Forging

Subjects of interest

- *Introduction/objectives*
- *Classification of forging processes*
  - Hammer or drop forging
  - Press forging
  - *Open-die forging*
  - *Closed-die forging*
- *Calculation of forging loads*
- *Effect of forging on microstructure*
- *Residual stresses in forgings*
- *Typical forging defects*

Objectives

• This chapter provides fundamental of metal working process for forging in order to understand mathematical approaches used in the calculation of applied forging loads required to cause plastic deformation to give the final product.

• Classification of metal forging methods is also provided with descriptions of defects observed from the forging processes.

• The solutions to tackle such defects will also be addressed.

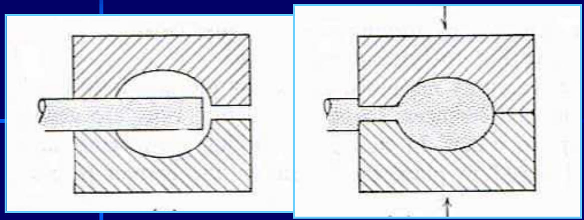
Introduction

www.eindiabusiness.com

www.prime-metals.com

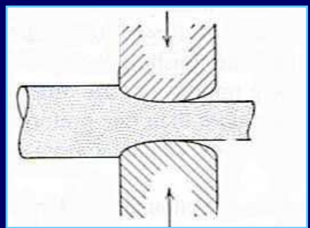
- ***Forging*** is the working of metal into a useful shape by hammering or pressing.
- The oldest of the metalworking arts (***primitive blacksmith***).
- Replacement of machinery occurred during early the ***Industrial revolution***.
- Forging machines are now capable of making parts ranging in size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

Forging operations

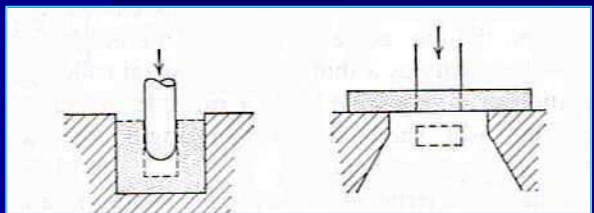


Edging is used to shape the ends of the bars and to gather metal. The metal flow is confined in the horizontal direction but it is free to flow laterally to fill the die.

www.jsc-pfm.com

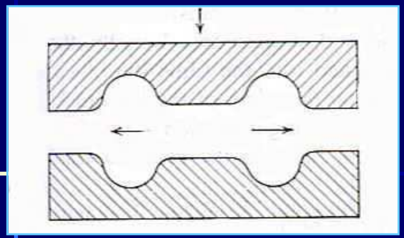


Drawing is used to reduce the cross-sectional area of the workpiece with concurrent increase in length.

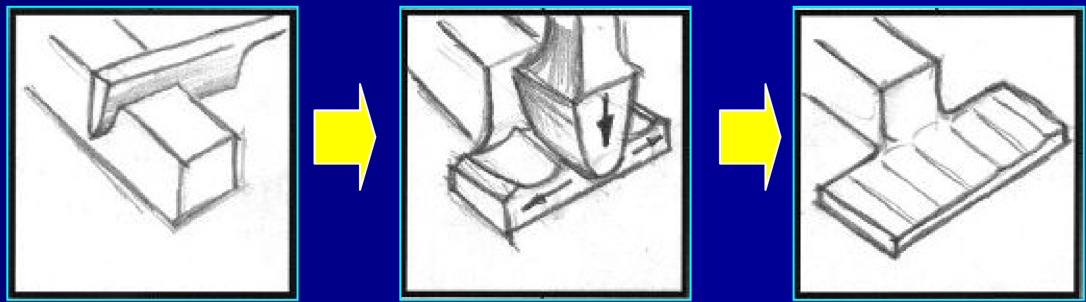


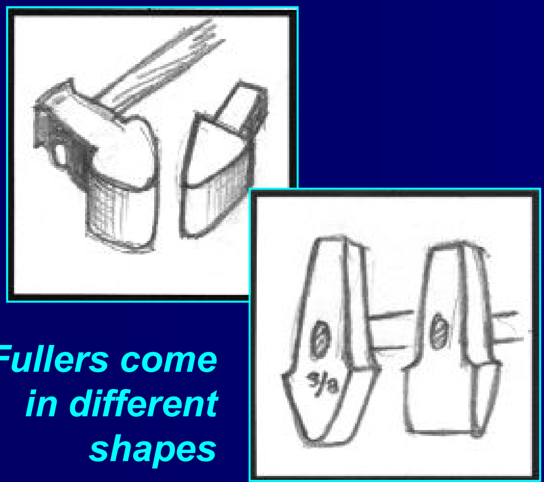
Piercing and punching are used to produce holes in metals.

Forging operations



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.





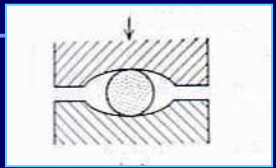
Fullers come in different shapes

• Fuller move fast and moves metal perpendicular to the face

www.anvilfire.com

Fullers

Forging operations



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

Swaging at the ends, ready for next forming process.

• 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.

