Forging

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- Classification of forging processes
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- Closed die forging
- Plane strain forging analysis
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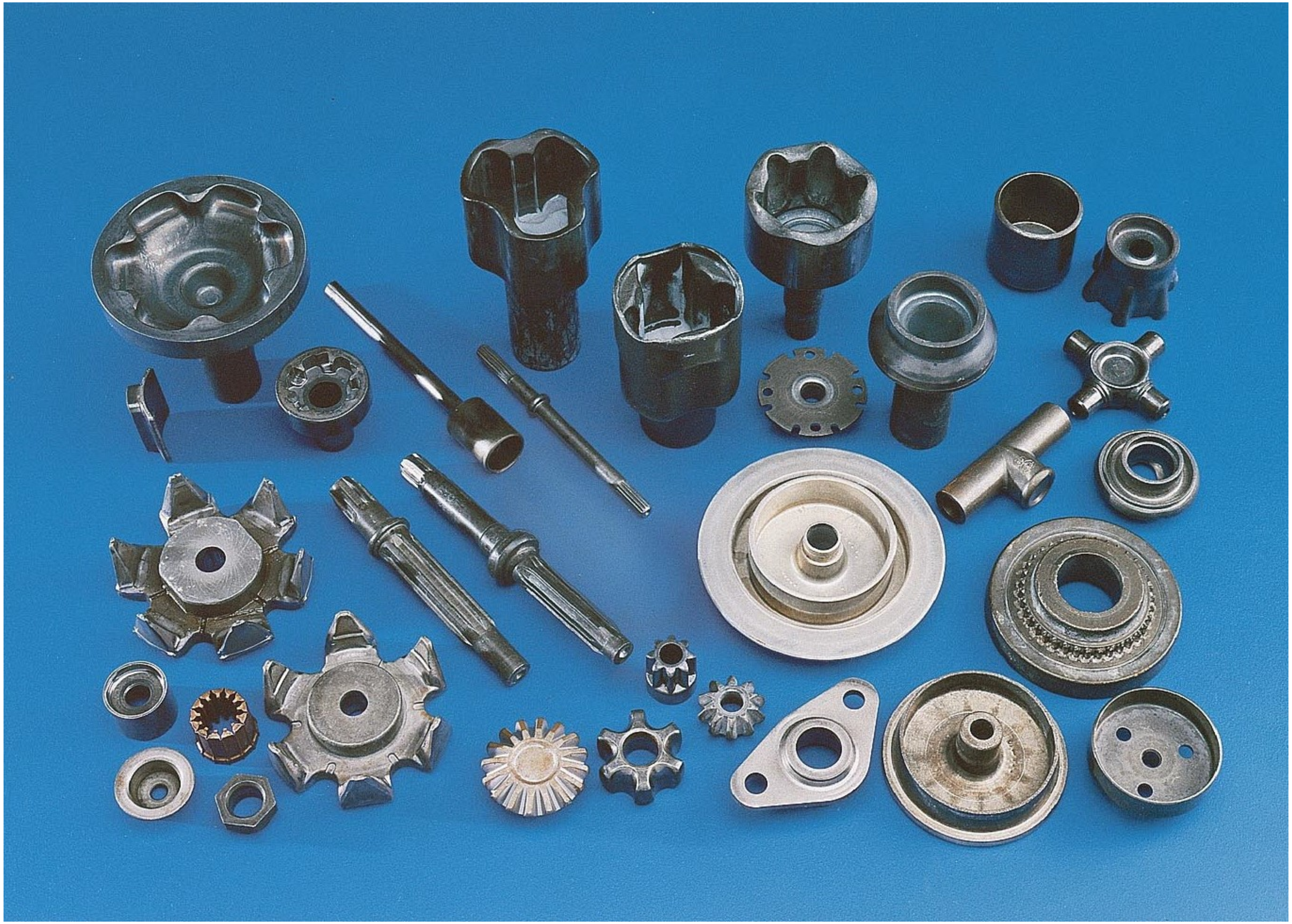
- Residual stresses in forging

Forging

- Forging is the working of metal into a useful shape by hammering or pressing.
- The oldest of the metalworking arts (primitive blacksmith).
- Replacement of machinery occurred during early the Industrial revolution.
- Forging machines are now capable of making parts ranging in size of a bolt to a turbine rotor.
- Most forging operations are carried out hot, although certain metals may be cold-forged.

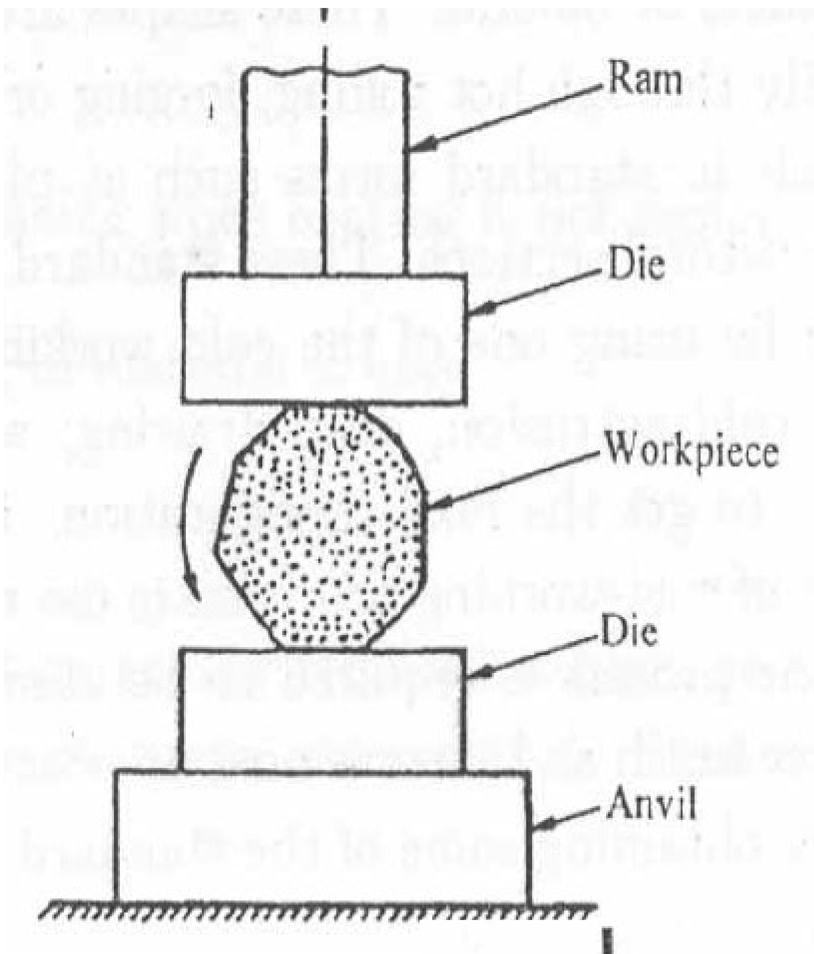
Range of cold, warm and hot forged parts



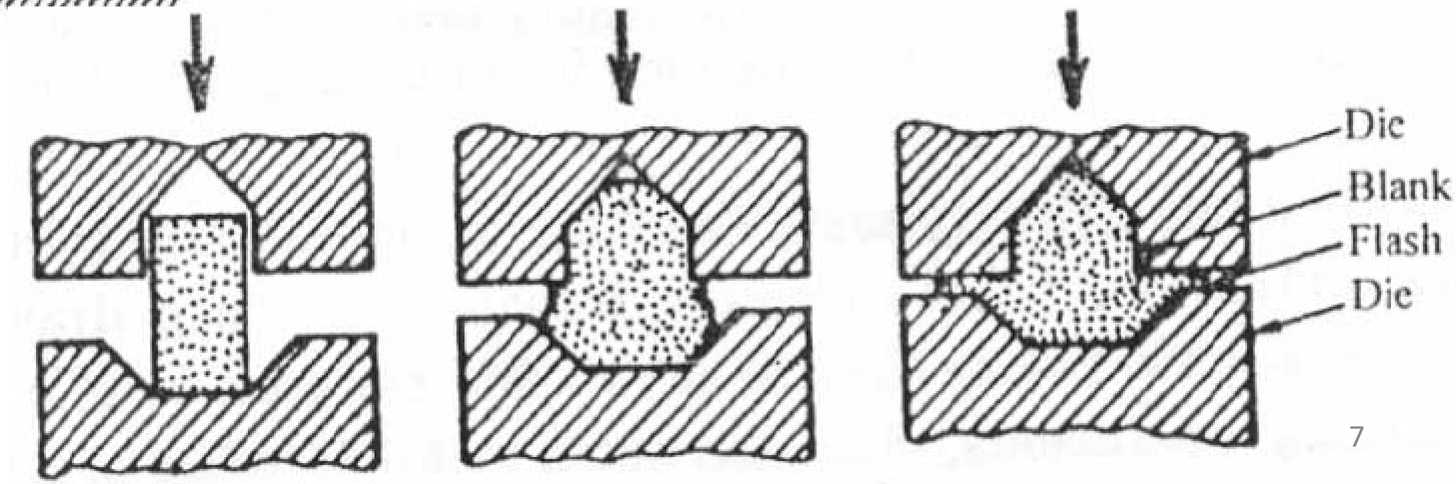
Examples such as coins, medals, cutlery and various hand tools, as well as cold-coined hot forged parts

- Forging is basically involves plastic deformation of material between two dies to achieve desired configuration. Depending upon complexity of the part forging is carried out as open die forging and closed die forging.
- In open die forging, the metal is compressed by repeated blows by a mechanical hammer or manually.
- In closed or impression die forging, the desired configuration is obtained by squeezing the workpiece between two shaped and closed dies.

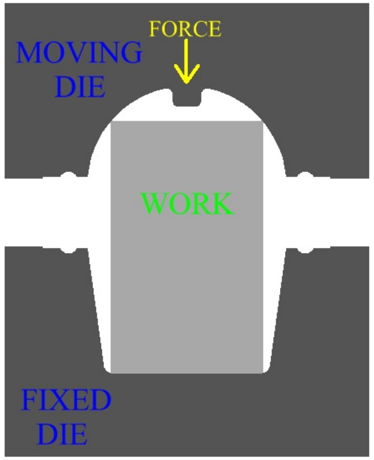
Open Die Forging

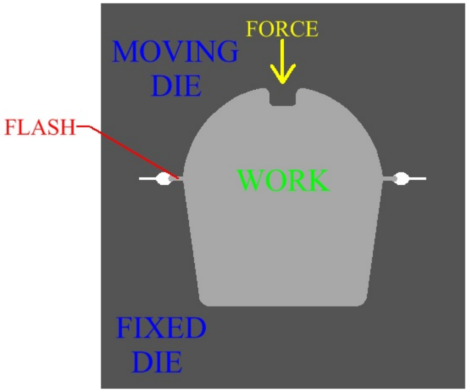


Closed Die Forging

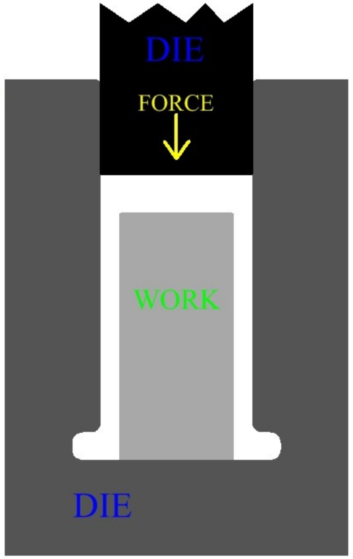


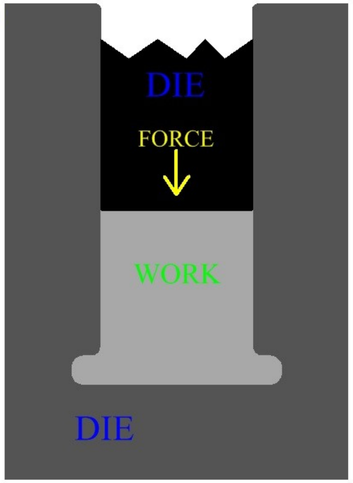
IMPRESSION DIE FORGING

1. 

