Bulk forming processes: Forging

Metal Forming Technologies

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:

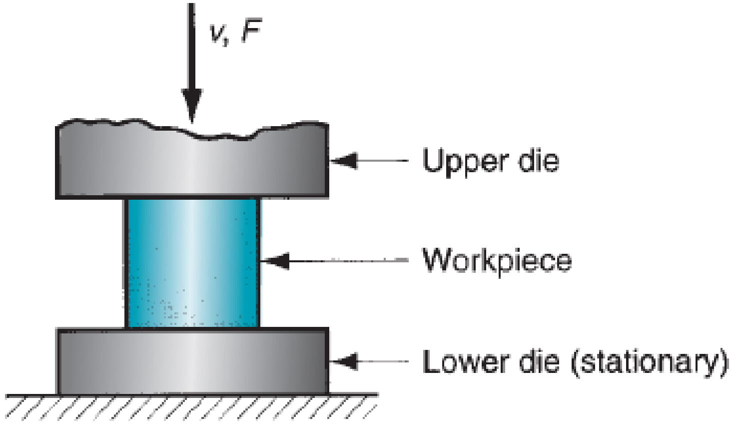
impact load => forging hammer;

gradual pressure => forging press

Category based on type of forming: Open die forging, impression die forging, flashless forging

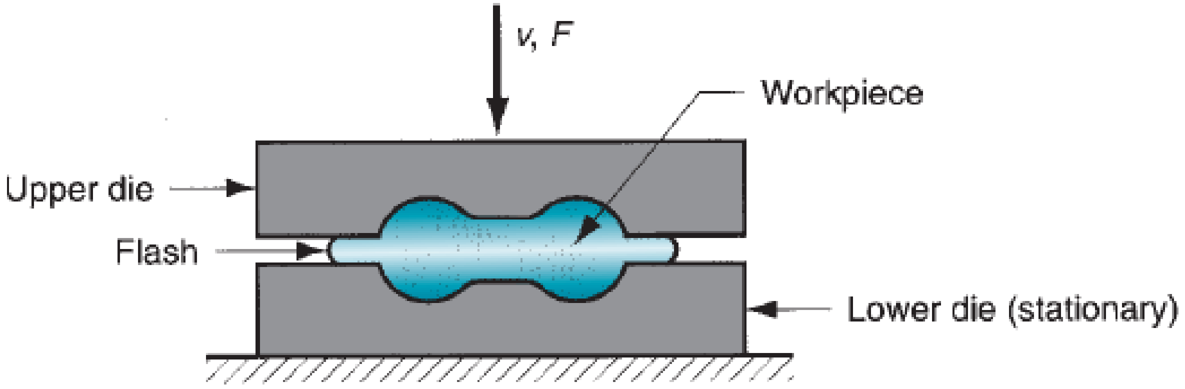
Open die forging

In open die forging, the workpiece 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.

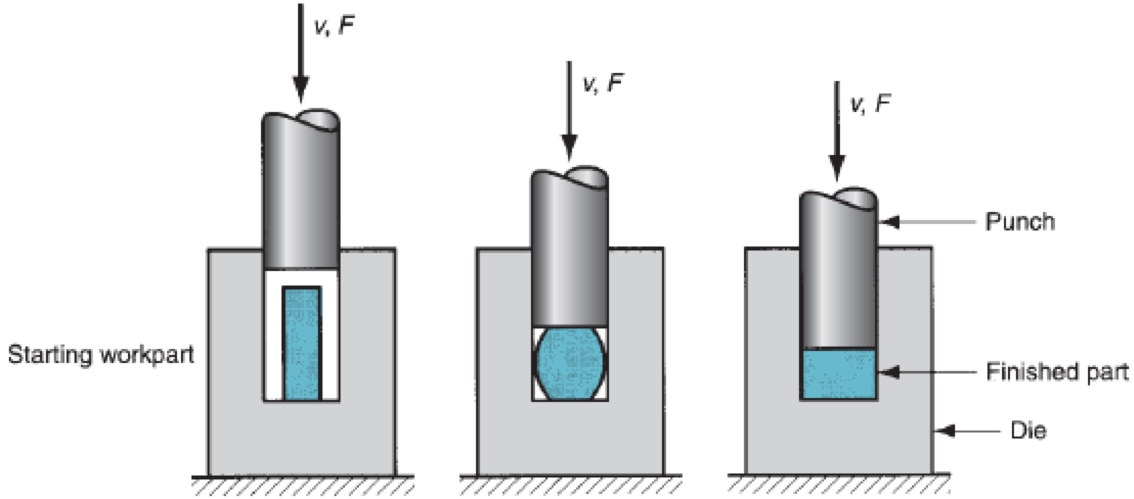


Impression die forging

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.



Flashless forging

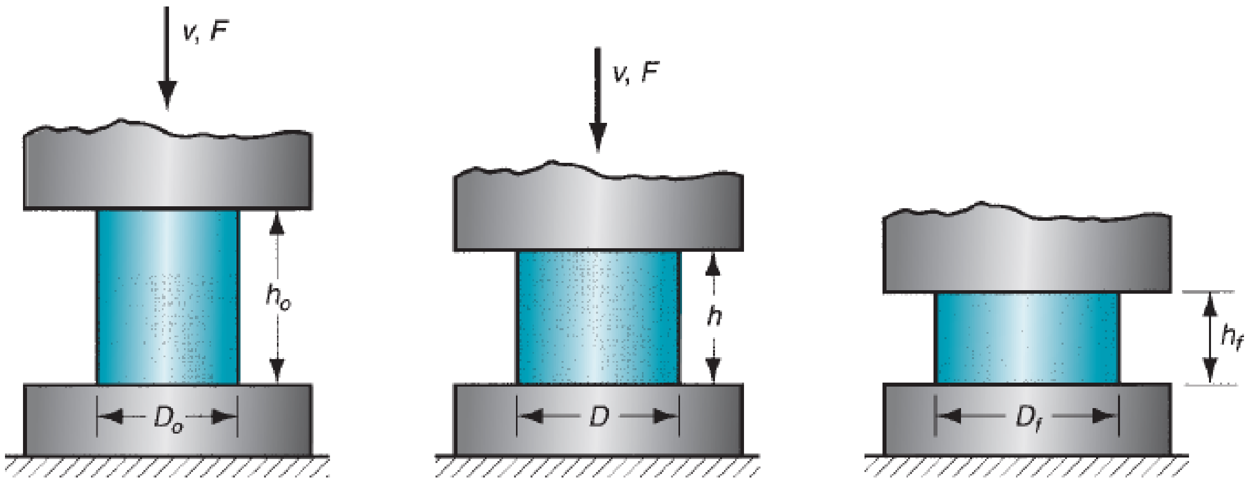


- In flashless forging, most important is that the work piece volume must equal the space in the die cavity within a very close tolerance.
- If the starting billet size is too large, excessive pressures will cause damage to the die and press.
- If the billet size is too small, the cavity will not be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

Open die forging

- 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.



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

In ideal condition: $\boldsymbol{\varepsilon = \ln (h_o/h)}$

$\boldsymbol{h = h_f}$ at the end of compression, $\boldsymbol{\varepsilon}$ will be maximum for the whole forming.

Also $\boldsymbol{F = \sigma_f A}$ is used to find the force required for forging,

where $\boldsymbol{\sigma_f}$ is the flow stress corresponding to $\boldsymbol{\varepsilon}$ at that stage of forming.

Open die forging (continue..)