Classification of forging processes

By equipment

1) Forging hammer or drop hammer
2) Press forging

By process

1) Open - die forging
2) Closed - die forging

Forming machines

There are four basic types of forging machines

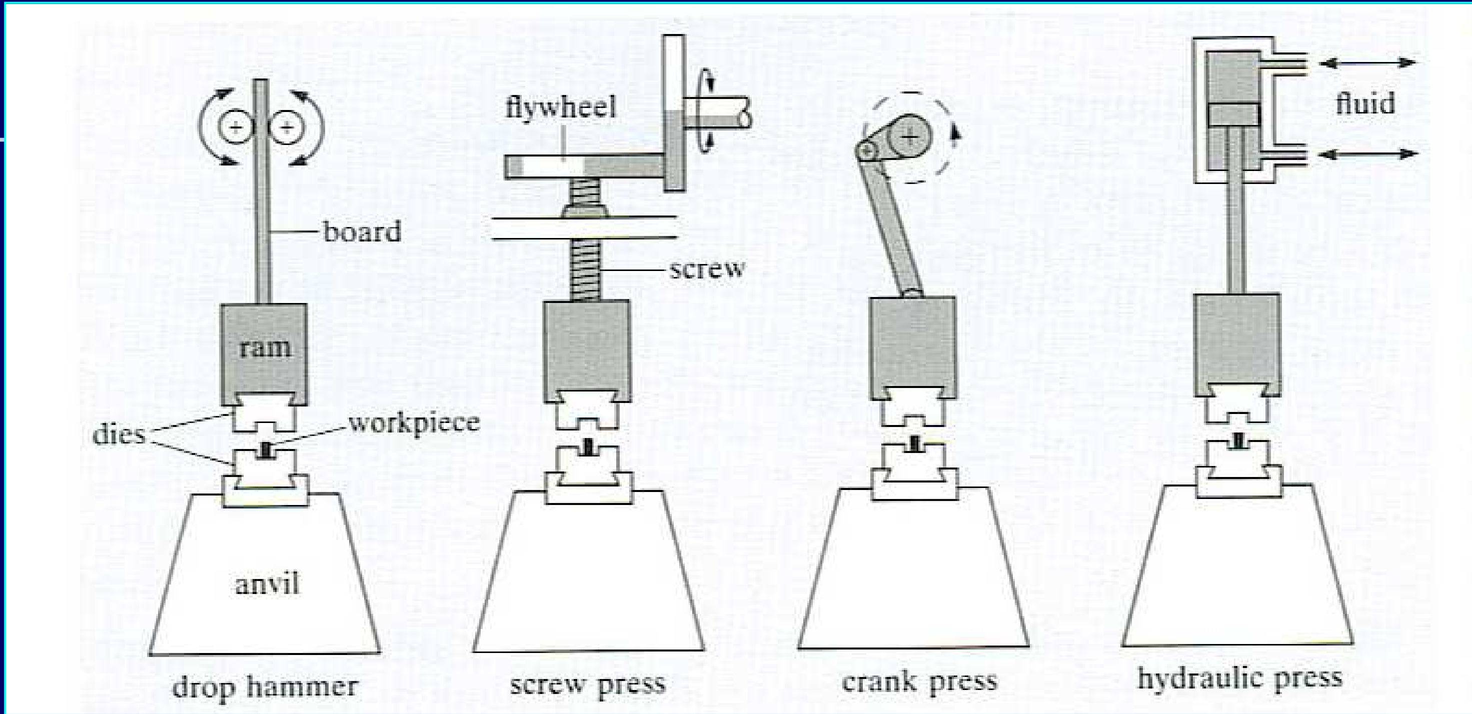


Table 3.3

Machine type	Load rating, F/kN	Available energy per blow, W/kJ	Ratio $W:F$ /m × 10^{-3}
drop hammer	12 250	1.6	1.3
friction screw press	12 250	8.0	6.4
crank press	12 250	20	16
hydraulic press	12 250	250	200

Hammer and press forging processes

Forging hammers

There are two basic types of forging hammers used;

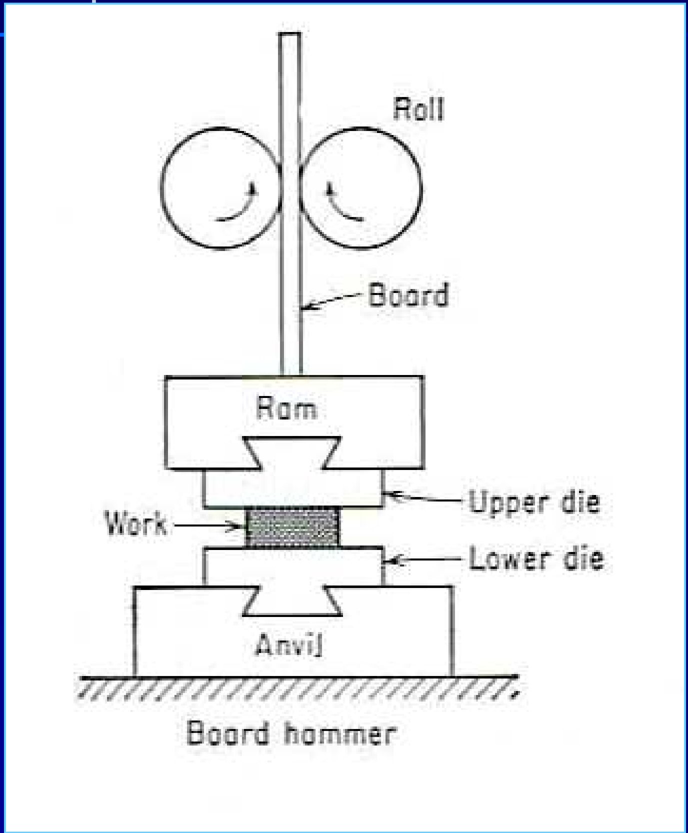
- ***Board hammer***
- ***Power hammer***