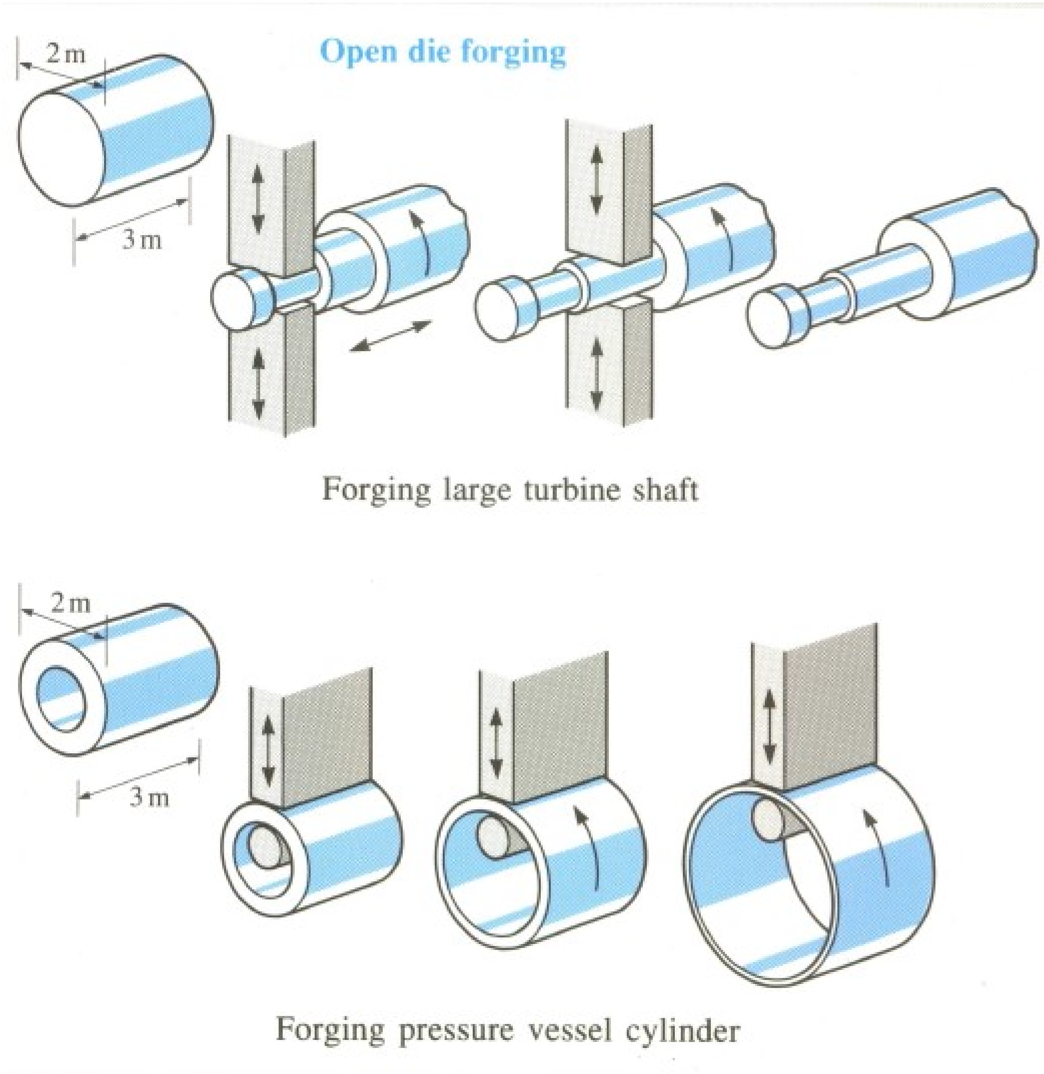
2. 

FLASHLESS FORGING

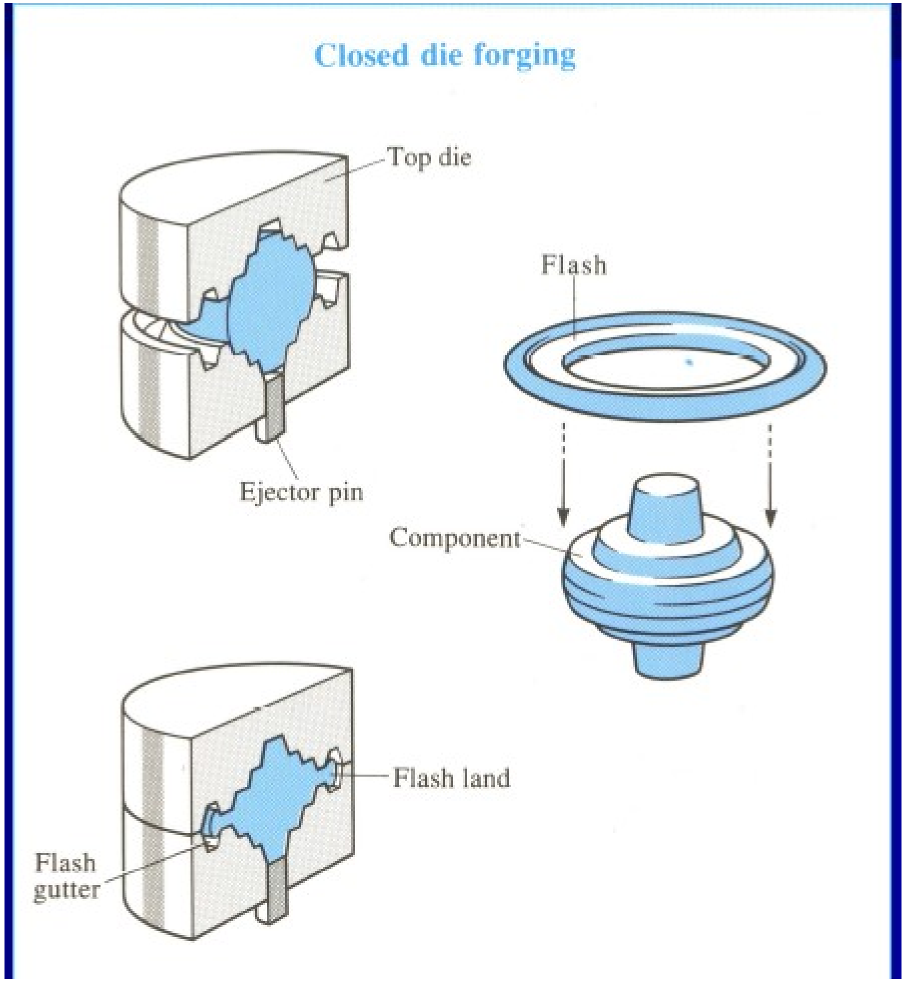
1. 

2. 

- Open-die forging is carried out between flat dies or dies of very simple shape.
- The process is used for mostly large objects or when the number of parts produced is small.
- Open-die forging is often used to preform the workpiece for closed-die forging.

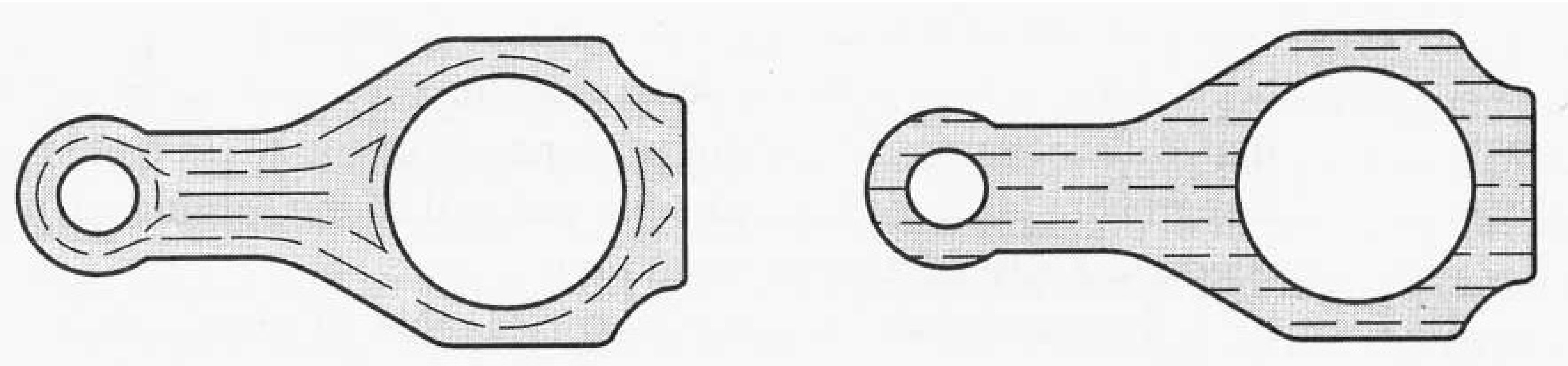


- In closed die forging, the workpiece is squeezed between two die halves which carry the impressions of the desired final shape.
- The workpiece is deformed under high pressure in a closed cavity.
- The process provide precision forging with close dimensional tolerance.
- Closed dies are expensive.



- On squeezing the die cavity gets completely filled and excess material comes out around the periphery of the die as flash which is later trimmed.
- Press forging and drop forging are two popular methods in closed die forging.
- In press forging the metal is squeezed slowly by a hydraulic or mechanical press and component is produced in a single closing of die, hence the dimensional accuracy is much better than drop forging.
- Both open and closed die forging processes are carried out in hot as well as in cold state.
- In forging favourable grain orientation of metal is obtained

Grain orientation in forging

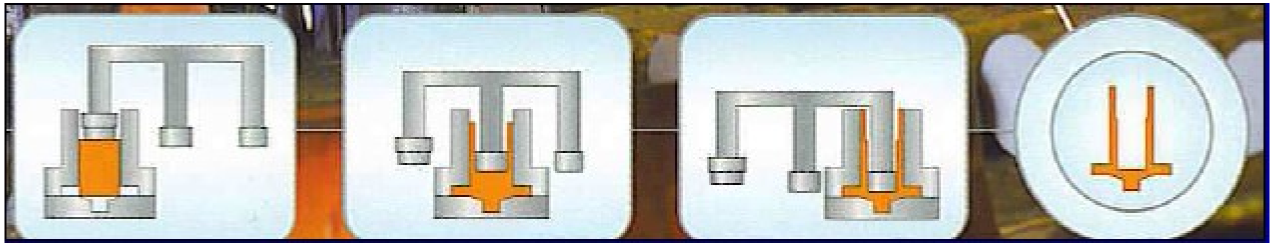


Forging

Machining

Closed Die Forging

Billet → Preshaped → Rough-forge → Finishing die → Trimming die → Final product



Flash is the excess metal, which squirts out of the cavity as a thick ribbon of metal.

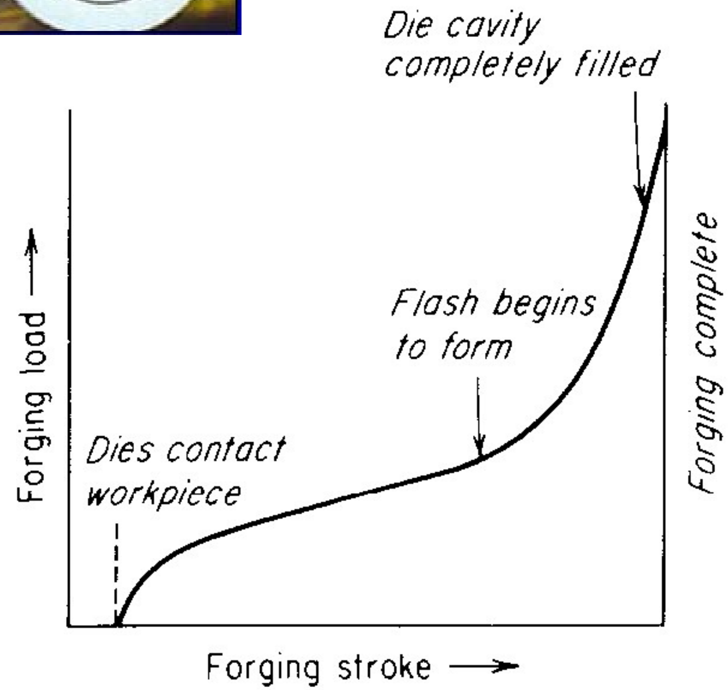
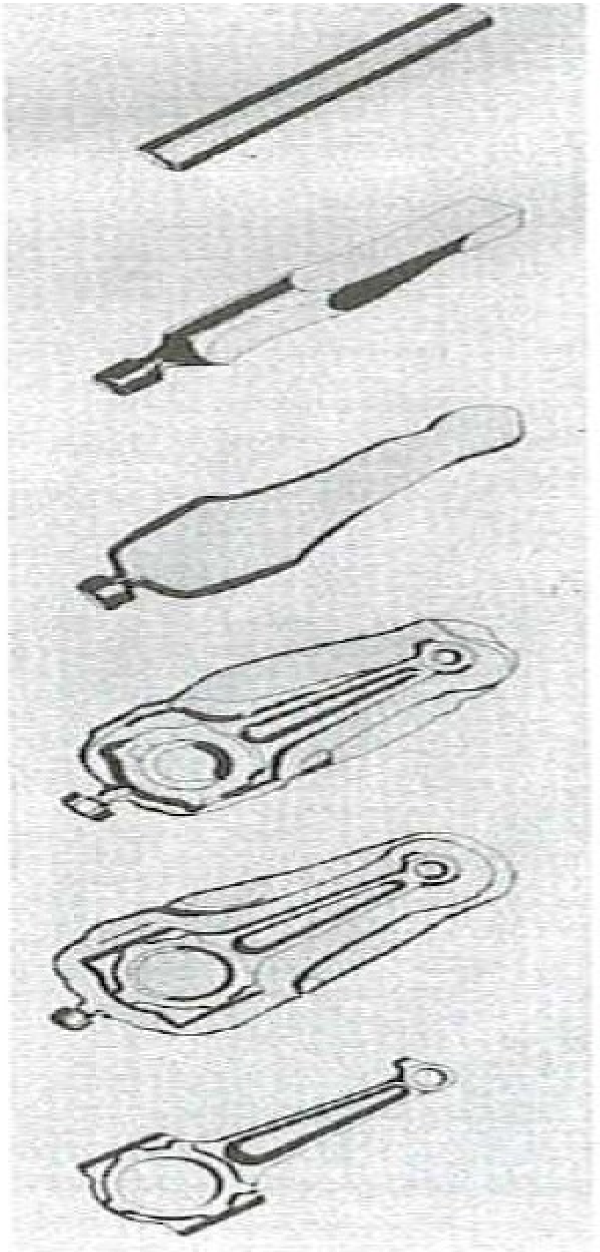


Figure: Typical curve of forging load vs. stroke for closed-die forging.

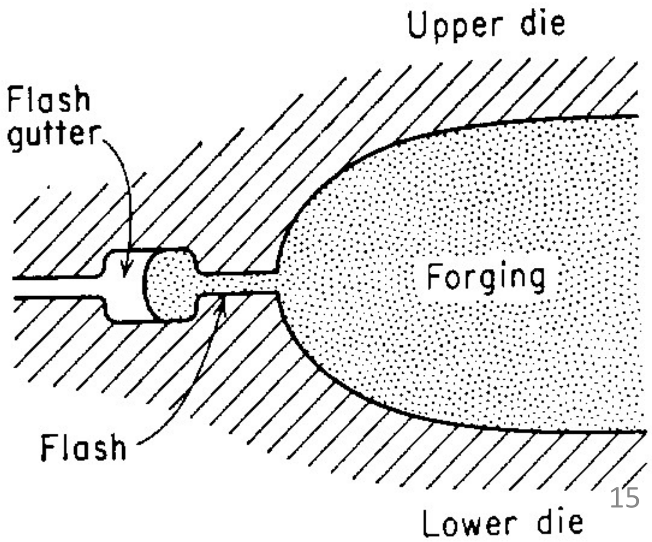


Functions of flash:

- Acts as a ‘safety value’ for excess metal
- Regulates the escape of metal
- Thin flash, builds up high pressure to ensure that the metal fills all recesses of the die cavity.