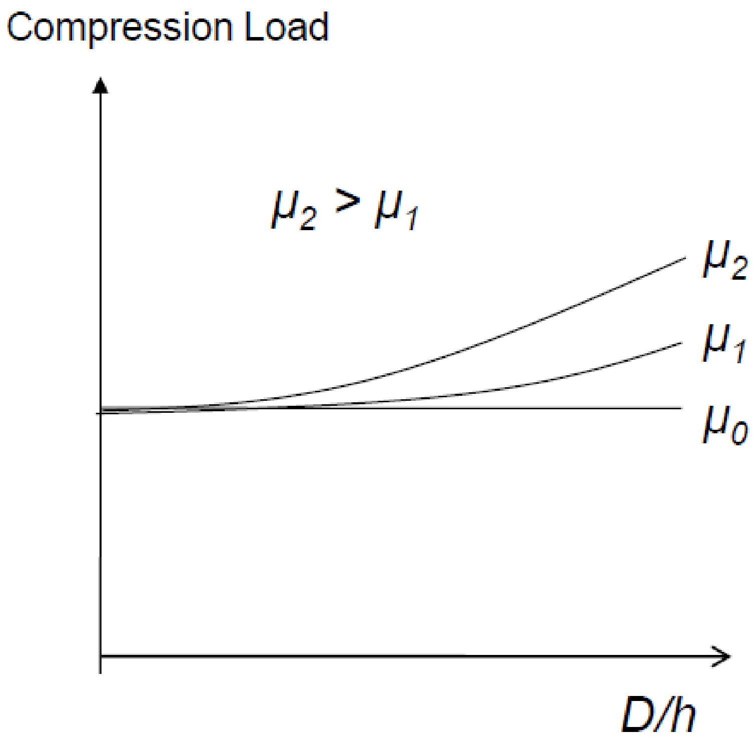
- In actual forging operation, the deformation will not be homogeneous as bulging occurs because of the presence of friction at the die-billet interface. This friction opposes the movement of billet at the surface. This is called ***barreling effect***.
- The barreling effect will be significant as the 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.
- In actual forging, the accurate force evaluation is done by using, $\boldsymbol{F = K_f \sigma_f A}$ by considering the effect of friction and ***D/h*** ratio. Here,

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

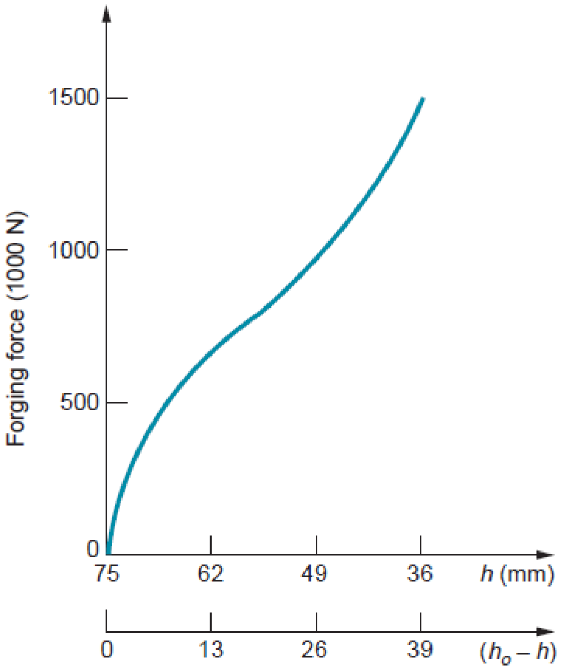
Where $\boldsymbol{K_f}$ = forging shape factor, $\boldsymbol{\mu}$ = coefficient of friction, ***D*** = work piece diameter, ***h*** = workpiece height

Open die forging (continue..)

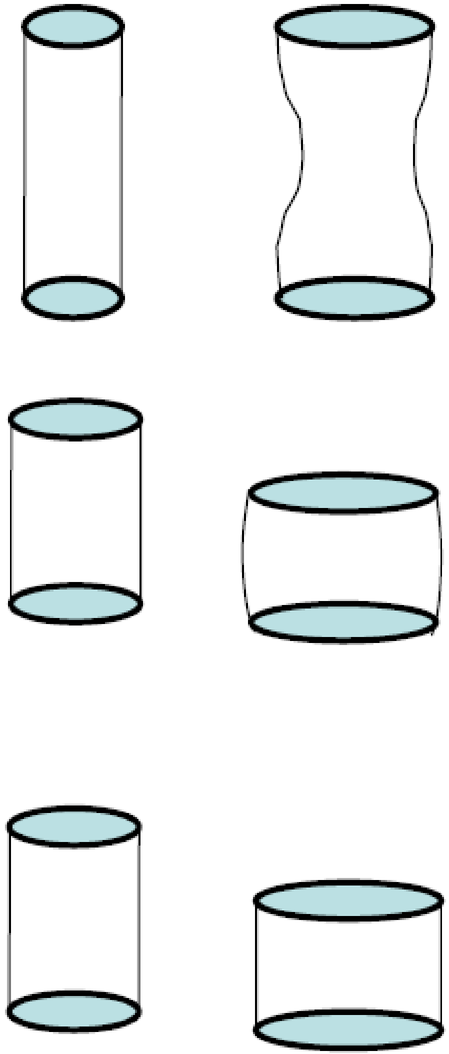
Effect of D/h ratio on load:



Typical load-stroke curve in open die forging



Effect of h/D ratio on barreling



Long cylinder: h/D >2

Cylinder having *h/D* < 2

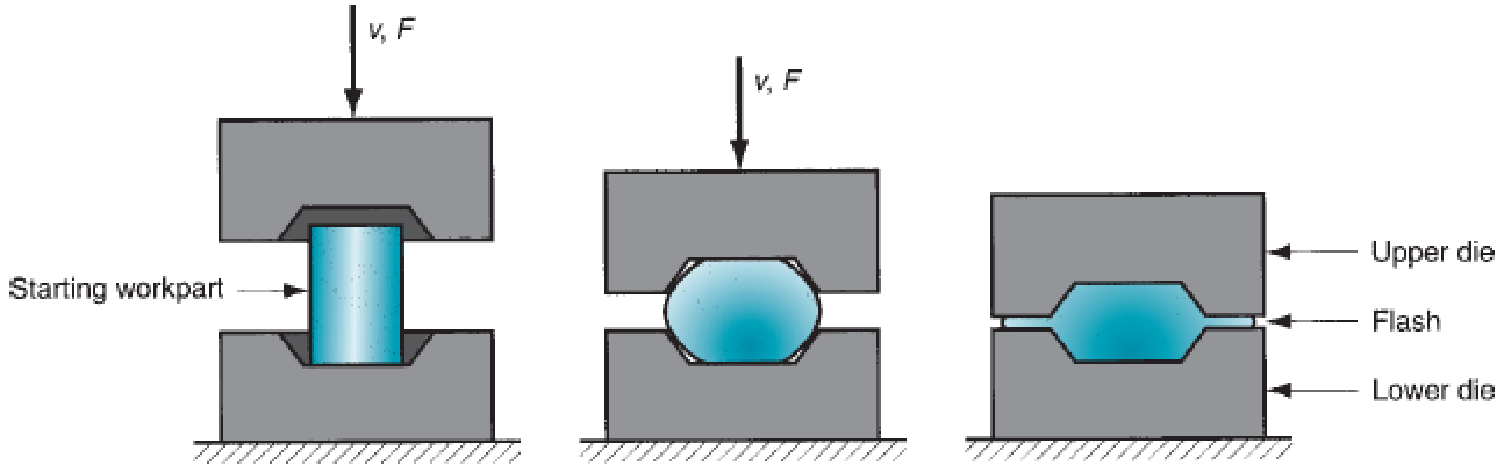
Frictionless compression

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 **Starting stage** **Final stage with flash formation**

Closed die forging (continue..)