Forging presses

There are two basic types of forging presses available;

- ***Mechanical presses***
- ***Hydraulic presses***

Board hammer –forging hammer



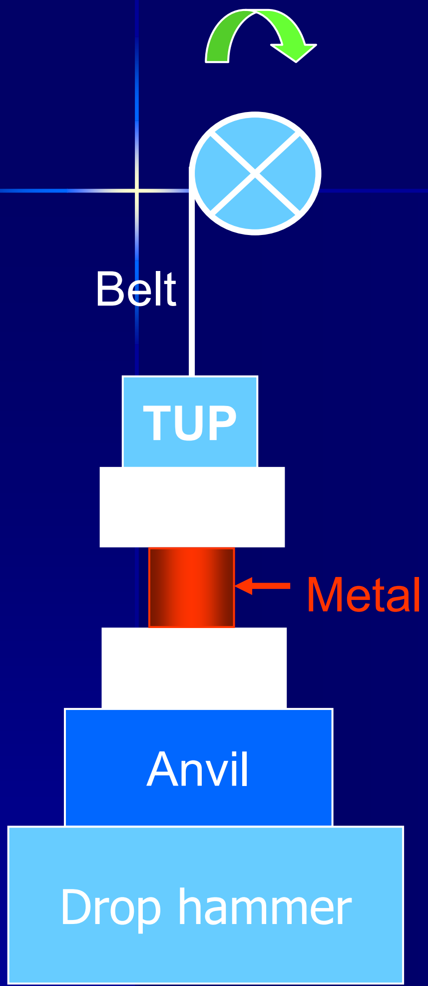
Board hammer

- 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 blows*** 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* *…Eq 1*

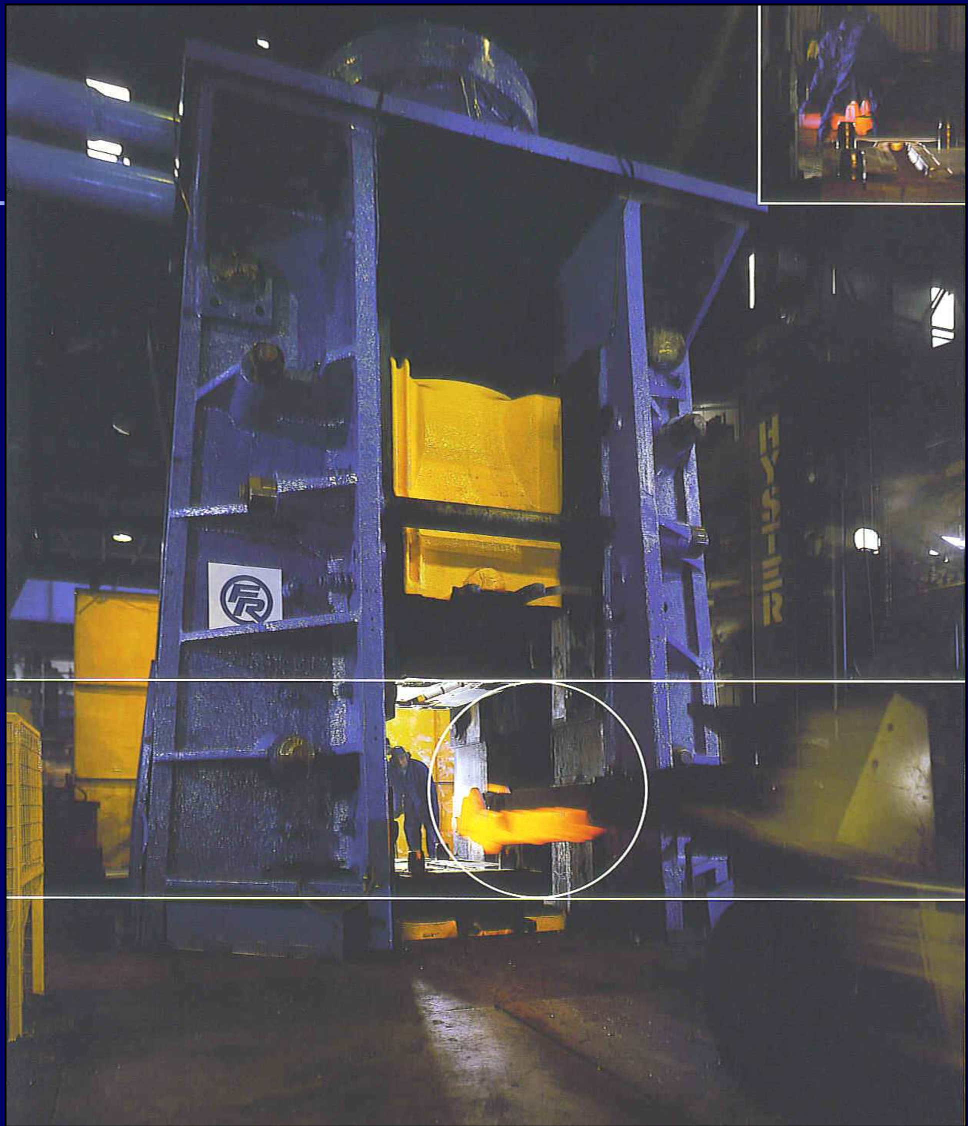
- This energy will be delivered to the metal workpiece to produce ***plastic deformation***.