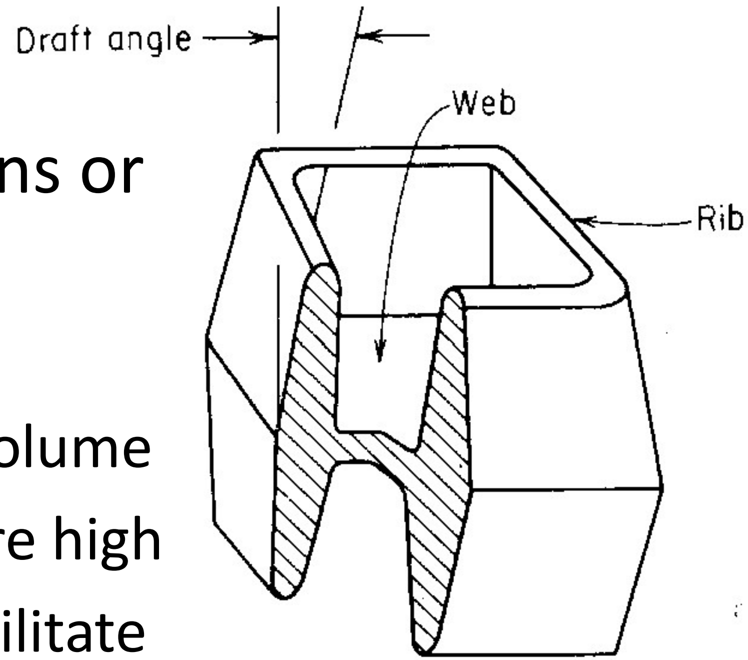
Flash gutter:

For wide flash, a ridge is provided

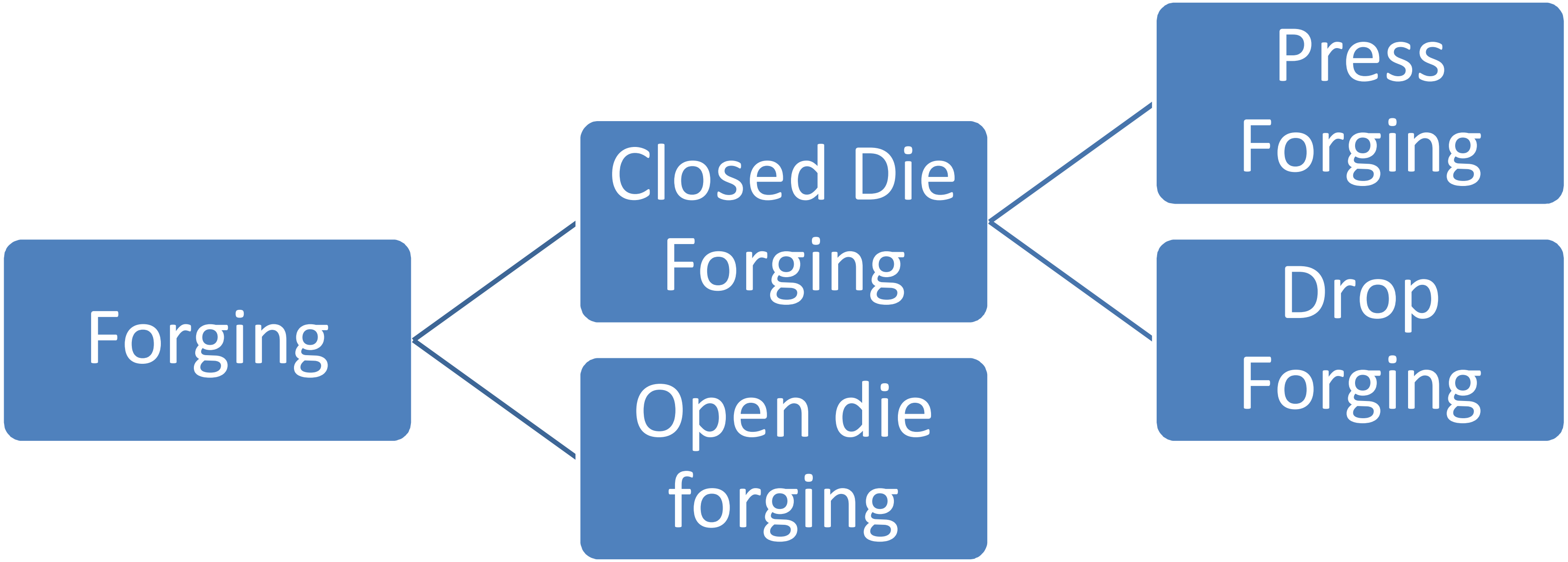


Metal flow is influenced by the part geometry.

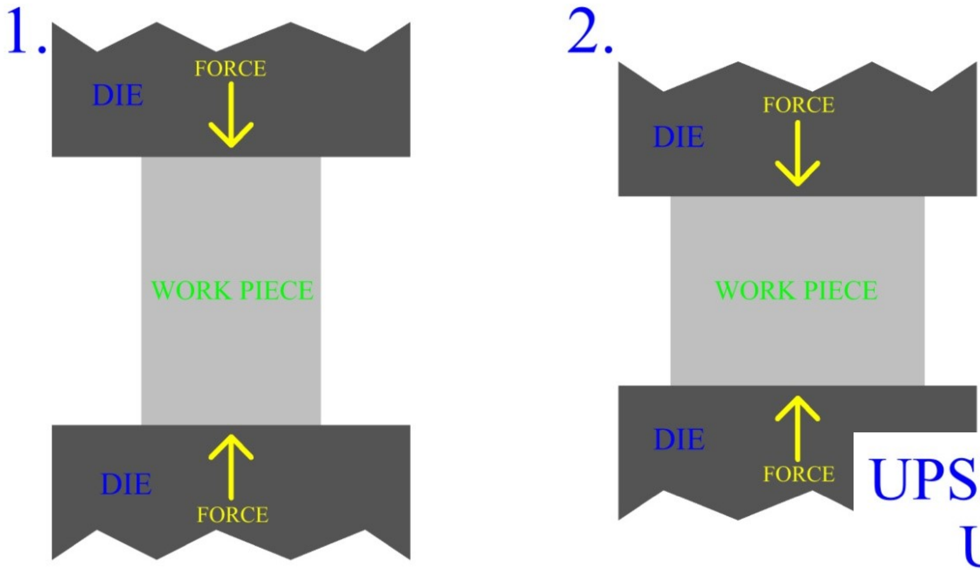
- Spherical and block like shapes are easy
- Shapes with thin and long sections or projections (ribs and webs) are difficult
  - due to high surface area per unit volume
  - Friction and temperature effects are high
  - Forging ties must be tapered to facilitate removal of the finished parts.
  - Draft allowance is ~5^0



Classification of Forging

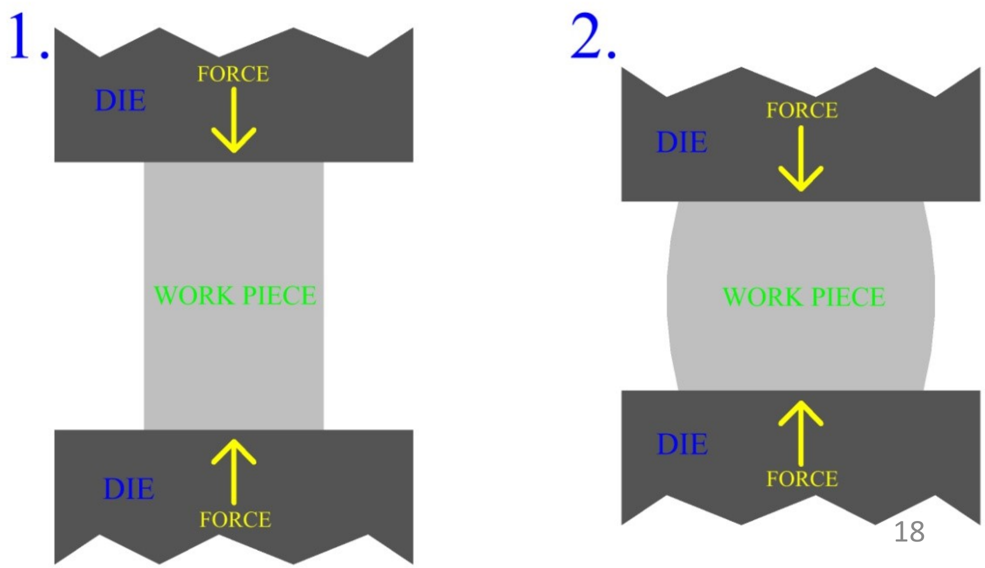


UPSETTING IN FLAT DIE FORGING UNDER IDEAL CONDITIONS



UPSETTING IN FLAT DIE FORGING UNDER REAL CONDITIONS

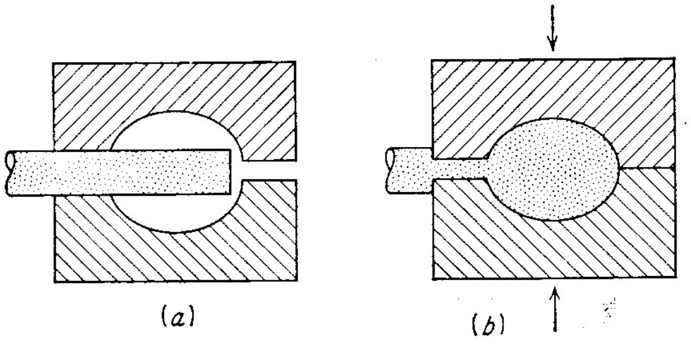
Metal will flow easily to the nearest free surface due to lowest frictional path



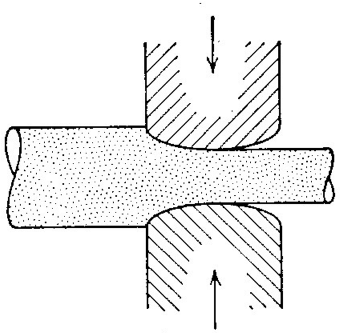
Types of Forging Operation

- Fullering
- Edging
- Cogging
- Upsetting
- Heading
- Swaging
- Radial forging etc.

Edging is used to shape the ends of the bars and to gather metal. The metal flow is confined in the horizontal direction but it is free to flow laterally to fill the die.



Drawing is used to reduce the cross-sectional area of the workpiece with concurrent increase in length.



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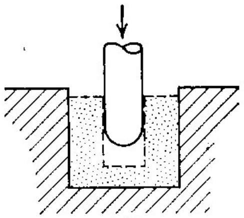

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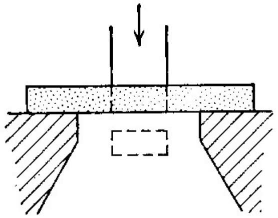
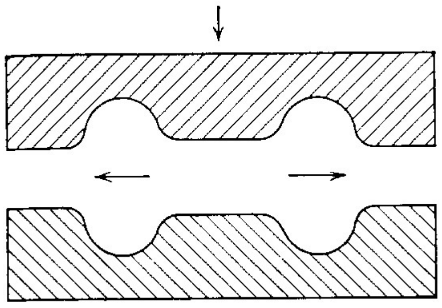


(g)

Piercing and punching are used to produce holes in metals.