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		

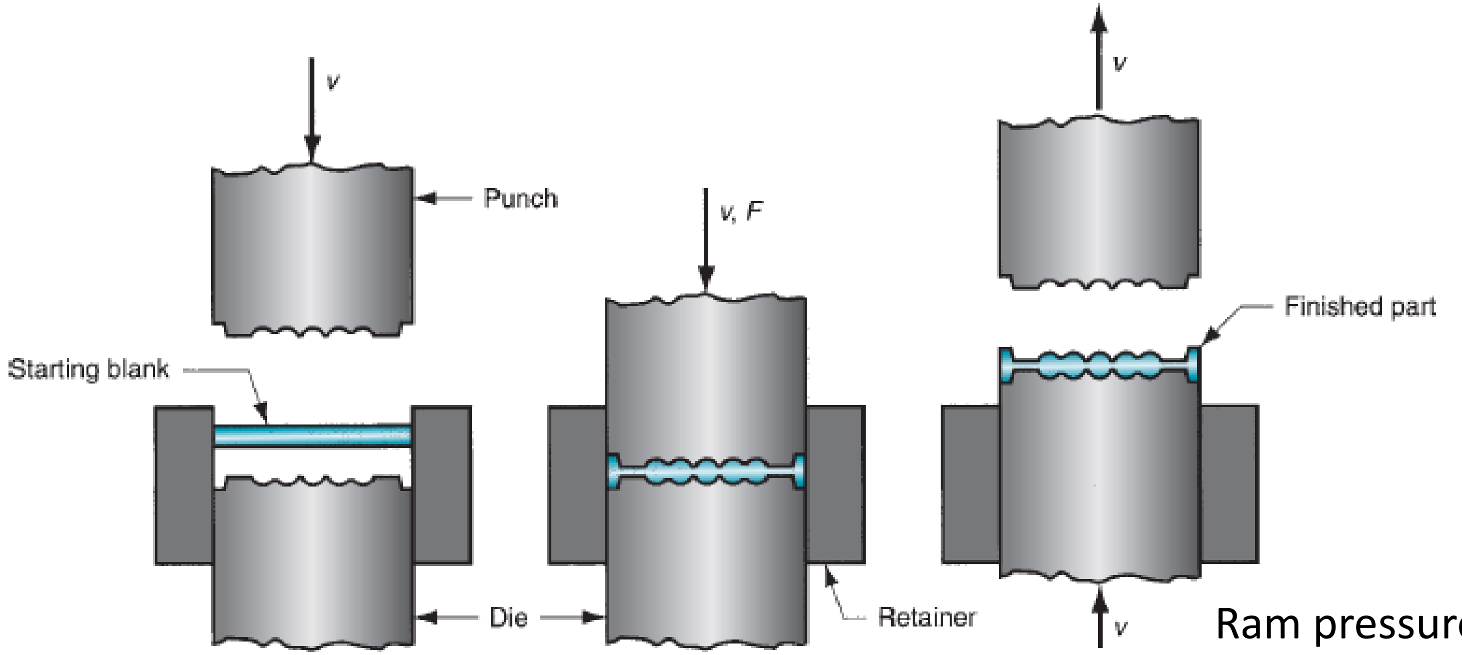
Impression die forging is not capable of making close tolerance objects. Machining is generally required to achieve the accuracies needed. The basic geometry of the part is obtained from the forging process, with subsequent machining done on those portions of the part that require precision finishing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

Coining

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

Forging hammers

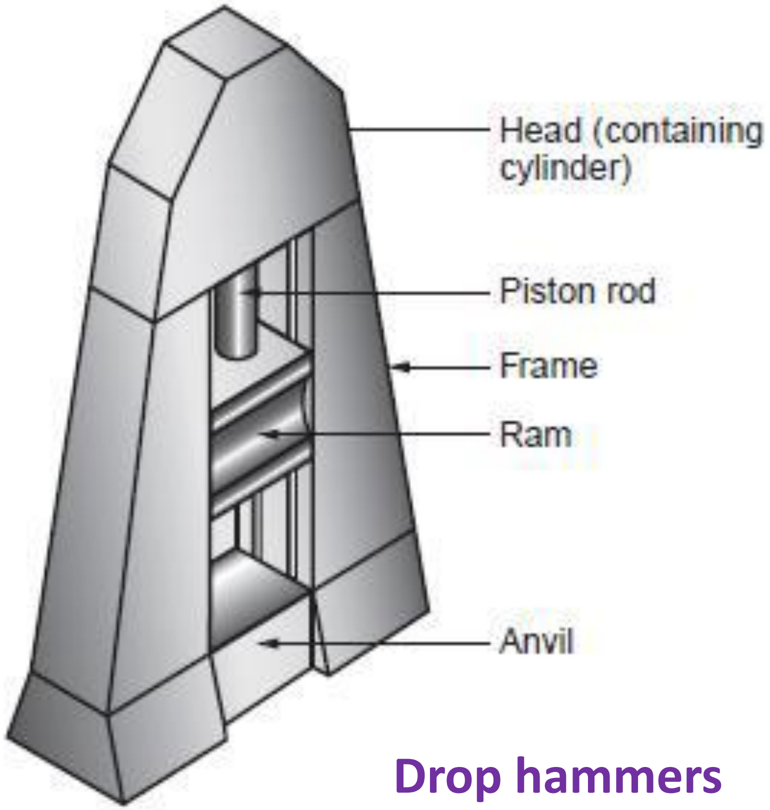
Hammers operate by applying an impact loading on the work piece. This is also called as drop hammer, owing to the means of delivering impact energy.