Forging hammer or drop hammer



- Provide rapid impact blows to the surface of the metal.
- Dies are in two halves
  - *Lower : fixed to anvil*
  - *Upper : moves up and down with the TUP.*
- Energy (from a gravity drop) is adsorbed onto the metal, in which the maximum impact is on the metal surface.
- Dies are expensive being accurately machined from special alloys (susceptible to thermal shock).
- ***Drop forging*** is good for mass production of complex shapes.

Example: Forging hammer or drop hammer



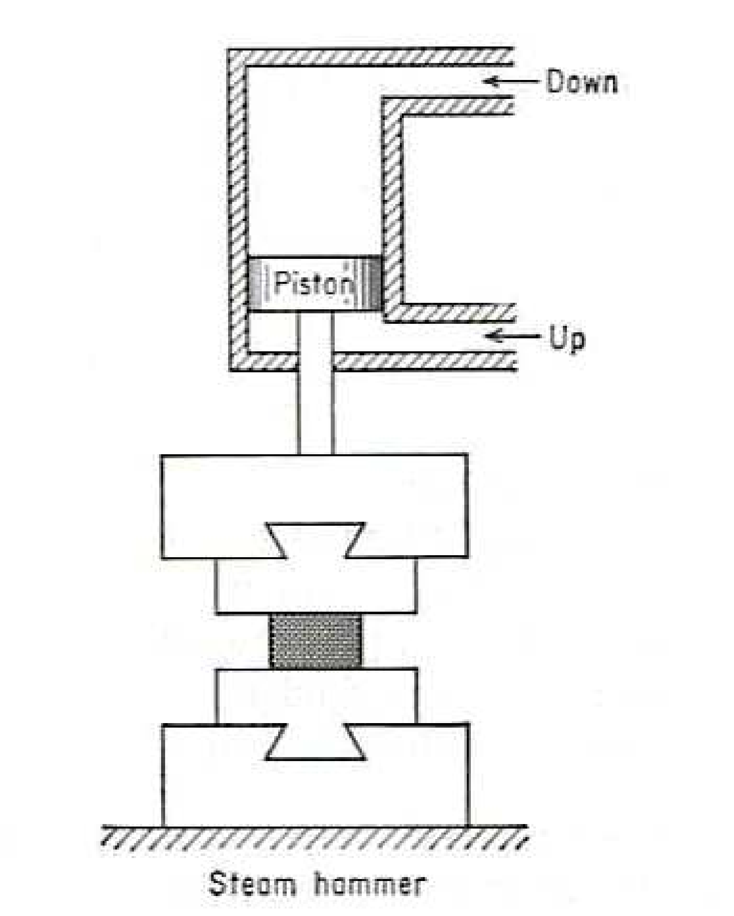
Forging machine

The energy supplied by the blow is equal to the potential energy due to the weight of the ram and the height of the fall.

Potential energy = *mgh*

…Eq 1

Power hammer



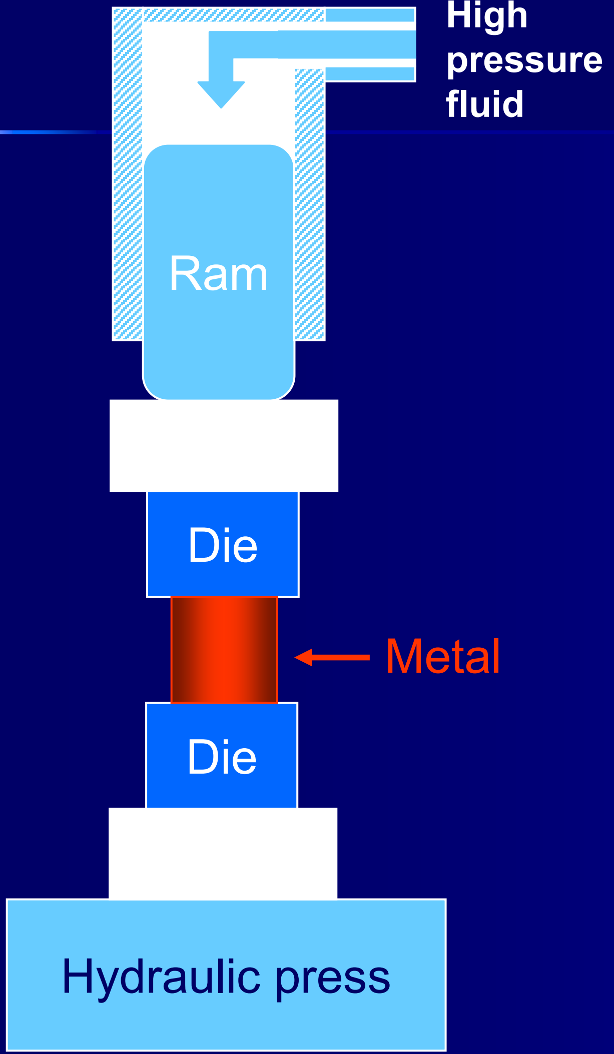
Power hammer

- ***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.
- *The **total energy** supplied to the blow in a power drop hammer is given by*