Fullering is used to reduce the cross-sectional area of a portion of the stock. The metal flow is outward and away from the centre of the fuller. i.e., forging of connecting rod for an internal combustion engine.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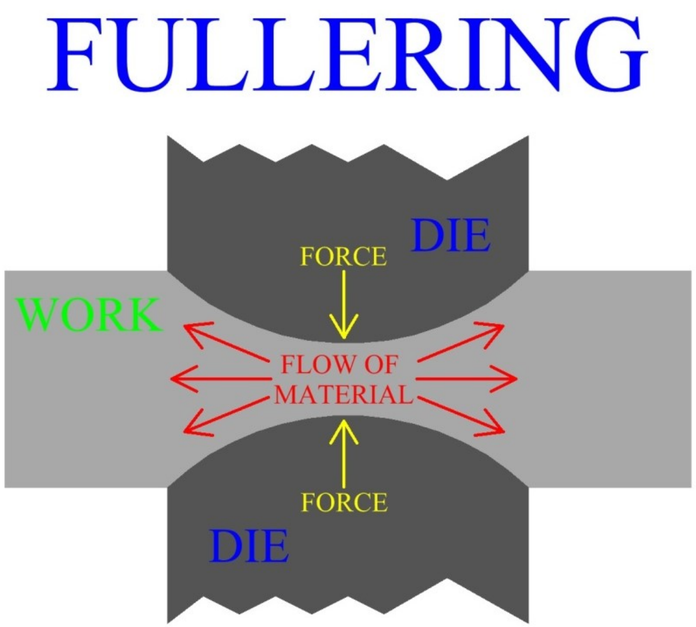
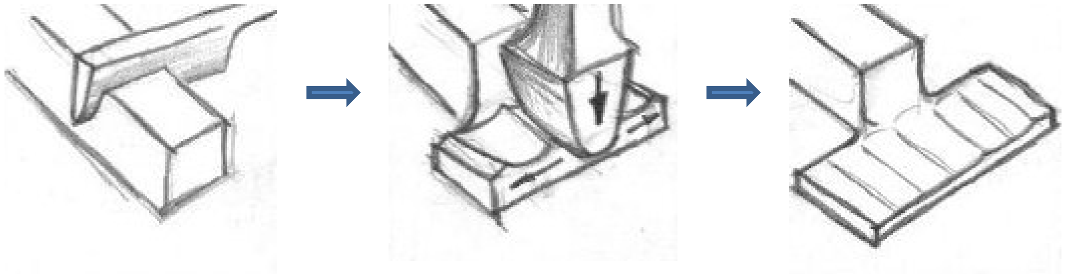
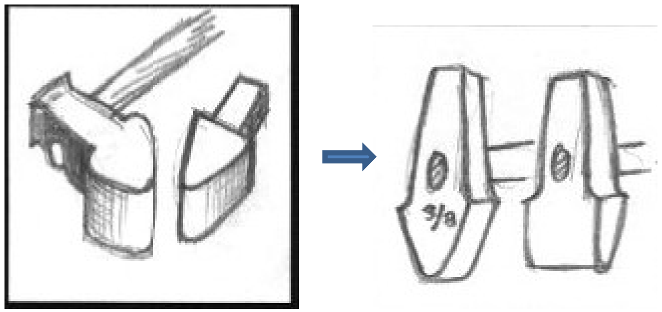


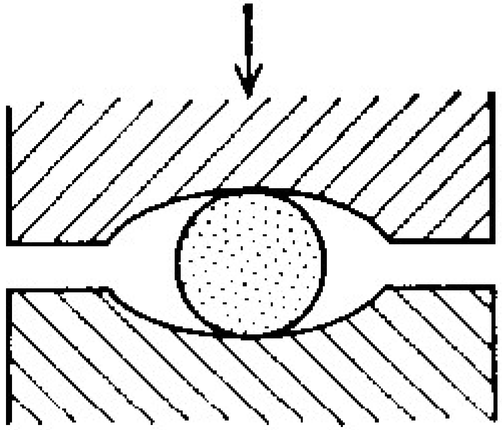
Fullers come in different shapes





Swaging is used to produce a bar with a smaller diameter (using concave dies).

- Swaging is a special type of forging in which metal is formed by a succession of rapid hammer blows
- Swaging provides a reduced round cross section suitable for tapping, threading, upsetting or other subsequent forming and machining operations.



(e)

Classification of Forging Process

By equipment

1) Forging hammer or drop hammer

2) Press forging

By process

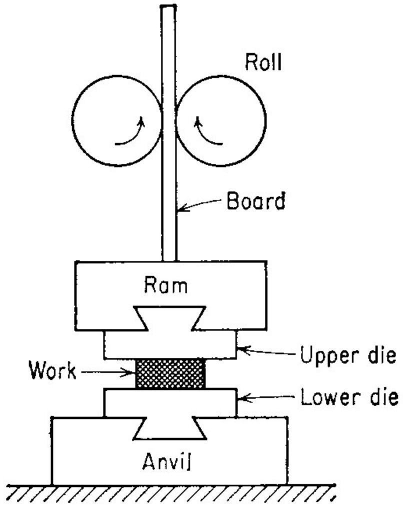
1) Open - die forging

2) Closed - die forging

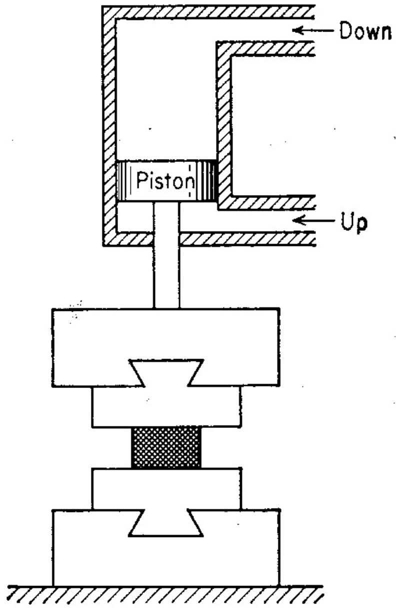
Hammer and press forging processes

- Forging hammers :
  - Forces is supplied by a falling weight or ram
  - Energy restricted machines (K.E. + P.E.)
  - There are two basic types of forging hammers used;
    - Board hammer
    - Power hammer
- Forging presses :
  - Stroke restricted machines
  - There are two basic types of forging presses available;
    - Mechanical presses
    - Hydraulic presses

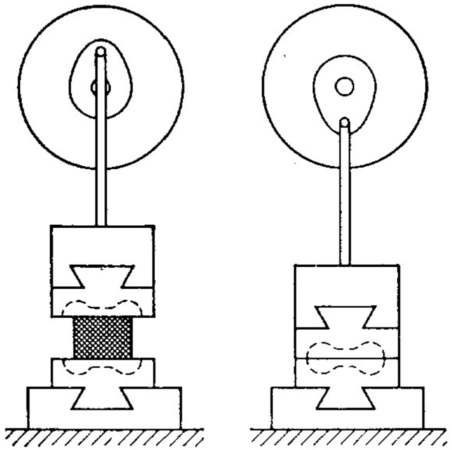
- Forging
  - Hammer
    - Board hammer
    - Steam hammer
  - Presses
    - Mechanical presses
    - Hydraulic presses



Board hammer

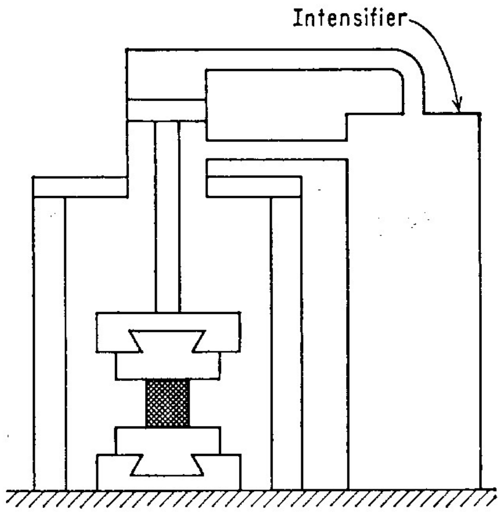


Steam hammer



Top stroke Bottom stroke

Crank press



Hydraulic press

Factors influences forging related to machine:

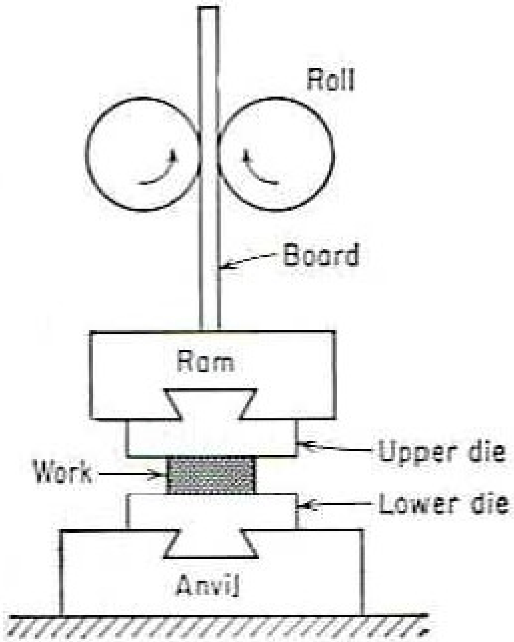
- Machine load > required load
- Machine energy > required energy
- No. of strokes per minute → production rate
- Contact time → time the workpiece remains in the die under load (Die wear)
- Dimensional accuracy → stiffness of the product

Board hammer –forging hammer

- The upper die and ram are raised by friction rolls gripping the board.
- After releasing the board, the ram falls under gravity to produce the blow energy.
- The hammer can strike between 60-150 blow per minute depending on size and capacity.
- The board hammer is an energy restricted machine. The blow energy supplied equal the potential energy due to the weight and the height of the fall.

  Potential energy = mgh

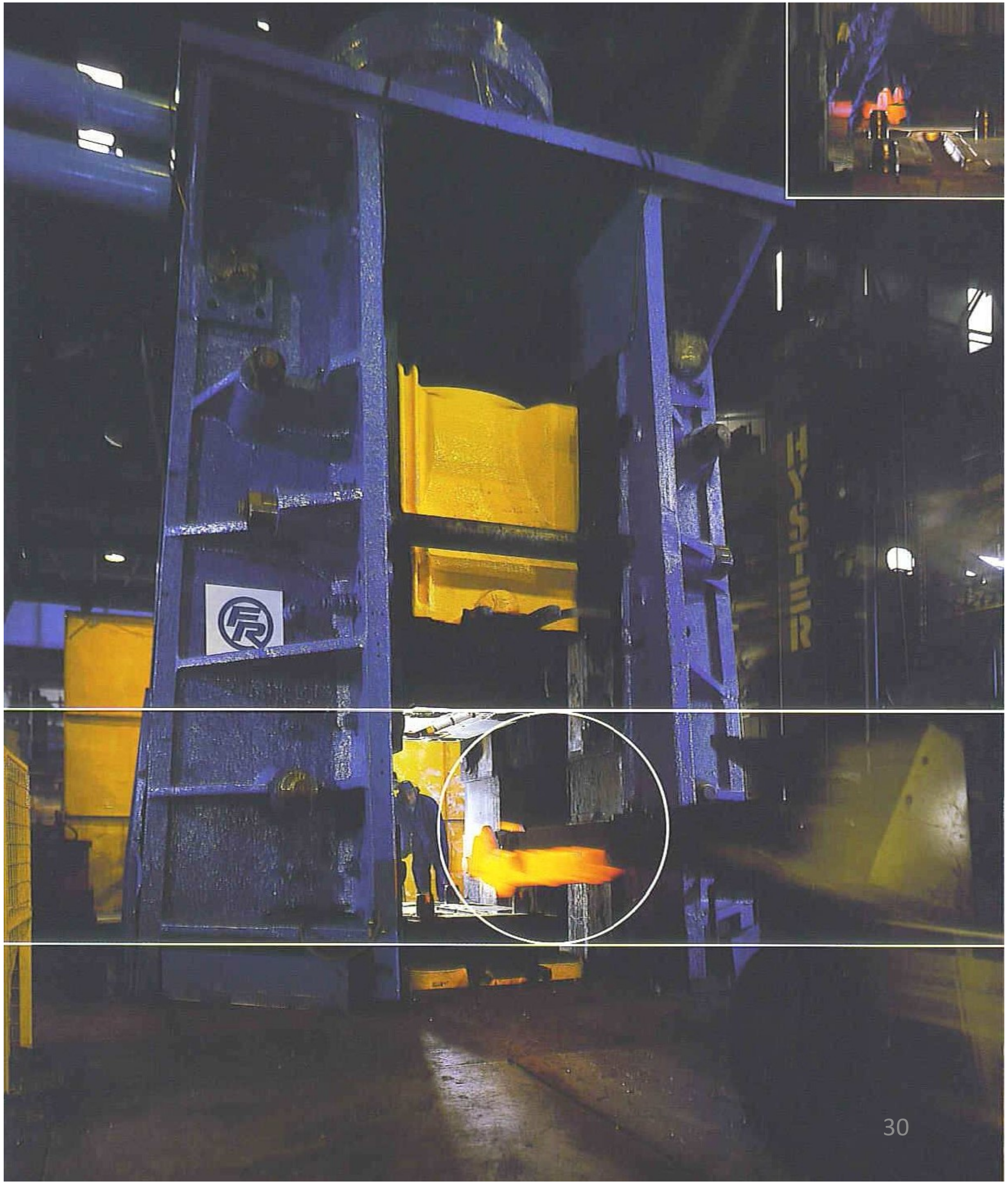
- This energy will be delivered to the metal workpiece to produce plastic deformation and elastic deformation of die.



Board hammer

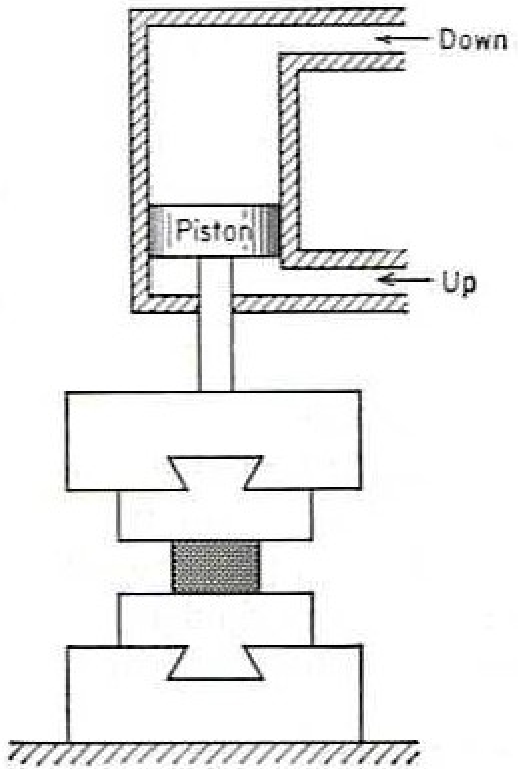
- Dies are expensive being accurately machined from special alloys (susceptible to thermal shock).

- Drop forging is good for mass production of complex shapes.
- Shortest contact time



Power hammer

- Power hammer provides greater capacity, in which the ram is accelerated on the downstroke by steam or air pressure in addition to gravity.
- Steam or air pressure is also used to raise the ram on the upstroke.
- Energy of the blow can be controlled whereas in the board hammer the mass and height of fall are fixed
- Preferred for closed die forging than board hammer



Steam hammer

- Forging weight varies from pound to tons
- It has shortest contact time
- The total energy supplied to the blow in a power drop hammer is given by

$$W = (½)mv^2 + pAH = (mg + pA)H$$

Where, m = mass

v=velocity of ram at start of deformation

g = acceleration of gravity

p = air or steam pressure acting on ram cylinder on down stroke

A = area of ram cylinder

H = height of the ram drop

Disadvantage of Forging hammer:

- Accuracy is not possible
- Problem in ground shock, noise and vibration.
  - Overcome this problems by counter blow hammer.