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

Forging Presses

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

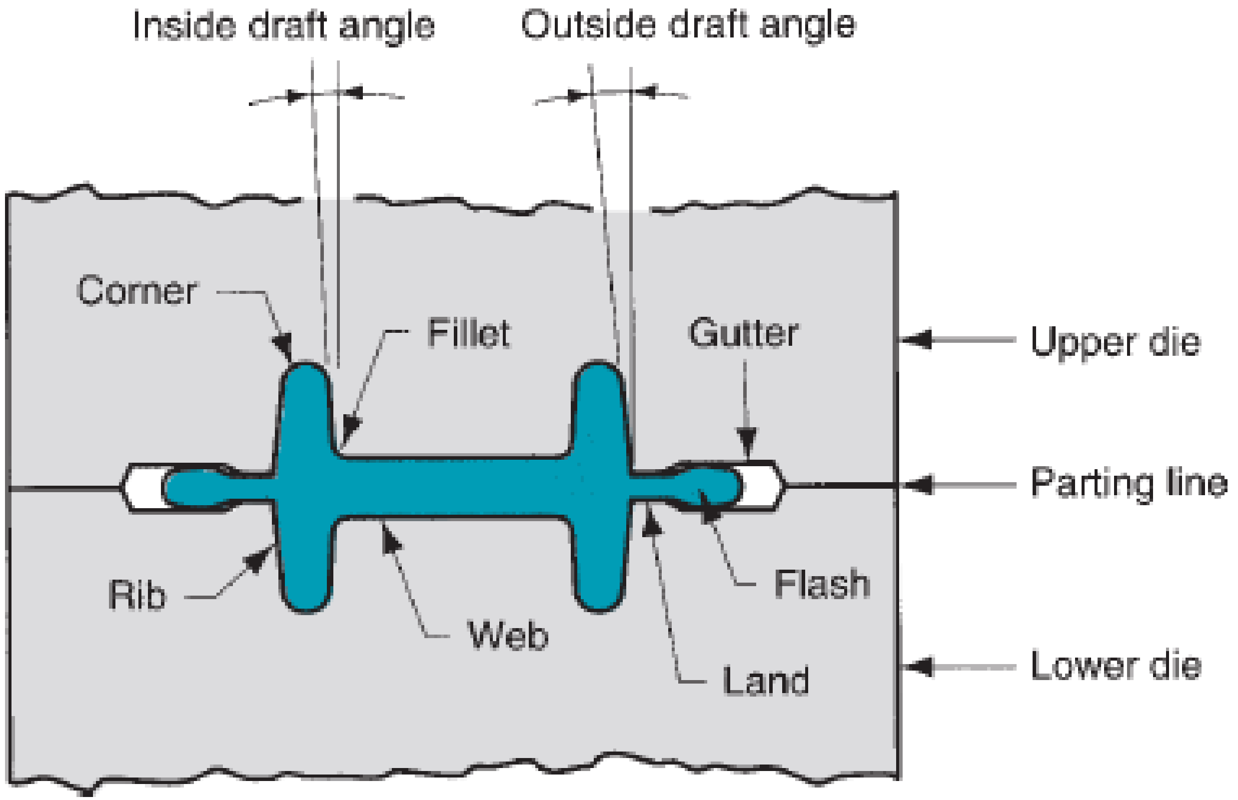
Mechanical presses: In these presses, the rotating motion of a drive motor is converted into the translation motion of the ram. They operate by means of eccentrics, cranks, or knuckle joints. Mechanical presses typically achieve very high forces at the bottom of the forging stroke.

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



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.

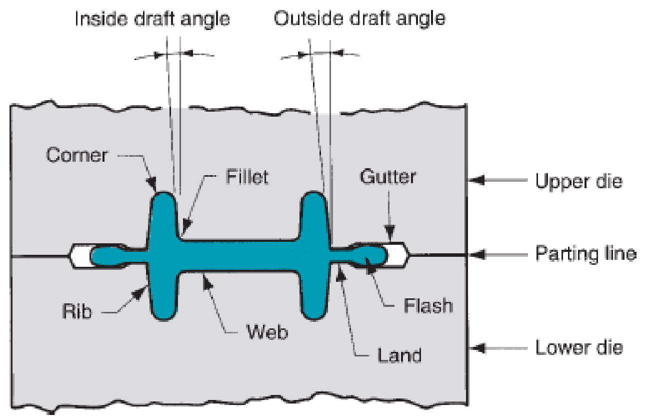
Draft: It is the amount of taper given on the sides of the part required to remove it from the die.

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.

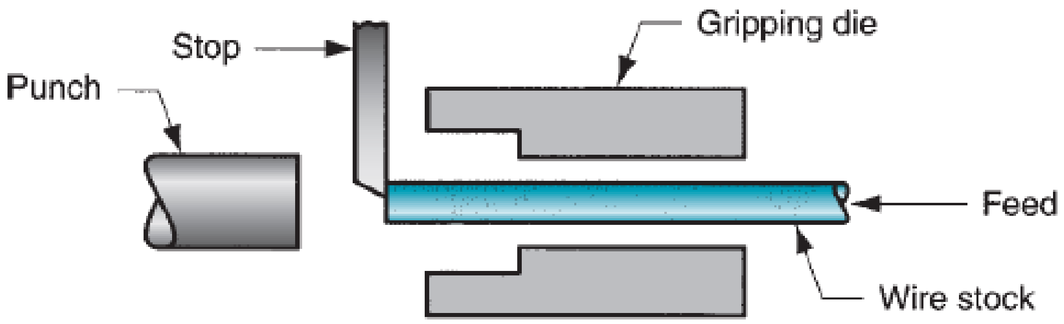
Fillet and corner radii: Small radii limits the metal flow and increase stresses on die surfaces during forging.

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

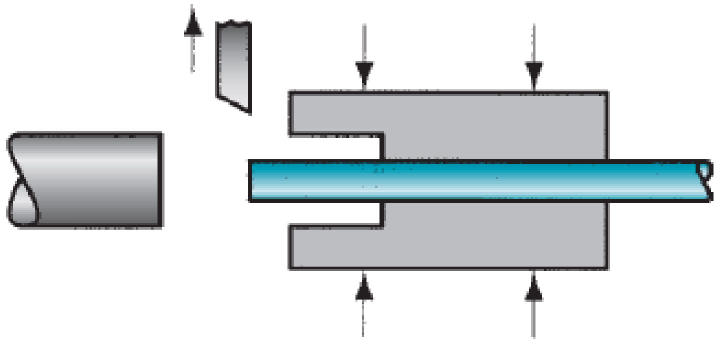


Upset forging

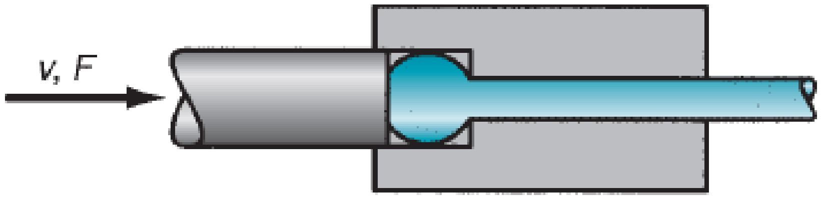
- It is a deformation operation in which a cylindrical work piece is increased in diameter with reduction in length. In industry practice, it is done as closed die forging.
- Upset forging is widely used in the fastener industries to form heads on nails, bolts, and similar products.