$$W = \frac{1}{2}mv^2 + pAH = (mg + pA)H \qquad \text{...Eq 2}$$

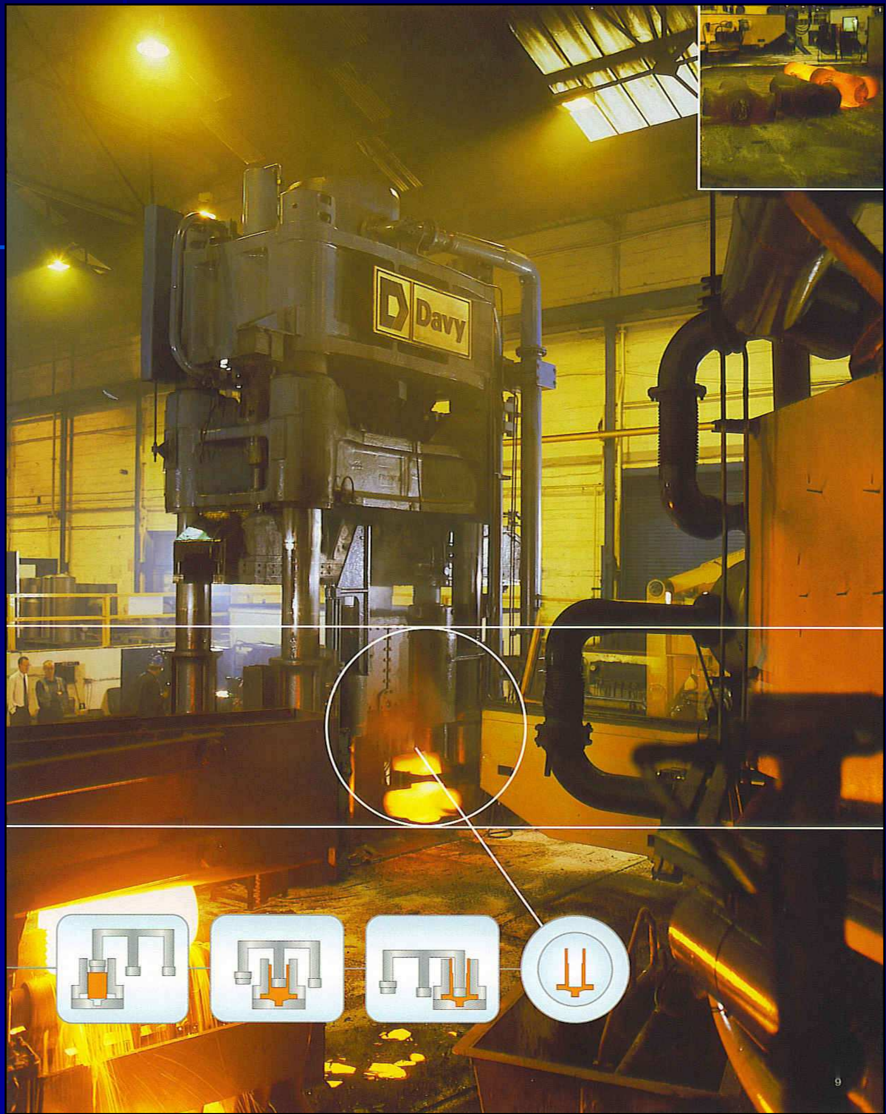
Where
- ***m*** = mass
- ***v*** = velocity of ram at start of deformation
- ***g*** = acceleration of gravity
- ***p*** = air or steam pressure acting on ram cylinder on downstroke
- ***A*** = area of ram cylinder
- ***H*** = height of the ram drop

Hydraulic press forging



- 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***.

Example: Hydraulic Press forging



- ***Hydraulic presses*** are load-restricted machines in which hydraulic pressure moves a piston in a cylinder.