Recently High Energy Rate Forging (HERF) Machine is available. It is used for mass production due to it's high velocity

Forging Press

- Using a hydraulic press or a mechanical press to forge the metal, therefore, gives continuous forming at a slower rate.
- Provide deeper penetration.
- Better properties (more homogeneous).
- Equipment is expensive.

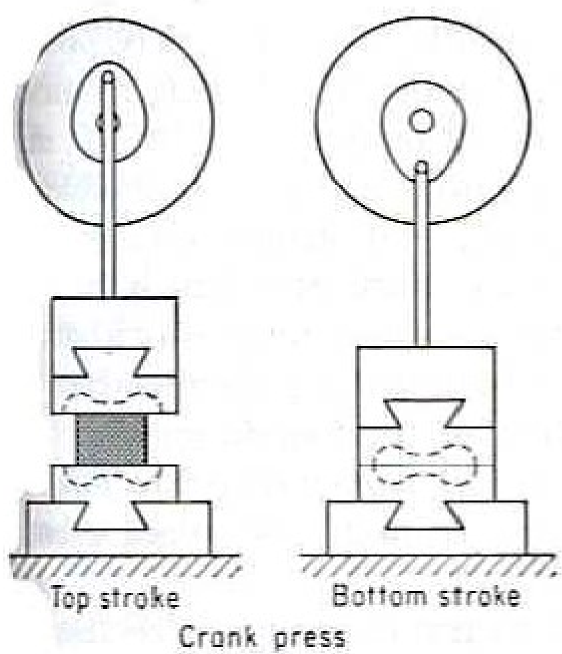
Mechanical press forging

Crank press translates rotary motion into reciprocating linear motion of the press slide.

• The ram stroke is shorter than in a hammer or hydraulic press.

• Presses are rated on the basis of the force developed at the end of the stroke.

• The blow press is squeeze the workpiece than like the impact of the hammer, therefore, dies can be less massive and die life is longer than with a hammer.



- The total energy supplied during the stroke of a press is given by

$$w = \frac{1}{2} I [\omega_0^2 - \omega_f^2]$$

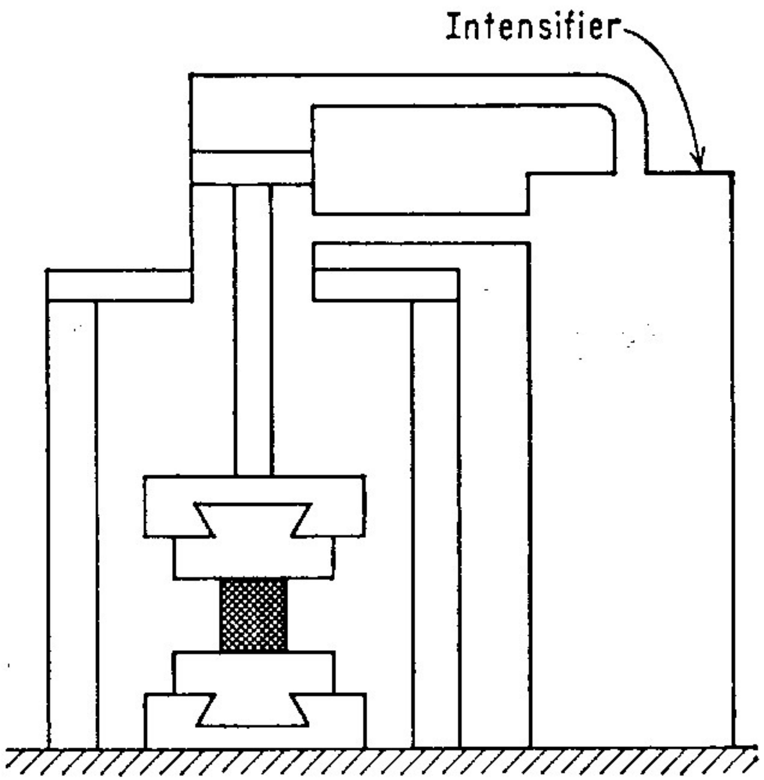
Where I is moment of inertia of the flywheel

ω is angular velocity, ω_o-original, ω_f-after deformation

- Load rating 300 – 12,000 tons

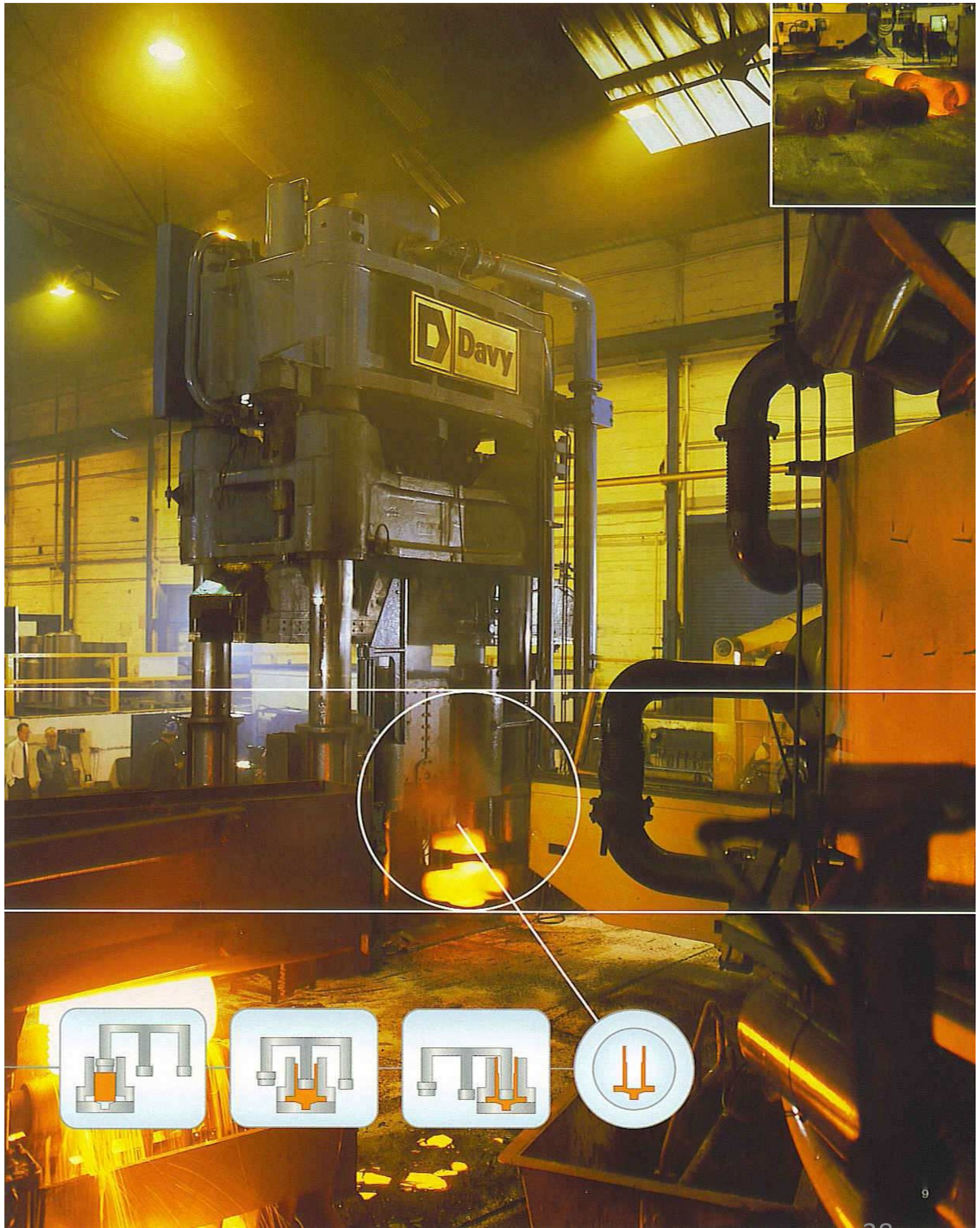
Hydraulic Press Forging

- Hydraulic presses are load restricted machines in which hydraulic pressure moves a piston in a cylinder.
- The full press load is available at any point during the full stroke of the ram. Therefore, hydraulic presses are ideally suited for extrusion-type forging operation.
- Provide close-tolerance forging.
- Load 500 to 50,000 tons



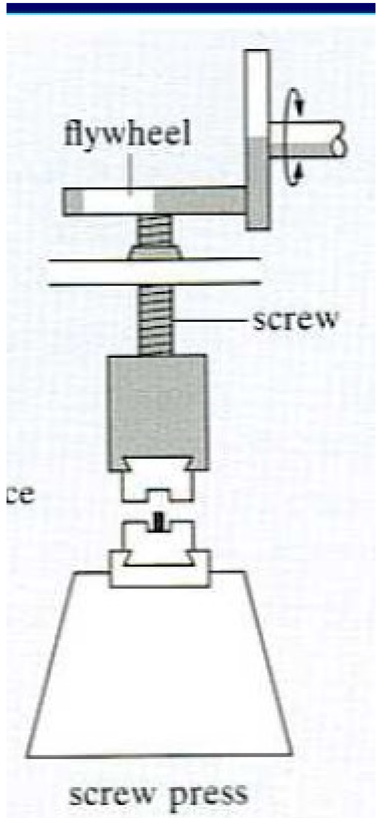
Hydraulic press

- Due to slow speed, contact time is longer at the die-metal interface, which causes problems such as heat lost from workpiece and die deterioration.
- Hydraulic presses are more expensive than mechanical presses and hammers



Screw Presses

- Used for hot and cold forgings
- Ram is connected to rotary joint of the spindle.
- The rotary motion of a fly wheel converts into linear motion of ram.



Typical values of velocity for different forging equipment

Forging machine	**Velocity range, ms-1**
Gravity drop hammer	3.6 – 4.8
Power drop hammer	3.0-9.0
HERF machine	6.0 -24.0
Mechanical press	0.06 -1.5
Hydraulic press	0.06-0.30

Forming machines

Machine Type	Load rating (F in kN)	Available Energy per blow (W in kJ)	Ratio (W/F) (in x 10^{-3})
Drop hammer	12250	106	1.3
Friction screw press	12250	8.0	6.4
Crank press	12250	25	16
Hydraulic press	12250	250	200

Die Materials

Required Properties:

- Thermal shock resistance
- Thermal fatigue resistance
- High temperature strength
- High wear resistance
- High toughness and ductility
- High hardenability
- High dimensional stability during hardening
- High machinability

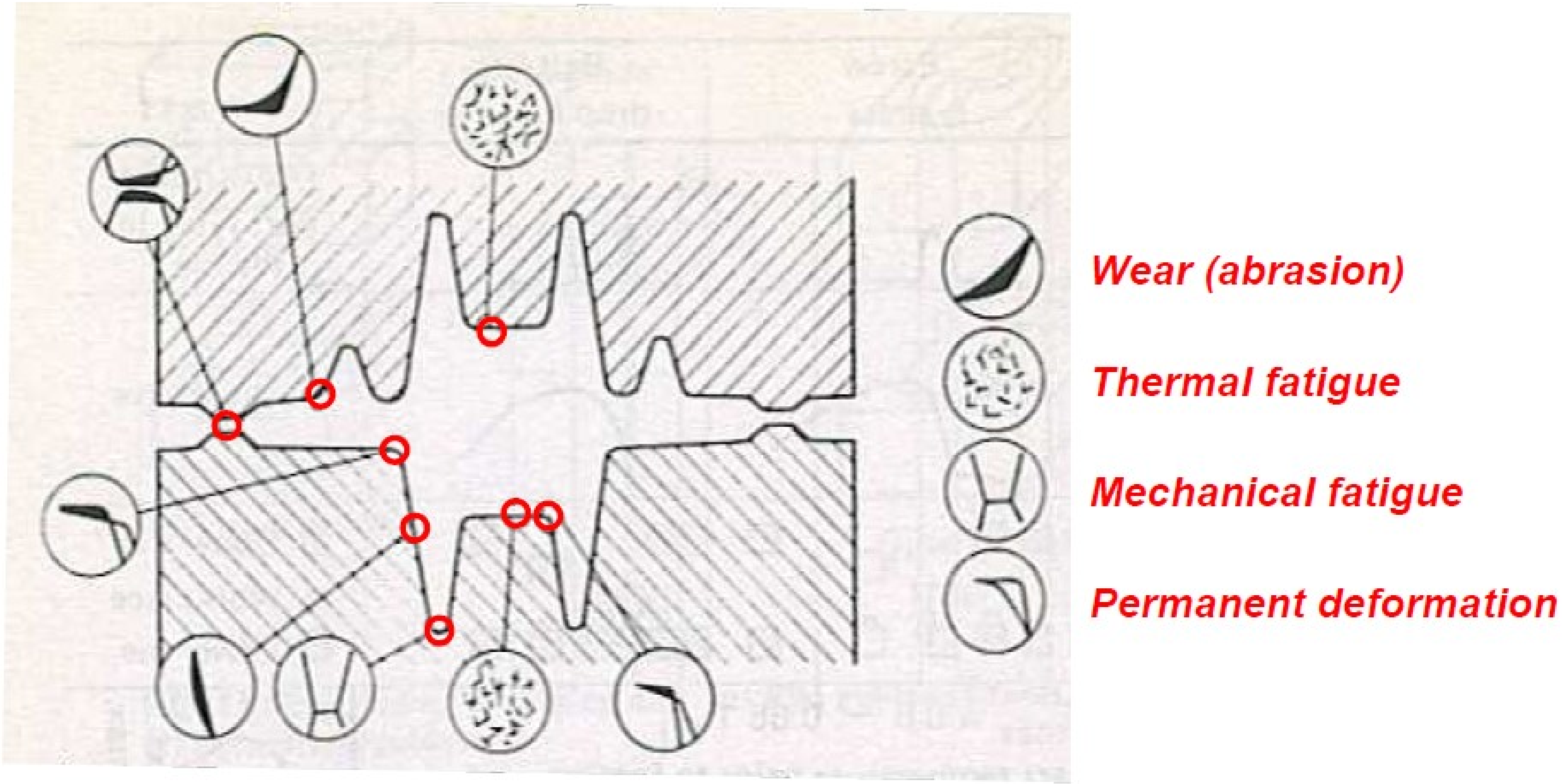
Die materials: alloyed steels (with Cr, Mo, W, V), tool steels, cast steels or cast iron. (Heat treatments such as nitriding or chromium plating are required to improve die life)

- Die life can be increased by
  - Using composite die
  - Using surface coating or self lubricating coating

- Ultra hard surface coating used on die surface due to
  - Improve die life.
  - Reduce energy input.
  - Reduce die-related uptime and downtime.
  - Reduce particulate emission from lubricants.