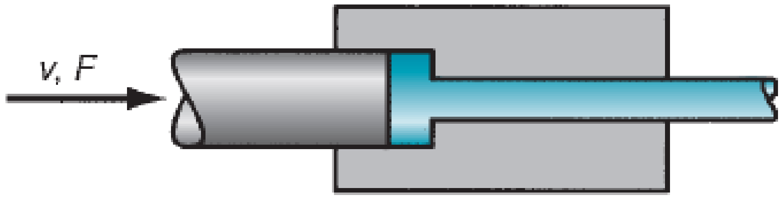
Feeding of work piece



Gripping of work piece and retracting of stop



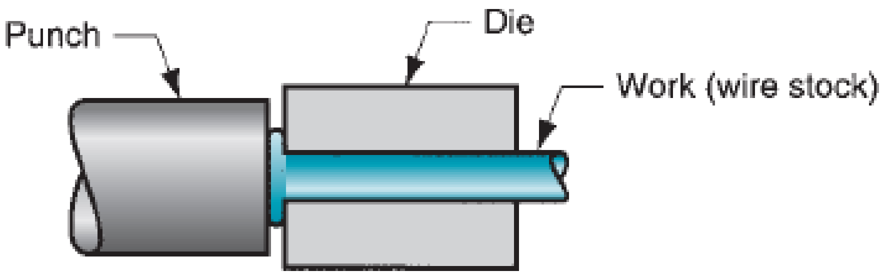
Forward movement of punch and upsetting



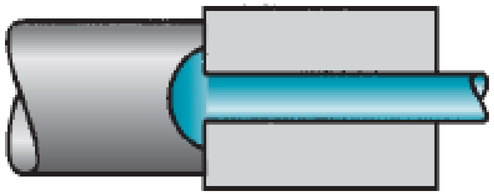
Forging operation completes

Heading

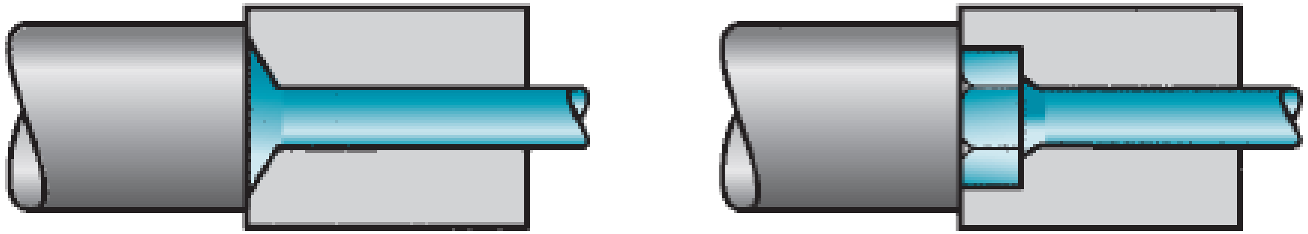
heading operations with different die profiles



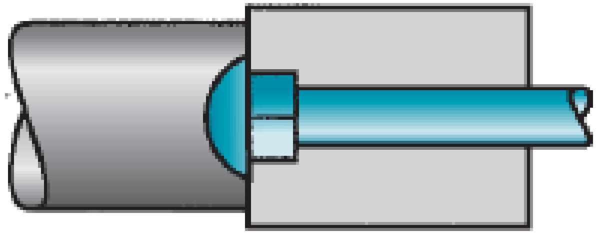
Heading a die using open die forging



Round head formed by punch only



Head formed inside die only



Bolt head formed by both die and punch

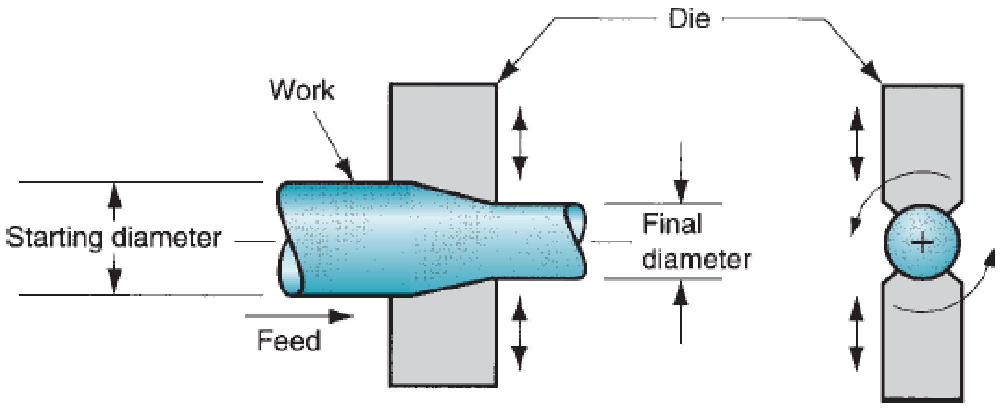
- Long bar stock (work piece) is fed into the machines by horizontal slides, the end of the stock is upset forged, and the piece is cut to appropriate length to make the desired product.
- The maximum length that can be upset in a single blow is three times the diameter of the initial wire stock.

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.

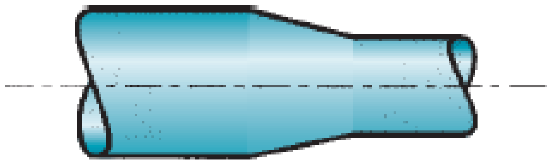
A mandrel is required to control the shape and size of the internal diameter of tubular parts during swaging.



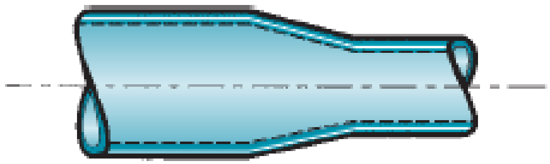
Swaging

Radial forging:

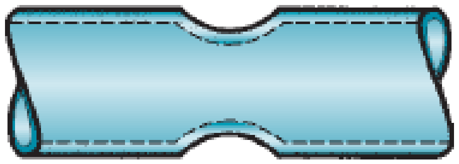
This operation is same as swaging, except that in radial forging, the dies do not rotate around the work piece, instead, the work is rotated as it feeds into the hammering dies.



Diameter reduction of solid work



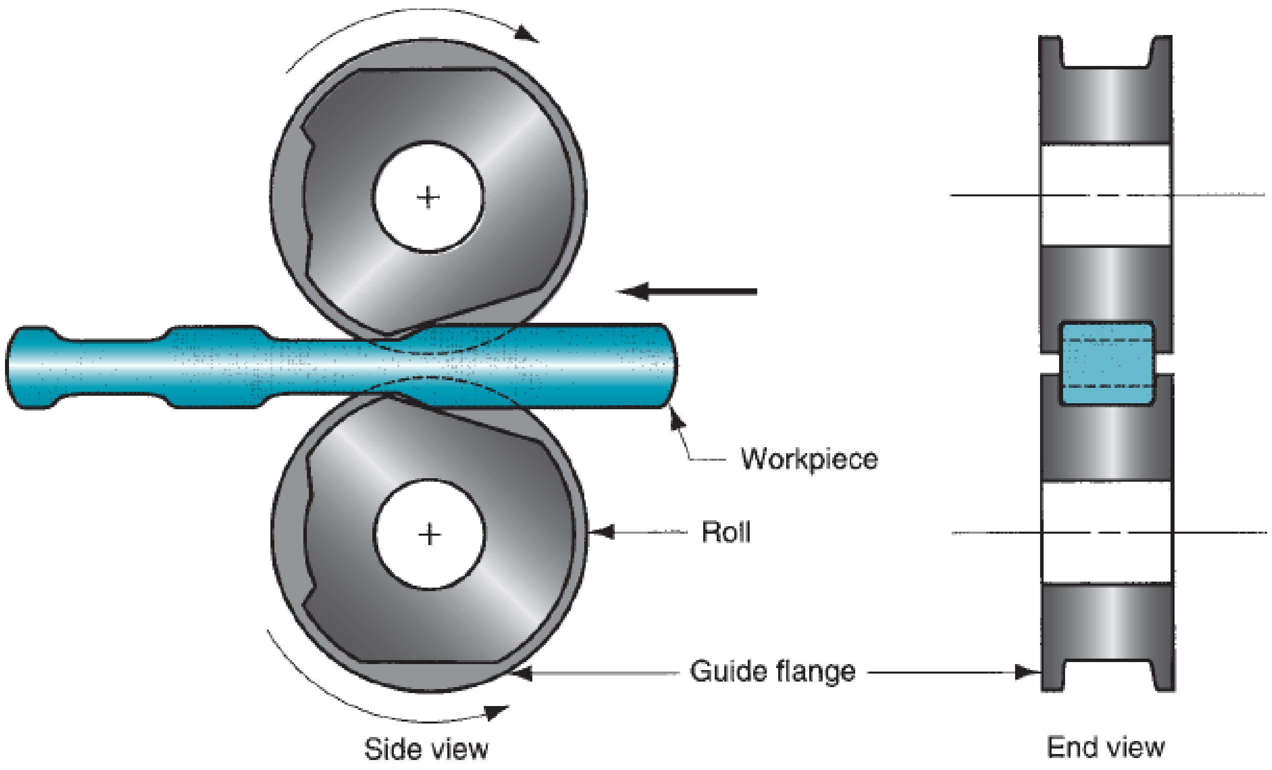
Tube tapering



Swaging to form a groove on the tube

Orbital 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.