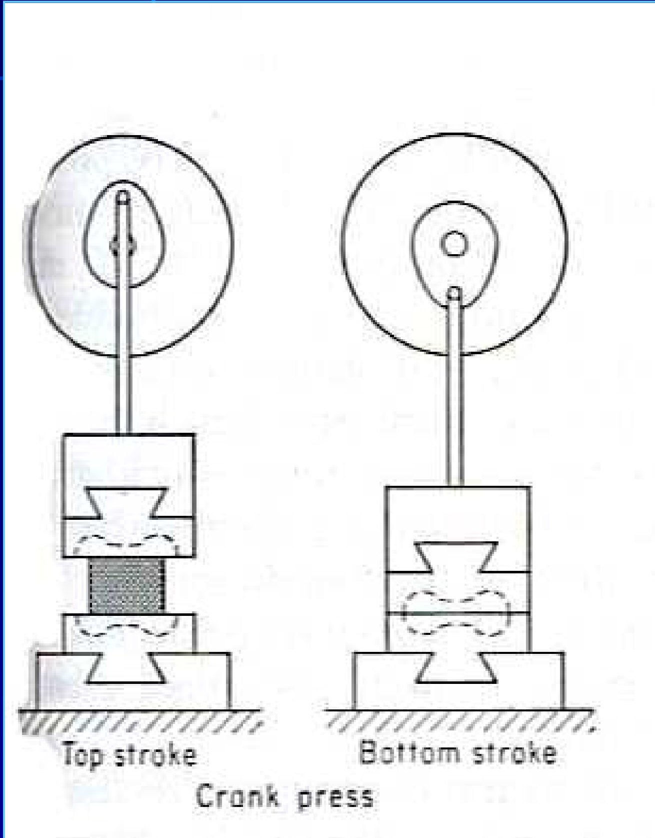
- The full press load is available at any point during the full stroke of the ram. Therefore, hydraulic presses are ideally suited for ***extrusion-type forging operation***.

- 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.

- Also provide close-tolerance forging.

- Hydraulic presses are ***more expensive*** than mechanical presses and hammers.

Mechanical press forging



Mechanical press

- 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 more like ***squeeze*** 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

$$W = \frac{1}{2} I\left[\omega_o^2 - \omega_f^2\right] \qquad \text{...Eq 3}$$

Where I is moment of inertia of the flywheel

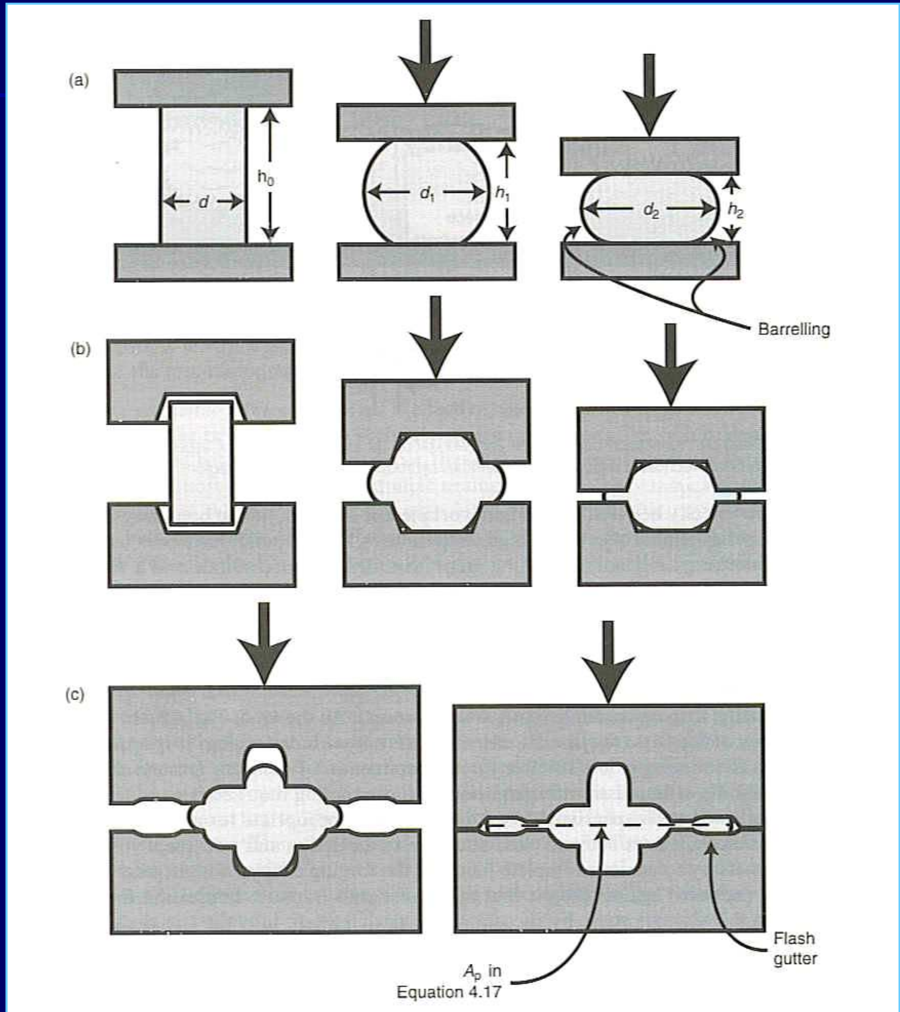
ω is angular velocity, ω_o-original, ω_f-after deformation, rad.s^{-1}