1) Carbon steels with 0.7-0.85% C are appropriate for small tools and flat impressions.
2) Medium-alloyed tool steels for hammer dies.
3) Highly alloyed steels for high temperature resistant dies used in presses and horizontal forging machines.

Die Failures

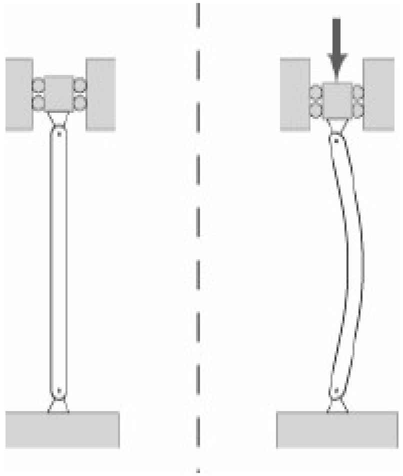


Different parts of dies are liable to permanent deformation and wear resulting from mechanical and thermal fatigue.

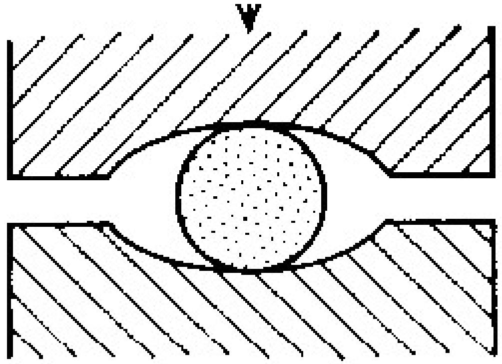
Typical forging defects

- Incomplete die filling: Loose scale or lubricant residue that accumulates and forms scale pockets on complex shape of the die cause underfill. Incomplete rescaling of the workpiece results in forged in scale on the finished part
- Die misalignment
- Incomplete forging penetration
  - Normally observed in large workpiece which should be forge on the forging press.
- Microstructural differences resulting in pronounced property variation.
  - Incomplete dendritic ingot structure. Observed by macroetching of dendritic structure.
- Pitted surface, due to oxide scales occurring at high temperature stick on the dies.

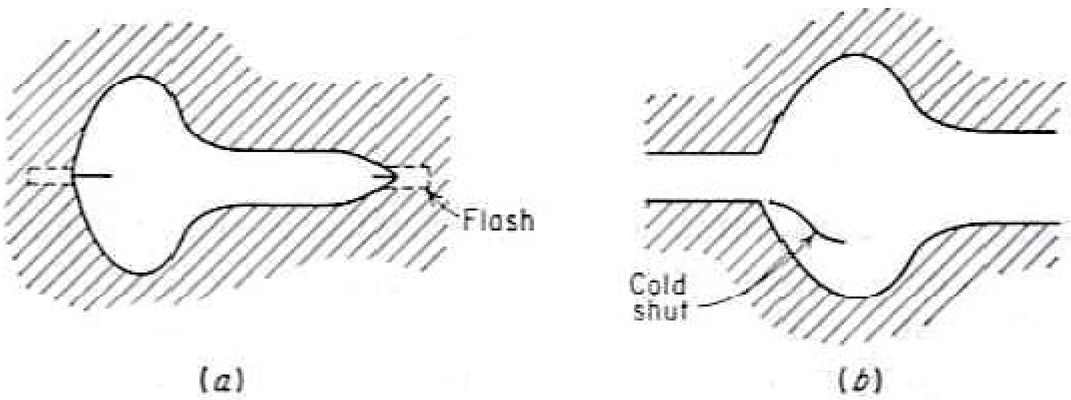
- Buckling, in upsetting forging.
  - Subject to high compressive stress of the workpiece develops circumferential tensile stresses
  - To avoid, concave dies are used
- Surface cracking Excessive working of the surface at low temperature or result of hot shortness (due to high sulphur concentration in steel and nickel.)
  - due to temperature differential between surface and centre
- Microcracking, due to residual stress.



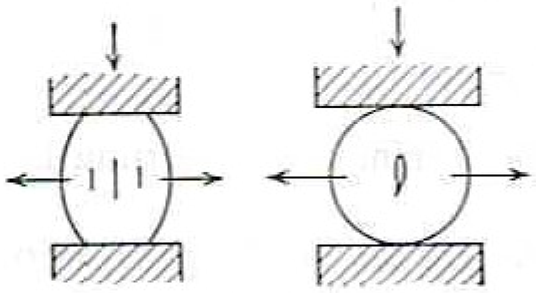
Buckling



swaging



- Flash line crack, after trimming occurs more often in thin workpieces.
  - Therefore, increase the thickness of the flash or relocating the flash position or less critical region of the forging
  - Avoided by hot trimming or stress relieving the forging prior to cold trimming of the flash
- Cold shut or fold, is discontinuity produced when two surfaces of metal fold against each other without welding completely, due to flash or fin from prior forging steps is forced into the workpiece. Due to
  - Metal flows past part of the die cavity that has already filled
  - Metal partly filled because the metal failed to fill in due to sharp corner
  - Excessive chilling
  - High friction
  - Small die radius



- Internal cracking
  - due to secondary tensile stress.
  - During upsetting of a cylinder or a round results circumferential tensile stresses
  - Proper die design can minimize this type of cracking
  - Less prevalent in closed die forging because lateral compressive stresses are developed by interaction workpiece with die wall

Residual Stresses

- Due to inhomogeneous deformation, RS is small in forging. Most of the forging done at high temperature which reduces the RS.
- Appreciable RS develops during quenching of steel forgings.
- Large forgings are subject to formation of small cracks or flakes at the center of the cross section.
- In addition, flakes are associated with H_2 gas
- Special cares are required for cooling large steel forgings.
  - Vacuum degassed steel largely eliminates problems with flaking
  - Large forgings are cooled slowly
  - Hot workpieces are
    - buried in ashes for several weeks
    - Undergoes controlled cooling treatment

Forging in Plane Strain

Consider forging stress 'P' acting on plate of constant thickness 'h' under plane strain condition.

1. Frictional shear stress τ_{xy} at the interface of die and workpiece
2. Lateral pressure σ_x.

Fictional force resist the workpiece deformatior in lateral pressure. The equilibrium in x direction is,

$$\sigma_x h - (\sigma_x + d\sigma_x)h - 2\tau_{xy}\,dx = 0$$

$$-d\sigma_x h - 2\tau_{xy}\,dx = 0$$

$$\frac{d\sigma_x}{dx} = -\frac{2\tau_{xy}}{h}$$

Von Mises' yield criterion for plane strain condition is,

$$\sigma_1 - \sigma_3 = \frac{2}{\sqrt{3}}\sigma_0 = \sigma_0'$$

If p=σ_z, then $\sigma_1 - \sigma_3 = \sigma_0' = p - \sigma_x$

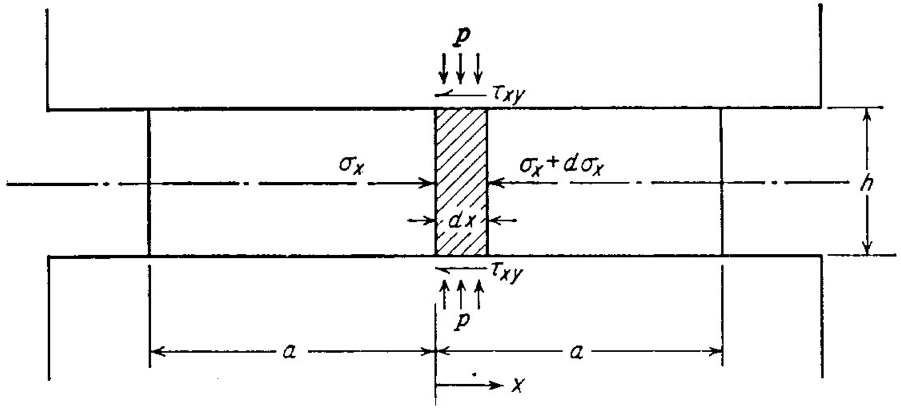


Fig.: Stresses action on a plate forged in plane strain

Differentiate the above equ. W.r.t x, then (σ_0' does not change with x)

$$\frac{dp}{dx} = \frac{d\sigma_x}{dx} = -\frac{2\tau_{xy}}{h}$$

Shearing stress is related to normal pressure by coulomb's law of sliding friction (τ_{xy} = μp),

$$\frac{dp}{dx} = -\frac{2\mu p}{h}$$

$$\frac{dp}{p} = -\frac{2\mu dx}{h}$$

$$\frac{dp}{p} = -\frac{2\mu dx}{h}$$

Integrate the above equation,

$$\ln p = -\frac{2\mu x}{h} + \ln c$$

Apply boundary condition, x→a σ_x=0 and p=σ_0'. Therefore,

$$\ln p = \ln \sigma_0' = -\frac{2\mu a}{h} + \ln C$$

$$\ln C = \ln \sigma_0' + \frac{2\mu a}{h}$$

$$\ln p = -\frac{2\mu x}{h} + \ln \sigma_0' + \frac{2\mu a}{h}$$

$$\ln p = \frac{2\mu(a-x)}{h} + \ln \sigma_0'$$

$$p = \sigma_0' \exp\left(\frac{2\mu(a-x)}{h}\right)$$

Usually μ is small number, $e^y = 1 + y + y^2/2! + \ldots$

$$p = \sigma_0'\left[1 + \frac{2\mu(a-x)}{h}\right]$$

The mean forging pressure is,

$$\bar{p} = \int_0^a \frac{p\,dx}{a} = \int_0^a \frac{\sigma_0'}{a}\left[1 + \frac{2\mu(a-x)}{h}\right]dx$$

$$\bar{p} = \frac{\sigma_0'}{a}\left[x + \frac{2\mu a x}{h} - \frac{\mu x^2}{h}\right]_0^a$$

$$\bar{p} = \sigma_0'\left(1 + \frac{\mu a}{h}\right)$$

If the ratio a/h increases, the forming pressure p and forming load rises rapidly .

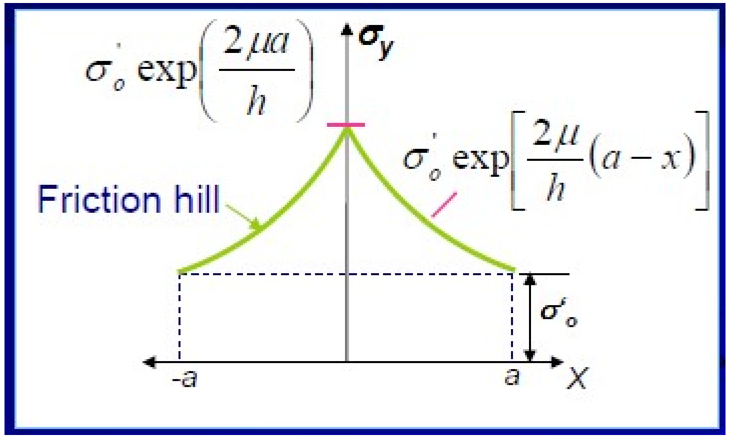


Fig.: Distribution of normal stress and longitudinal stress for compression between plates.

- In high friction condition (sticking friction), the mean forging pressure is,

$$\overline{p} = \sigma_0'\left(\frac{a}{2h} + 1\right)$$

The forming load is dependent on the flow stress of the materials and the geometry of the workpiece.

For example, a/h =8 then, $\overline{p} = 5\sigma_0'$

To reduce the forming load,

- reduce friction coefficient μ
- Changing the workpiece geometry
- Reducing σ_0' by increasing the temperature.

Problem: A block of lead 25x25x150 mm^3 is pressed between flat dies to a size 6.25x100x150 mm^3. If the uniaxial flow stress σ_o = 6.9 MPa and μ = 0.25, determine the pressure distribution over the 100 mm dimension at x = 0, 25 and 50 mm and the total forging load in the sticky friction condition.