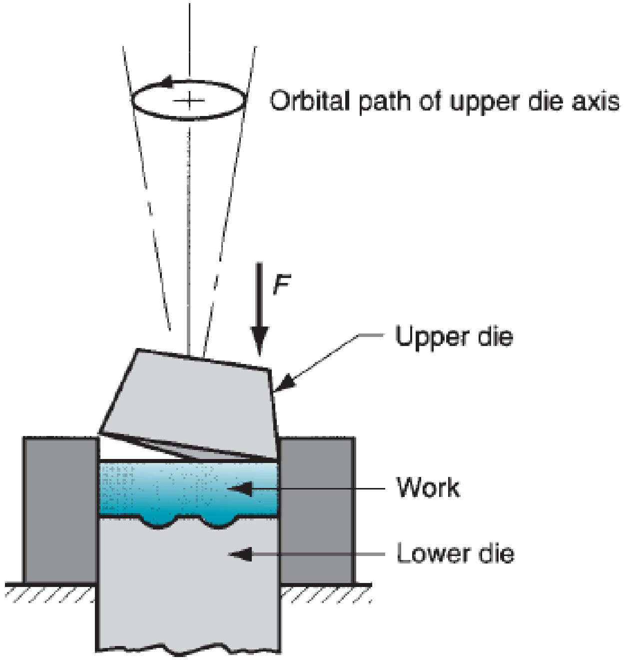
Roll-forged parts are generally stronger and possess desired grain structure compared to machining that might be used to produce the same part.

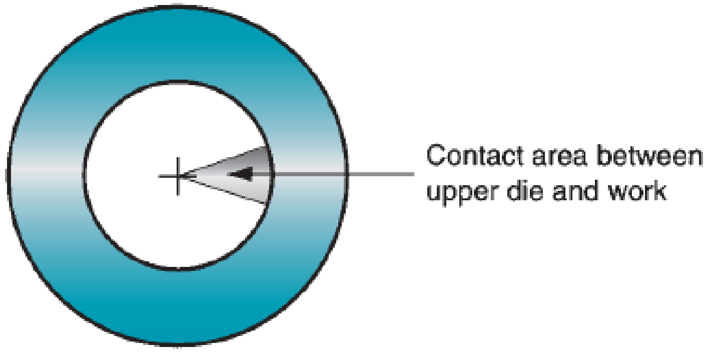
Orbital forging

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 workpiece 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.

Forging in Plane Strain

Reference: Dieter Section 16.3

Open Die forging

Dieter: Sec16.4

OPEN – DIE FORGING

Typically deals with large, relatively simple shapes that are formed between simple dies in a large hydraulic press or power hammer.

Parts made : Ship propeller shafts, rings, gun-tubes, pressure vessel etc.

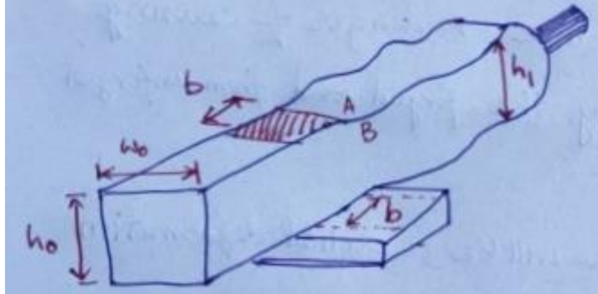
Workpiece usually larger than the tool → Deformation confined to a small portion of workpiece.

Deformation is mainly by compression accompanied by spreading in the lateral directions.

Simplest open die forging → Cogging a billet between flat tools to reduce the cross-sectional area, without changing the final shape of the cross section.

Open Die forging

Coefficient of spread $S = \left(\frac{\text{width elongation}}{\text{thickness Contraction}}\right) = \frac{\ln(w_1/w_0)}{\ln(h_0/h_1)}$ — (1)



- ~~with~~ Width natural strain is difficult to measure due to barreling of the bar but increase in length can be measured accurately

- From vol^m constancy

$$\frac{h_1 w_1 l_1}{h_0 w_0 l_0} = 1 \quad \text{—— (2)}$$

$$\text{or} \quad \ln\left(\frac{h_1}{h_0}\right) + \ln\left(\frac{w_1}{w_0}\right) + \ln\left(\frac{l_1}{l_0}\right) = 0$$

Substituting in Eq^n (1) gives coefficient of elongation

$$(1-S) = \left(\frac{\text{length Elongation}}{\text{thickness Contraction}}\right) = \left[\frac{\ln(l_1/l_0)}{\ln(h_0/h_1)}\right] \quad \text{—— (3)}$$

$S = 1$ all of the deformation could manifest itself as spread

$S = 0$ " " " " would go into elongation.

Eq^n (1) often expressed in terms of "Spread law"

$$\beta = \left(\frac{1}{\gamma}\right)^S \qquad \beta = \text{Spread ratio} = (w_1/w_0)$$

$$\gamma = \text{Squeeze ratio} = (h_1/h_0)$$

'S' chiefly depends on bite ratio (b/w_0) as

$$S = \left[\frac{(b/w_0)}{1+(b/w_0)}\right]$$

Open Die forging

In open-die forging, only that part of the surface under the bite is being deformed at any one time → danger of causing surface laps at the step separating the forged ~~and~~ from unforged portion of the workpiece.

For a given geometry of tooling there will be a critical deformation which will produce lap.

Recommended squeeze ratio (h_0/h_1) less than 1·3.

Open die forging frequently done on large sections

↓

Therefore it is important to ensure that the billet is deformed through to the centre

Bite ratio $(b/h) < 1/3$ is recommended to minimize inhomogeneous deformation.

Open Die forging

Load required to forge a flat section open-die forging (P):

$$\boxed{P = \bar{\sigma} A C}$$

C = constraint factor, allow for inhomogeneous deformation

Deformation resistance increases with $\Delta = h/L$

Hill, constructed slip lines field for forging with various Δ &

summarize that

$$\boxed{\begin{array}{l} C = (0.8 + 0.2\, h/b) \\ C = (0.8 + 0.2\, \Delta) \end{array}}$$

Closed Die forging

- Reference: DIETER: 15.6
- Die quenching
- Load requirement

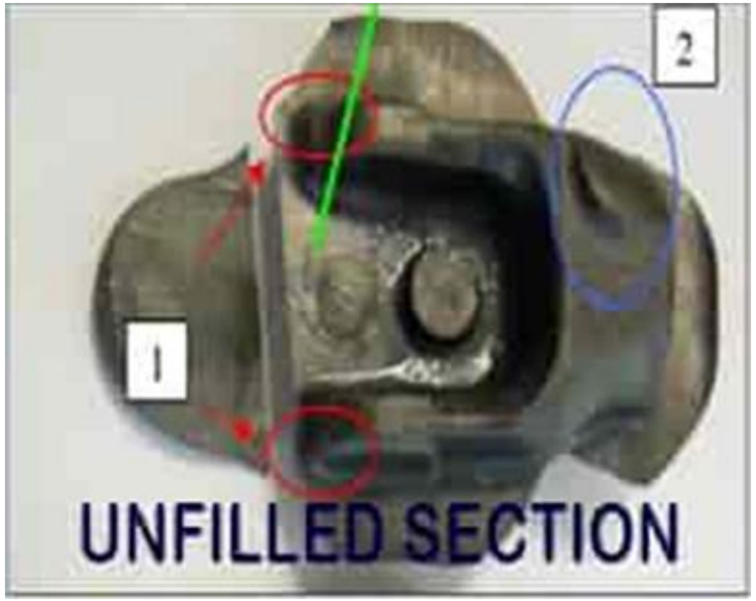
Defects in Forging

Incomplete filling of dies:

Undersize of forging due to less amount of metal.

