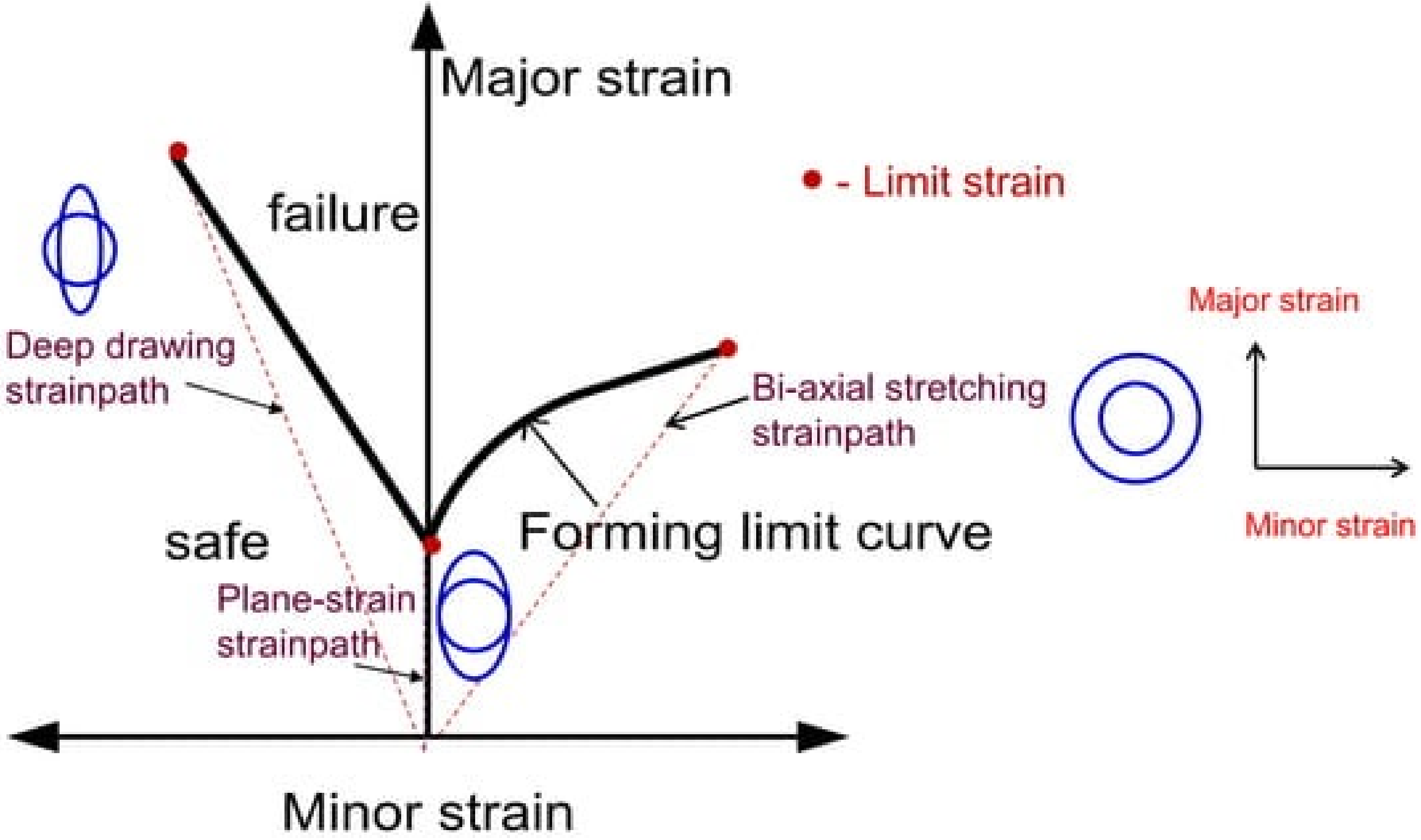
- When the tension is released, the metal has been plastically deformed. The combined effect of stretching and bending results in relatively less springback in the part.



Stretching/stretch forming

Photo from public resource

Forming limit diagram (FLD)

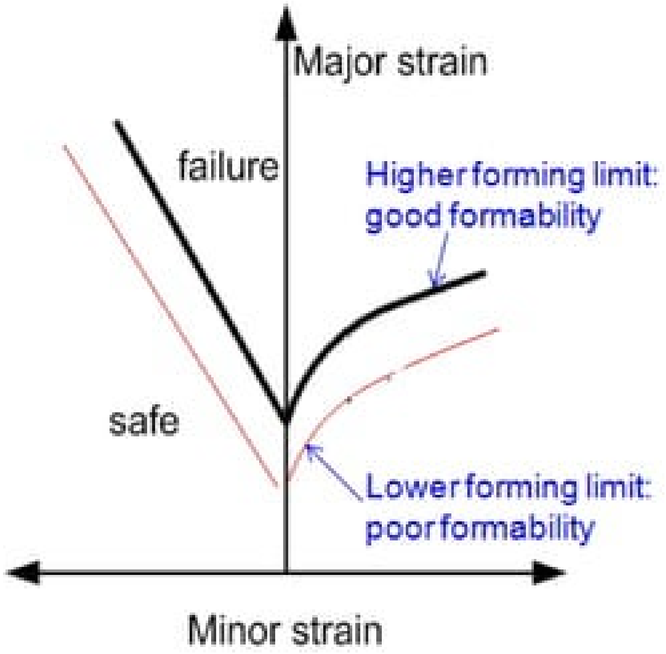


From tensile test we get only ductility, work hardening exponent, but it is in a uniaxial tension without friction, which cannot truly represent material behaviours obtained from actual sheet forming operations.

In sheet forming, mainly in stretching, FLD gives quantification about formability of sheet material. It tells about quality of the material.

In this diagram, *forming limit curve* (*FLC*), plotted between major strain (in Y-axis) and minor strain (in X-axis), is the index that says the amount of safe strains that can be incorporated into the sheet metal.

The FLC is the locus of all the limit strains in different strain paths (like deep drawing, biaxial stretching, plane strain) of the sheet material. The plane-strain condition possesses the least forming limit, when compared to deep drawing and stretching strain paths.



A sheet material with higher forming limit is considered good.