Since 150mm dimension does not change the deformation is plane strain.

$$p = \sigma'_0 \exp\left(\frac{2\mu(a-x)}{h}\right) \qquad \sigma'_0 = \frac{2}{\sqrt{3}}\sigma_0$$

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$$p = \sigma_0' \exp\left(\frac{2\mu(a-x)}{h}\right) \qquad \sigma_0' = \frac{2}{\sqrt{3}}\sigma_0$$

At the center line of the slap,

$$p = \frac{2(6.9)}{\sqrt{3}} \exp\left(\frac{2(0.25)}{6.25}(50-0)\right) = 435 MPa$$

$$p = \frac{2(6.9)}{\sqrt{3}} \exp\left(\frac{2(0.25)}{6.25}(50-25)\right) = 58.9 MPa$$

$$p = \frac{2(6.9)}{\sqrt{3}} \exp\left(\frac{2(0.25)}{6.25}(50-50)\right) = 8 MPa$$

The mean forging load at sticky friction condition,

$$\bar{p} = \frac{2\sigma_0}{\sqrt{3}}\left(\frac{a}{2h}+1\right) = \frac{2(6.9)}{\sqrt{3}}\left(\frac{50}{2(6.25)}+1\right) = 39.8 MPa$$

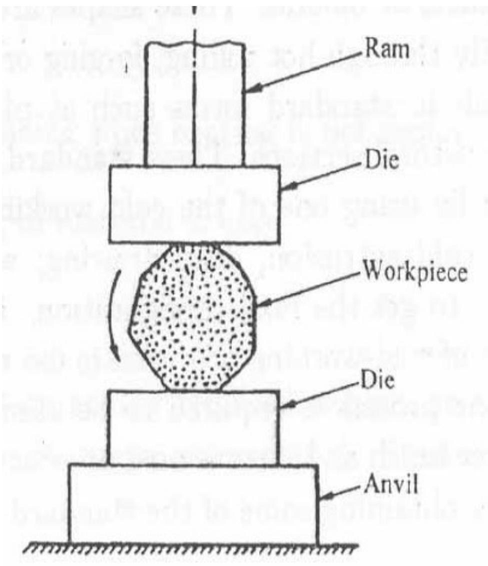
Total forging load is, Load = stress X area = $(39.8 \times 10^6) \times (150 \times 10^{-3} \times 100 \times 10^{-3})$

= 597kN

Open-Die Forging

- In open die forging, the metal is compressed by repeated blows by a mechanical hammer or manually.
- Deals with large, relatively simple shapes that are formed between simple dies in a large hydraulic press or power hammer.

  Ex: propeller shafts, rings, gun tubes and pressure vessels.
- Workpiece is larger than the tool.
- Chief mode of deformation is compression, workpiece is spreading in lateral directions.
- Simplest open-die forging operation is cogging a billet between fat tools to reduce the cross sectional area without changing the final shape.



Coefficient of spread S,

$$S = \frac{width\_elongation}{thickness\_contraction} = \frac{\ln(w_1/w_0)}{\ln(h_0/h_1)}$$

Width can be expressed as length by using constant volume relationship,

$$\frac{h_1 w_1 l_1}{h_0 w_0 l_0} = 1$$

$$\ln(h_1/h_o) + \ln(w_1/w_o) + \ln(l_1/l_o) = 0$$

The coefficient of elongation,

$$1 - S = \frac{length\_elongation}{thickness\_contraction} = \frac{\ln(l_1/l_0)}{\ln(h_0/h_1)}$$

If S=1, the workpiece spread

S=0, all the deformation go into elongation.

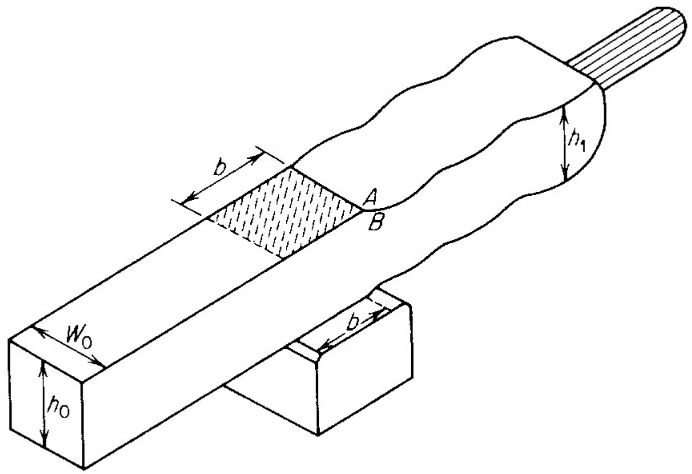


Fig.: Cogging operation. Shaded are shows where contact would occur between workpiece and upper die.

S can be expressed by bite ratio (b/w_o), since $S = \dfrac{b/w_o}{1 + b/w_o}$

The spread law, $\beta = \left(\dfrac{1}{\gamma}\right)^S$ where β=spread ratio = w_1/w_0

γ=squeeze ratio=h_0/h_1

Since only part of the surface is undergo deformation at a time, there is possibility of surface laps. For a given geometry, the critical deformation produce laps. Since,

- Squeeze ratio s h_0/h_1 should be ≤ 1.3 which make billet is deformed through to the center
- Bite ratio b/w_0 should be ≥ 1/3 to minimize inhomogeneous deformation.

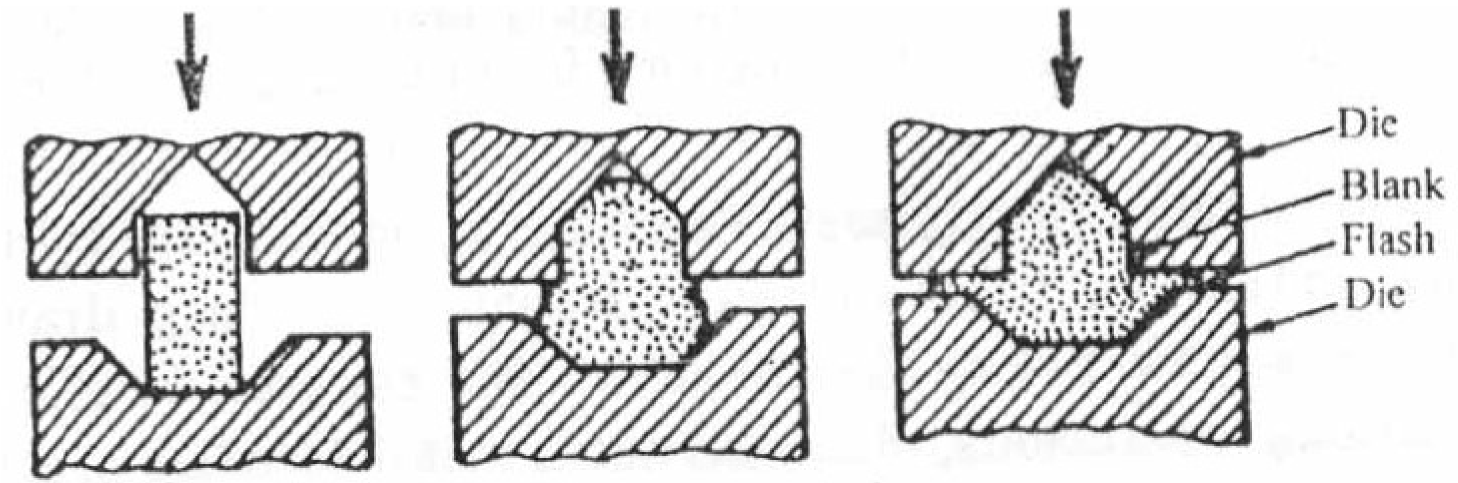
The load required to forge a flat section in the open dies is,

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

Where C is a constraint factor to allow for inhomogeneous deformation.

Closed Die Forging

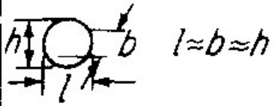
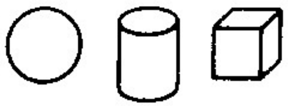
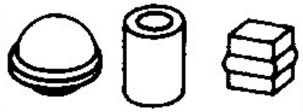
- In closed die forging, the desired configuration is obtained by squeezing the workpiece between two shaped and closed dies.
- The deformation in closed die forging is very complex.
- The success of the forging operation requires the understanding of
  - Flow stress of the materials
  - Frictional conditions
  - Flow of the materials to fill the die

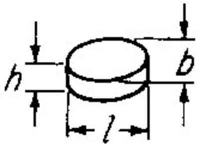
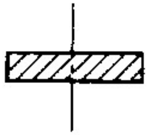
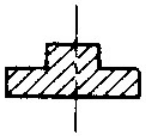
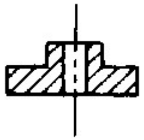
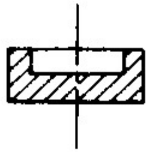
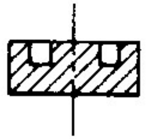
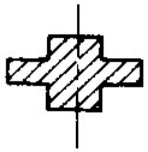
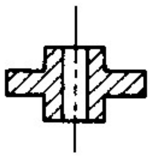
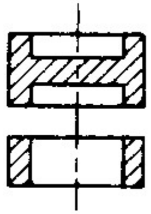
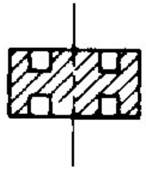


- Special problems in it is, rapid cooling of the workpiece by the colder dies results
  - Raise of flow stress
  - Raise of loads,
  - Incomplete die fill and
  - Loss of dimensional tolerance.
- To avoid this problem, isothermal forging is used. For forging aerospace materials, the die which is made up of superalloy is heated for isothermal forging.
- The design of a component, place important role in closed die forging. It involves
  - Workpiece volume and weight
  - no. of preforming steps and their configuration
  - Flash dimensions in preforming and finishing dies
  - The load and energy requirements for each forging operation

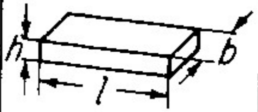
Proper design assures, defect-free flow, complete die fill and minimum flash loss. For that it is important to understand the metal flow.

- Classification of closed die forging are listed in diagram.

Shape class 1 compact shape  $l \approx b \approx h$ Spherical and cubical	Subgroup	101 No subsidiary elements 	102 Unilateral subsidiary elements 	103 Rotational subsidiary elements 	104 Unilateral subsidiary elements 

Shape class 2 disc shape	Sub-group / Shape-group	No subsidiary elements	With hub	With hub and hole	With rim	With rim and hum
 $l \approx b > h$ Parts with circular, square and similar contours cross piece with short arms upset heads and long shapes (flanges, valves) ETC.	21 Disc shape with unilateral element	211 	212 	213 	214 	215 
	22 Disc shape with bilateral element		222 	223 	224 	225 

Shape class 3
oblong shape

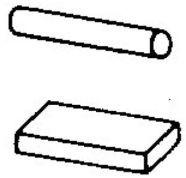
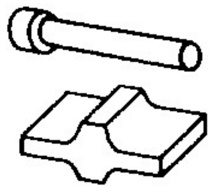
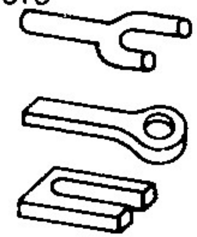
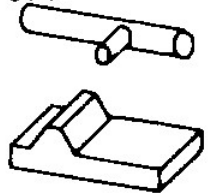
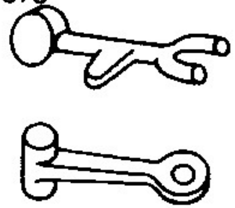
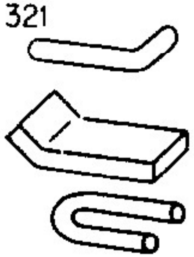
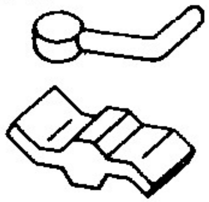
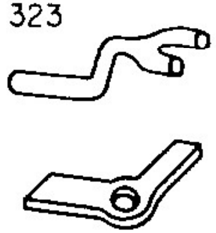
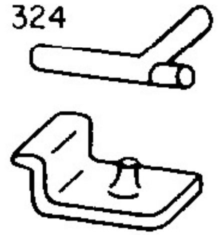
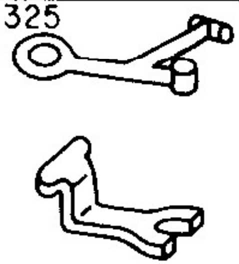
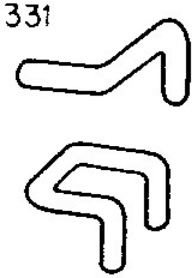
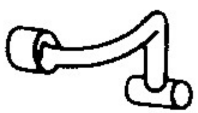
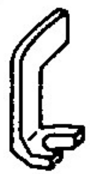
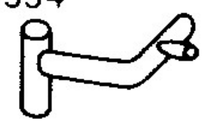
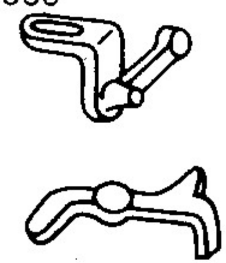


$l > b \gtrapprox h$

Parts with pronounced longit axis length groups:

1. *Short parts* $l > 3b$
2. *Av. length* $l = 3 \cdots 8b$
3. *Long parts* $l = 8 \cdots 16b$
4. *V. long pts.* $l > 16b$

Length group numbers added behind bar–
e.q.: 334/2

Sub-group / *Shape group*	*No subsidiary elements*	*Subsidiary elements parallel to axis of principal shape*	*With open or closed fork element*	*With subsidiary elements asymmetrical to axis of principal shape*	*With two or more subsidiary elements of similar size*
31 *Principal shape element with straight axis*	311 	312 	313 	314 	315 
32 *Longit. axis of principal shape element curved in one plane*	321 	322 	323 	324 	325 
33 *Long. axis of principal shape element curved in several planes*	331 	332 	333 	334 	335 