It is caused by an insufficient amount of metal, insufficient number of blows, incorrect die design or low temperature of stock.

Remedy: Ingot size must be sufficient, hammering should be done properly, die should be designed correctly and the temperature of stock should be sufficient



Defects in Forging

Cold Shut

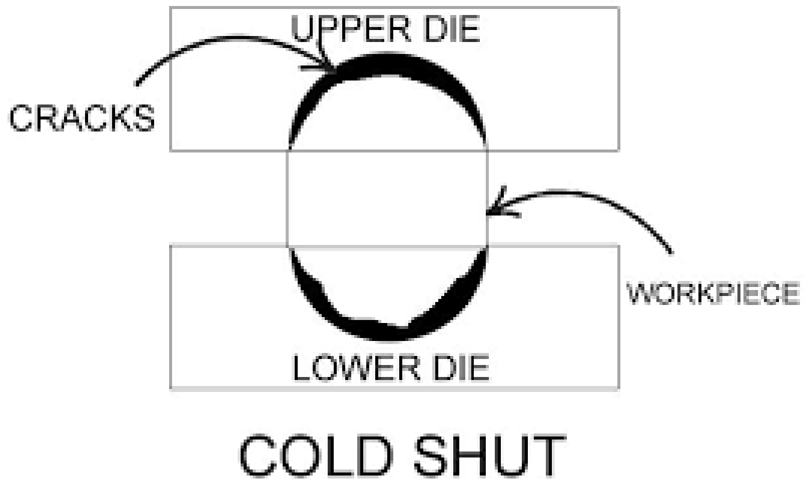
Short cracks at corners and at right angles to the surface of forging.

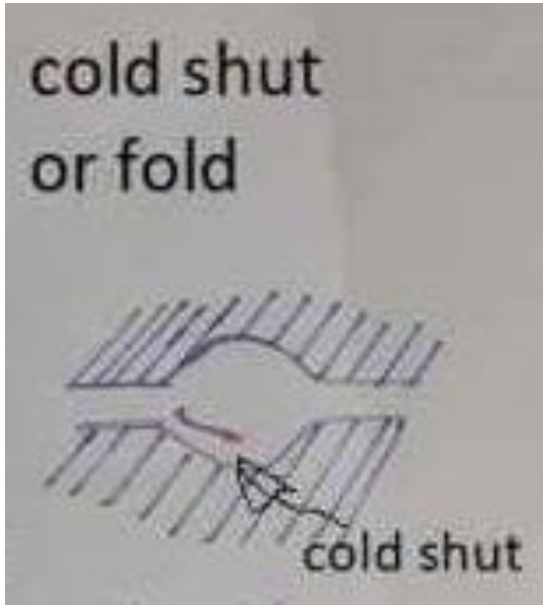
It is caused due to metal surface folding against itself during forging.

This is caused mainly by the improper design of the die. Where in the corner and the fillet radii are small as a result of which metal does not flow properly into the corner and the ends up as a cold shut.

Cause: Sharp corner (less fillet), excessive chilling, high friction

Remedy: increase fillet radius on the die





Defects in Forging

Incomplete forging penetration:

The dendritic ingot structure at the interior of forging is not broken. Actual forging takes place only at the surface.

Cause: Use of light rapid hammer blows

Remedy: To use forging press for full penetration.

Die Shift

Die shift is caused by the misalignment of the top and the bottom dies making the two halves of the forging to be the improper shape.

Remedy: Proper mechanism should be used to avoid mismatching

Defects in Forging

Scale Pits

Scale pits are seen as irregular deputations on the surface of the forging that is caused primarily due to improper cleaning of the stock used for forging. The oxide and scale get embedded into the finish forging surface. When the forging is cleaned by pickling, these are seen as deputations on the forging surface.

Small pits (Depressions) on the surface. It is caused by scale. When scales are removed from the surface, depressions remain which are known as scale pits. This is seen as irregular depurations on the surface of the forging.

This is primarily caused because of improper cleaning of the stock used for forging. The oxide and scale get embedded into the finish forging surface. When the forging is cleaned by pickling, these are seen as depurations on the forging surface.

Remedy: Pure ingots should be selected and dies must be cleaned properly before the operation.

Scale pockets and underfills:

- They are loose scale/ lubricant residue which accumulates in deep recesses of the die.
- Cause: Incomplete descaling of the work
- Remedy: Proper decaling of work prior to forging

Defects in Forging

Surface Cracking

– Cause: Excessive working on the surface and too low temperature. High sulfur in furnace leading to hot shortness

– Remedy: To increase the working temperature

Cracking at the flash:

– This crack penetrates into the interior after flash is trimmed off.

– Cause: Very thin flash

– Remedy:-Increasing flash thickness, relocating the flash to a less critical region of the forging, hot trimming, and stress relieving.