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

Remark: HERF – High Energy Rate Forging

Closed and open die forging processes



Open-die forging

Closed-die forging

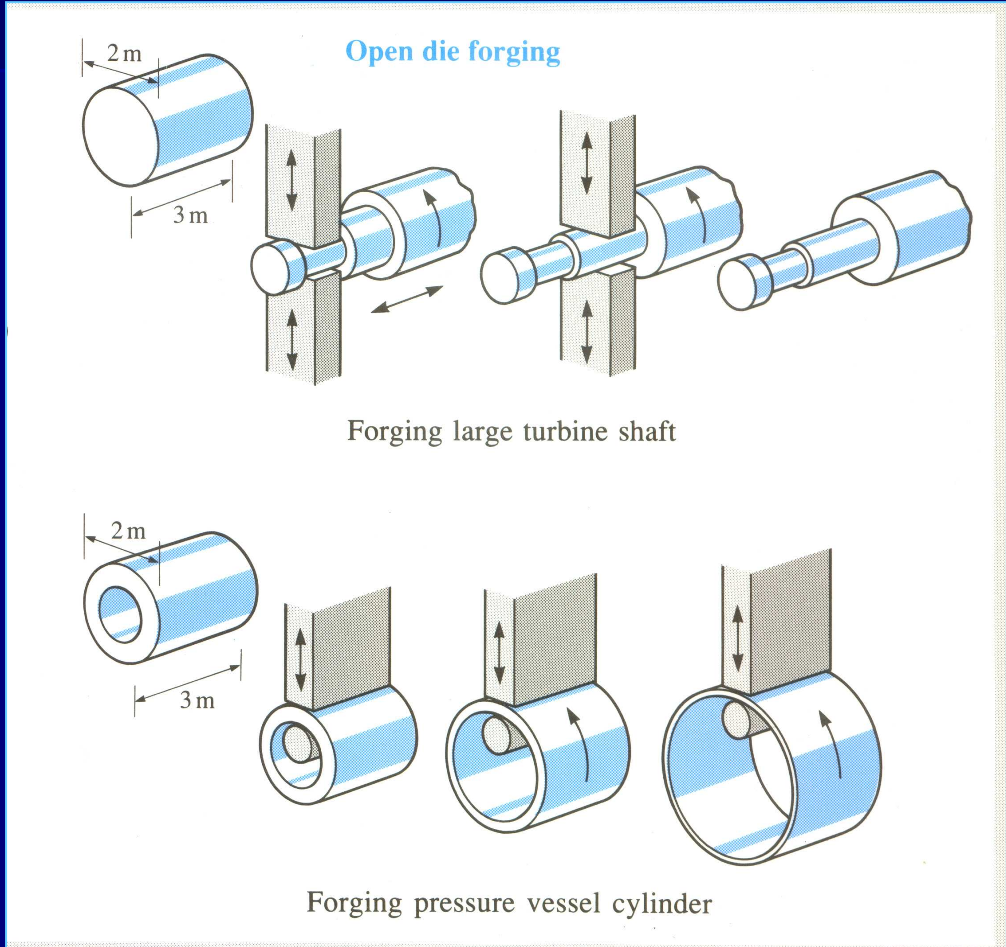
Impression-die forging

Open-die forging

• ***Open-die forging*** is carried out between flat dies or dies of very simple shape.

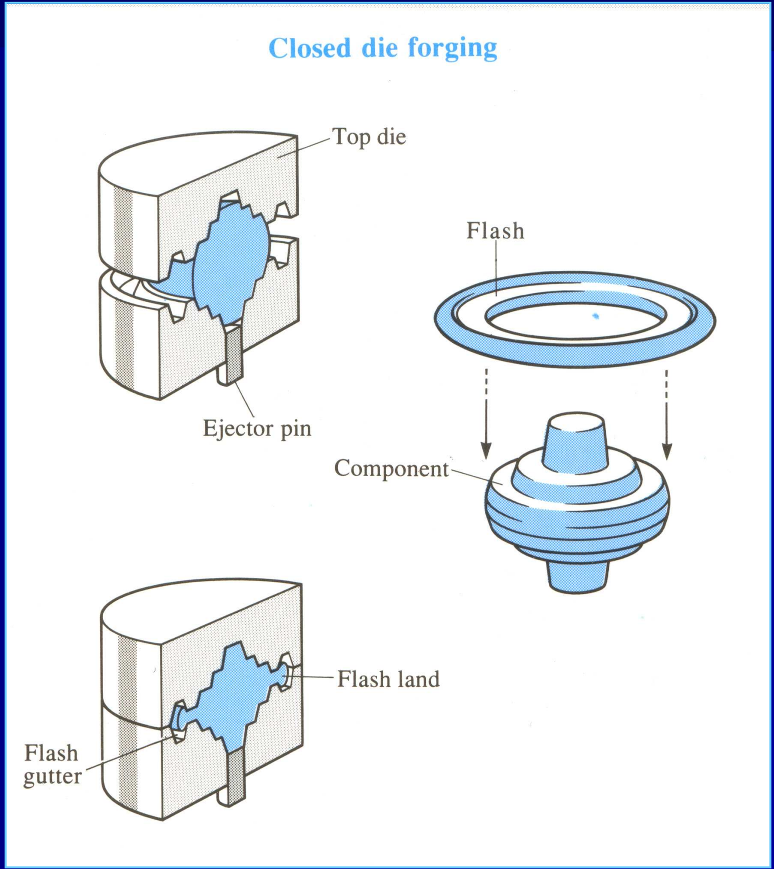
• The process is used for mostly ***large objects*** or when the number of parts produced is small.

• Open-die forging is often used to ***preform*** the workpiece for closed-die forging.