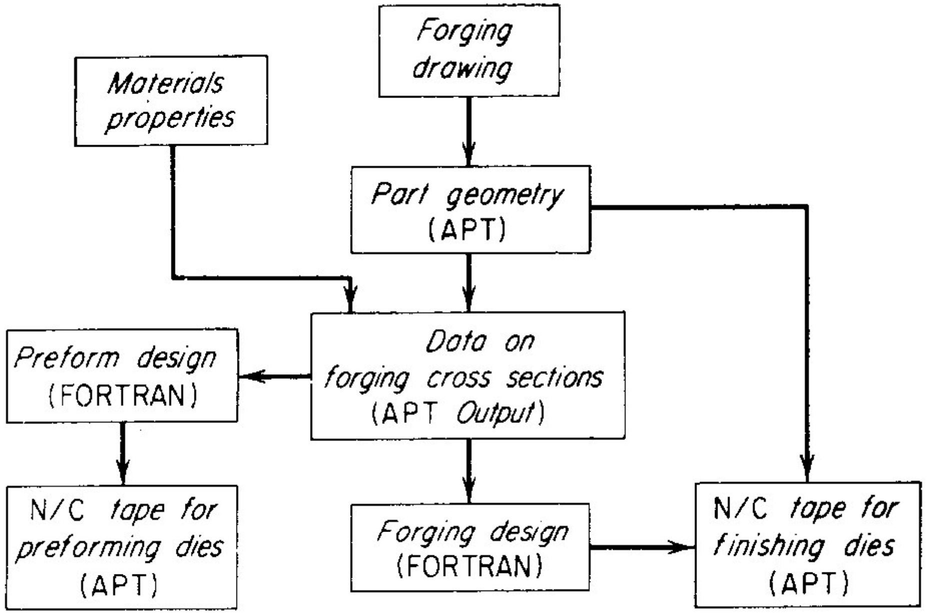


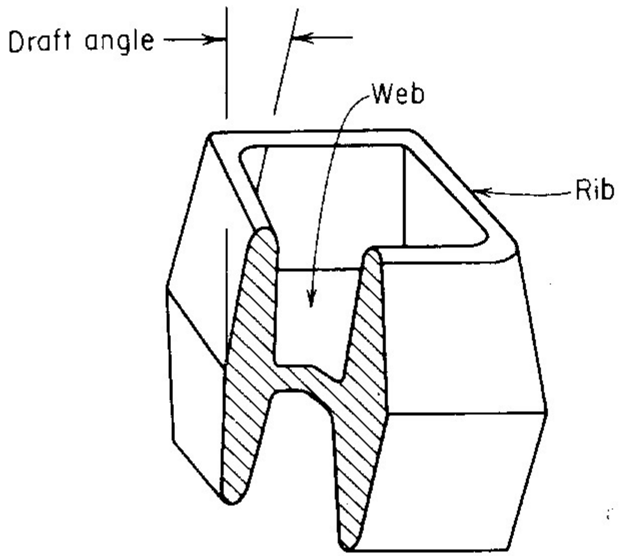
Figure: Flow diagram for computer-aided design (CAD) and computer-aided manufacturing (CAM) systems applied to closed die forging

N/C – numerically controlled machine

APT – specialized computer language describing geometric changes produced in metal cutting which is hear of N/C machining

General considerations for preform design

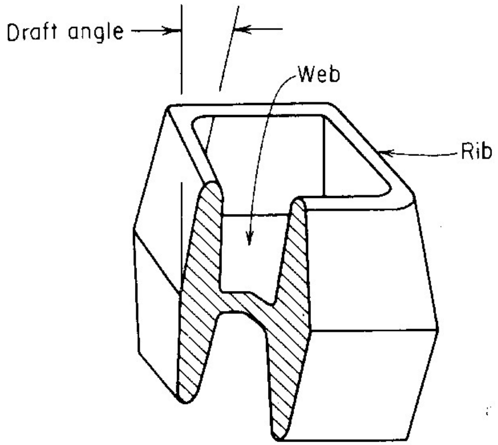
- Area of each cross section = area in the finished cross section + flash.
- Concave radii of the preform > radii on the final forging part.
- Cross section of the preform should be higher and narrower than the final cross section, so as to accentuate upsetting flow and minimise extrusion flow.

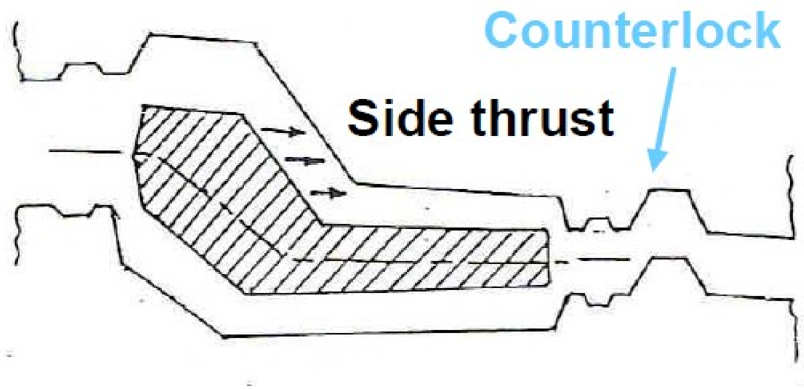


Shape with thin and long sections or projections (ribs and webs) are more difficult to process because they have higher surface area per unit volume increasing friction and temperature effects.

General rules of closed-die design

- The die set should be designed for smooth metal flow – symmetry dies (spherical or block like) are the easier than thin and long section.
- Shape changes in section are to be avoided.
- Dies should be designed for the minimum flash to do the job.
- Generous fillet dimensions should be allowed, therefore, forging dies must be tapered or drafted to facilitate removal of the finished piece.
- Draft allowance is approximately 3-5^o outside and 7-10^o inside.
- Dies with inclined angles should have counterlock to prevent the dies from sliding apart from each other due to side thrust.

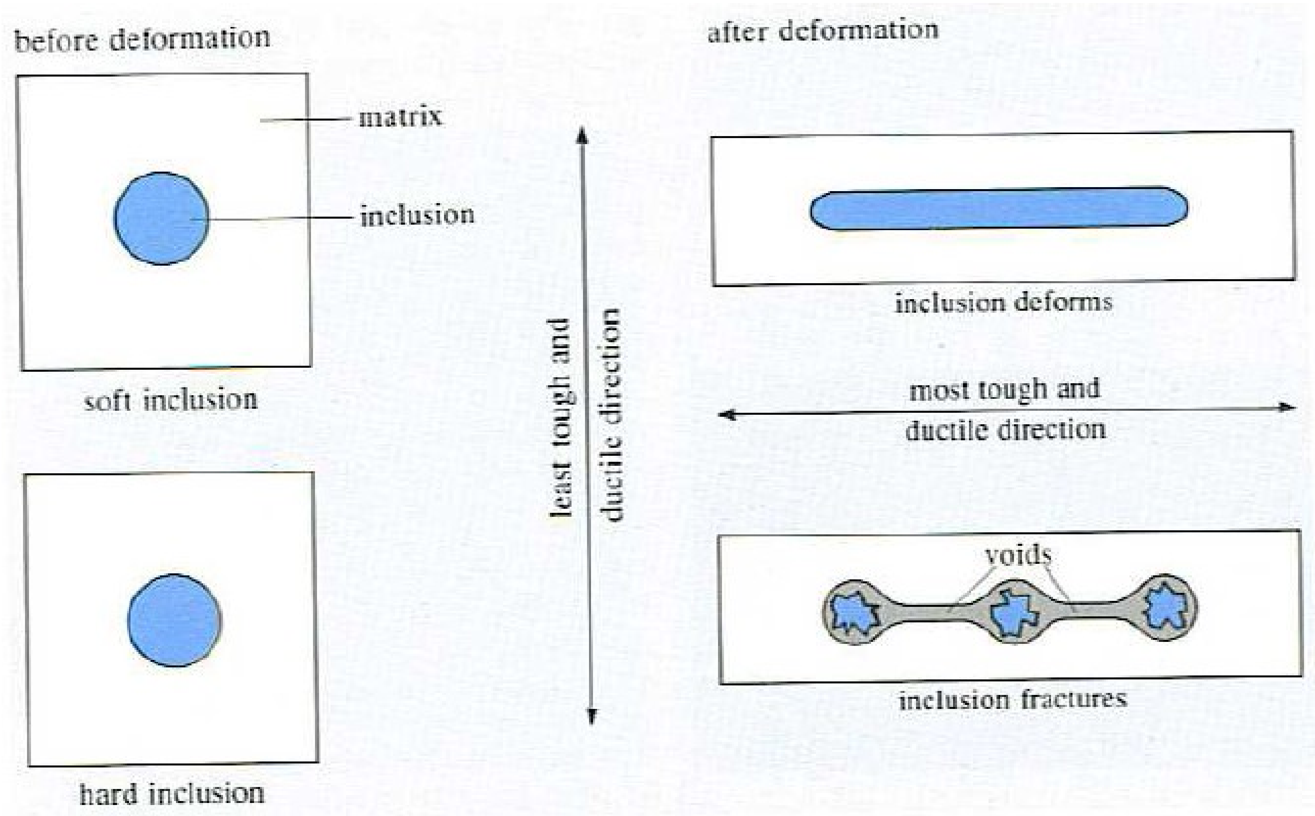




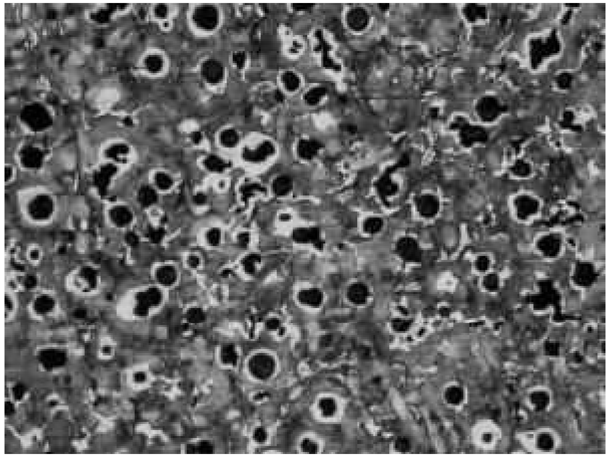
Forming textures

- Redistribution of metal structures occurring during forming process involves two principle components;
  - redistribution of inclusions and
  - crystallographic orientation of the grains

1) The redistribution of inclusions

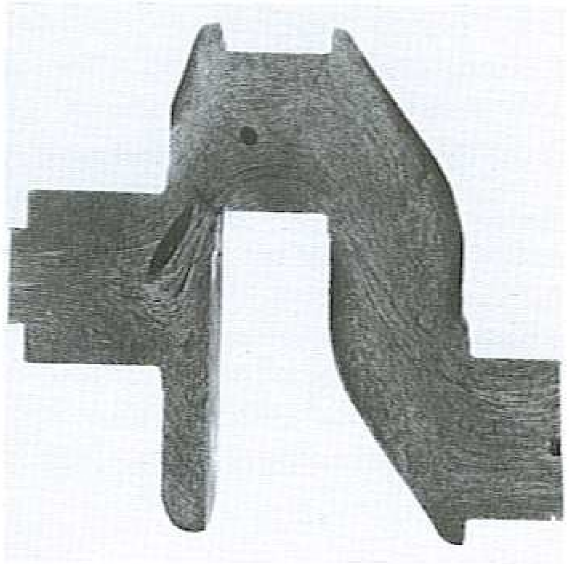


- Crystallographic orientation of the grains



Cast iron

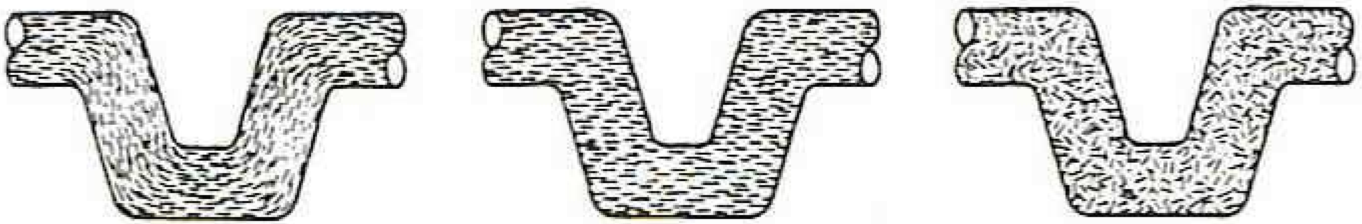
Mainly epitaxial, dendritic or equiaxed grains



Fibre structure in forged steels

Redistribution of grains in the working directions

Effect of forging on microstructure



(a) Forging: true grain flow | (b) Bar stock: grain flow broken by machining | (c) Casting: no grain flow

- The formation of a grain structure in forged parts is elongated in the direction of the deformation.
- The metal flow during forging provides fibrous microstructure (revealed by etching). This structure gives better mechanical properties in the plane of maximum strain but (perhaps) lower across the thickness.
- The workpiece often undergo recrystallisation, therefore, provide finer grains compared to the cast dendritic structure resulting in improved mechanical properties.

Powder Metallurgy Forging

- Now, P/M forging is in growing area
- Advantage:
  - Improved materials utilisation through reduction or elimination of machining
  - Forming to final size in one forging stoke
  - Uniformity of structure and reduced directionality of properties relative to conventionally forged parts.
- Working in a sintered powdered parts preform introduces new aspects to the mechanics of interconnected parts.

- Challenges:
  - P/M parts contains dispersion of interconnected voids
  - Work-piece volume is decreases during plastic deformation as the elimination of porosity.
  - Presence of voids decreases the local ductility which may lead to fracture during forging. Forming limit concept has to be applied to overcome this issue.
  - Presence of voids increases the surface area which may increases the oxidation and contamination reaction.

- The basic plasticity mechanics of a porous powder metallurgy preform described with the relationship of densification and plastic Poisson ratio ‘ν’.

$$\nu = 0.5\left(\frac{\rho}{\rho_t}\right)^2$$

- Kuhn modified the von Mises’ yield criterion by considering the porous materials densification with plastic deformation,

$$\sigma_o(\rho,\varepsilon) = \left[\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}+(1-2\nu)(\sigma_1\sigma_2+\sigma_2\sigma_3+\sigma_3\sigma_1)\right]^{1/2}$$