Internal cracks

Cause: Secondary tensile stresses developed during forging

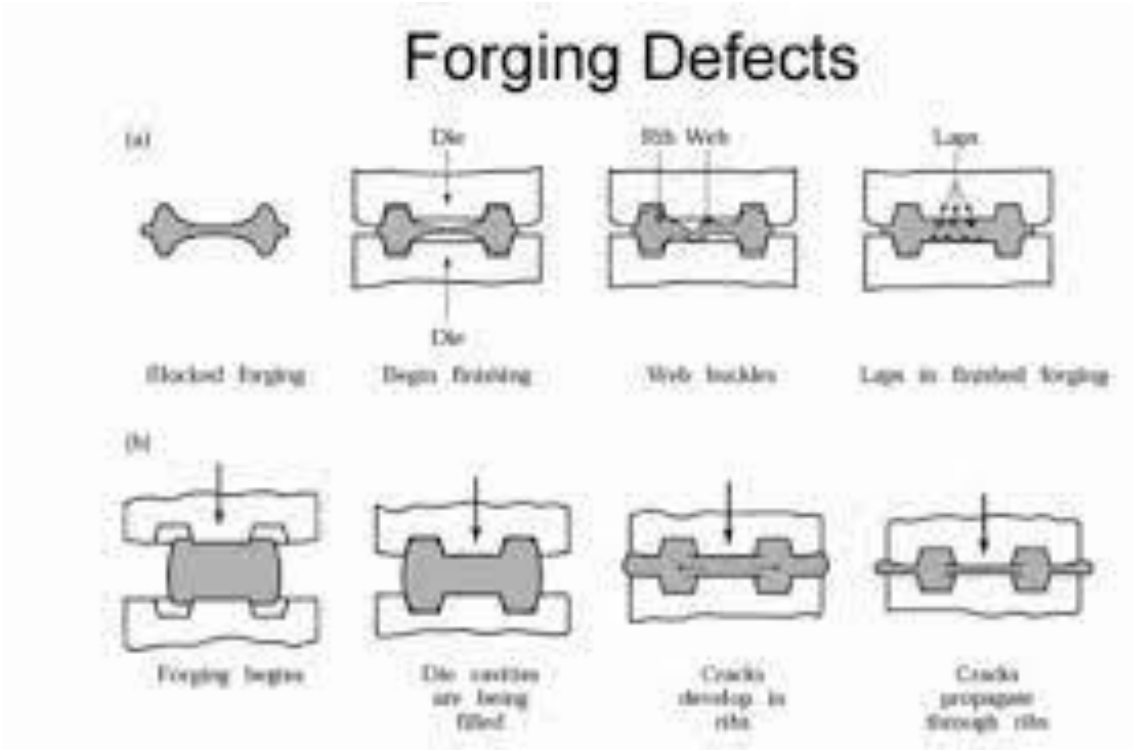
Remedy: Proper die design

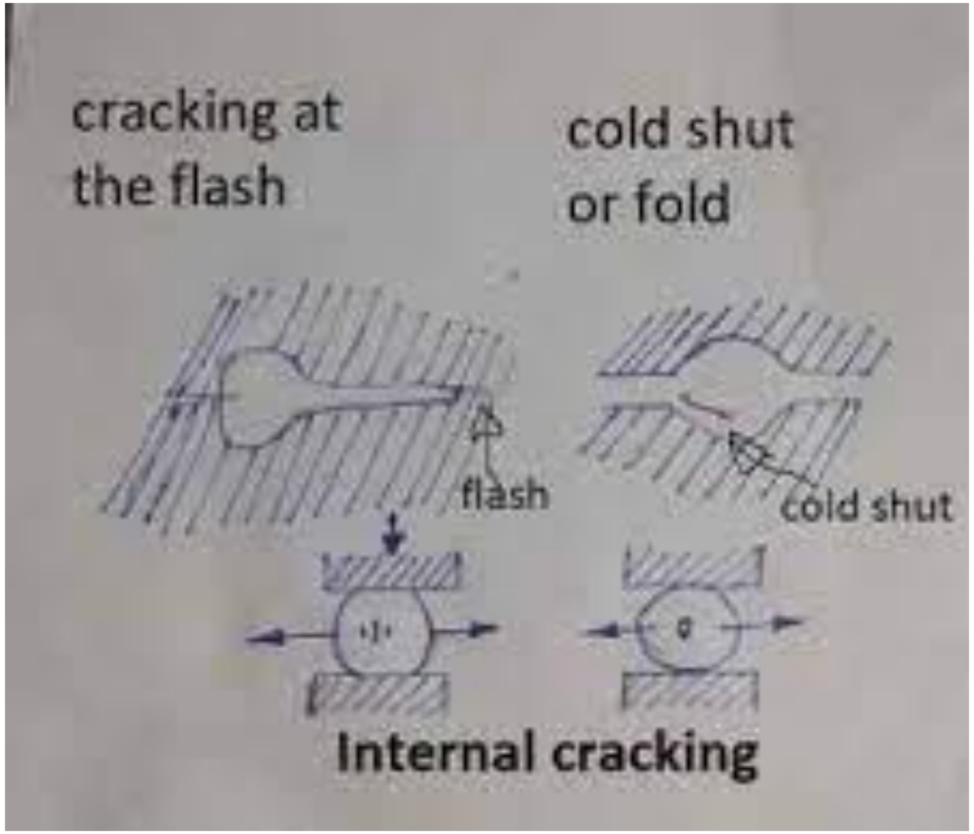
Dents:

Dents are the result of careless work.

Flakes:

These are basically internal ruptures caused by the improper cooling of the large forging. Rapid cooling causes the exterior to cool quickly causing internal fractures. This can be remedied by following proper cooling practices.


Forging Defects
(a)
Die
Rib Web
Laps
Die
Blocked forging
Begin finishing
Web buckles
Laps in finished forging
(b)
Forging begins
Die cavities are being filled
Cracks develop in ribs
Cracks propagate through ribs

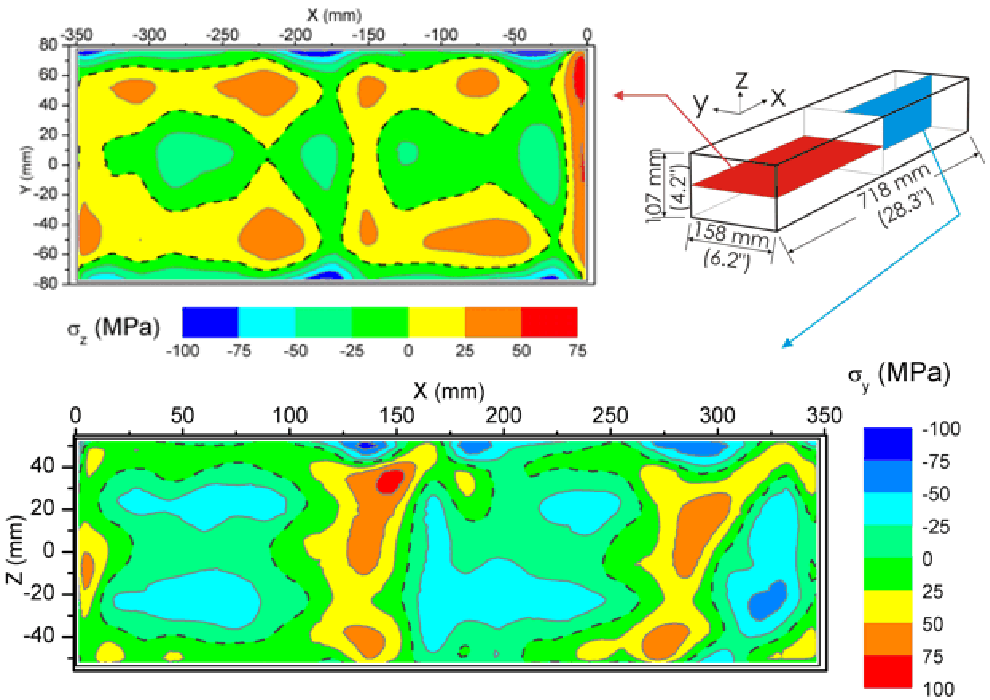

cracking at the flash
cold shut or fold
flash
cold shut
Internal cracking

Defects in Forging

Residual stress in forging

Residual stress problems is generally occurs in cold working forging. When forging workpiece not properly cooled that time residual stress occurs in forging.

Residual stress is reduced when workpiece is heated upto recrystallization temperature and then cool slowly.



Cold-Compressed Aluminum Forgings
Courtesy: https://www.lanl.gov/contour/forgings.html

Remedies for Forging Defects

Defects in forging can be removed as follows:

- Surface cracks and decarburized areas are removed from forging parts by grinding on special machines. Care should also be taken to see that the job is not under heated, decarburized, overheated, and burnt.
- Shallow cracks and cavities can be removed by chipping out of the cold forging with a pneumatic chisel or with hot sets.
- The parting line of a forging should lie in one plane to avoid mismatching.
- Destroyed forgings are straightened in presses, if possible.
- Die design should be properly made taking into consideration all relevant and
- important aspects that may impart forging defects and ultimate spoilage
- The mechanical properties of the metal can be improved by forging to correct the fiber line.
- The internal stresses developed due to heating and cooling of the job can be removed by annealing or normalizing

Classification of residual stress measurement methods