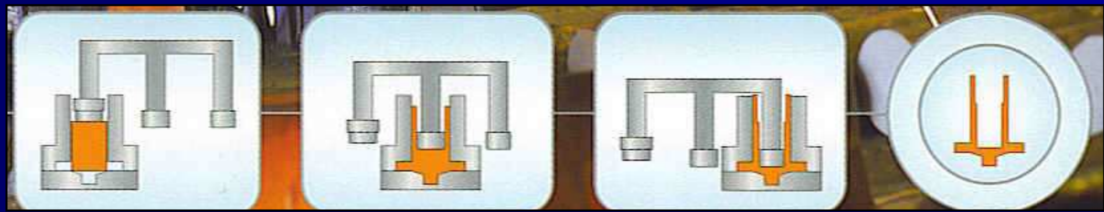
Closed-die forging (or impression-die forging)

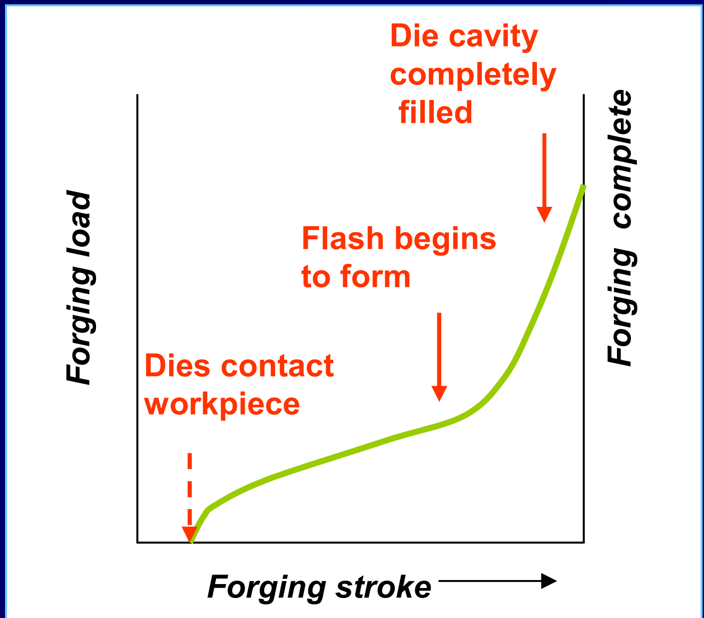
- The workpiece is deformed between two die halves which carry the ***impressions*** of the desired final shape.
- The workpiece is deformed under high pressure in a closed cavity.
- Normally used for ***smaller components***.
- The process provide precision forging with ***close dimensional tolerance***.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



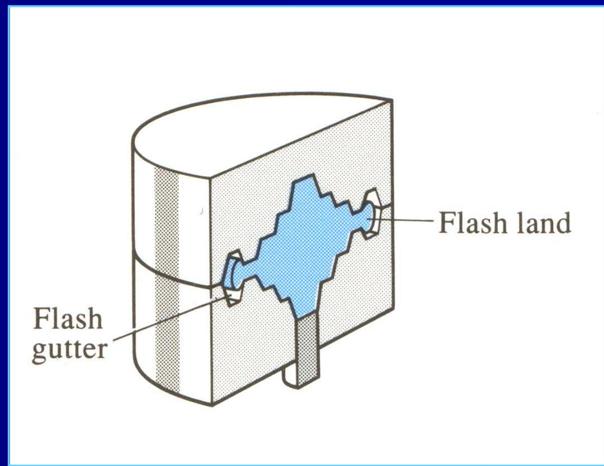
Closed-die forging operation

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



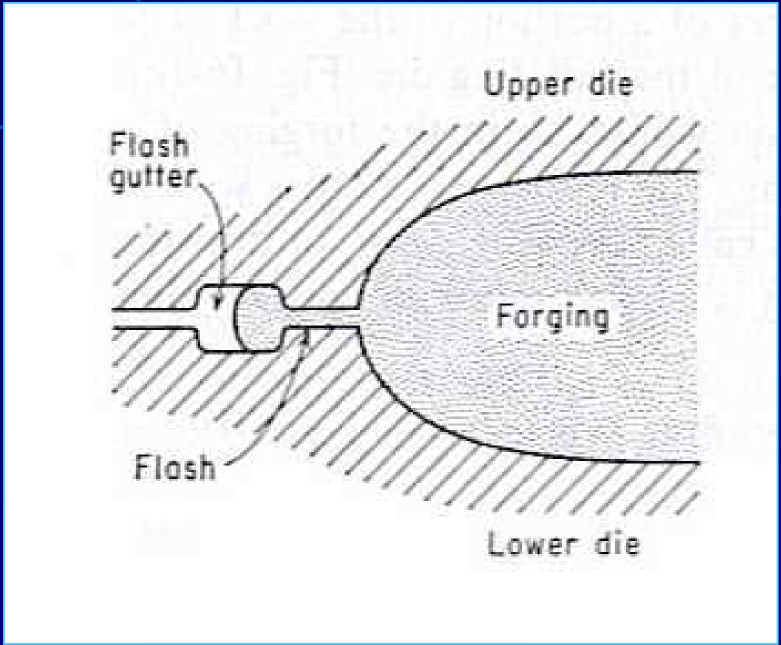


Typical curve of forging load vs. stroke for closed-die forging.



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

Functions of flash

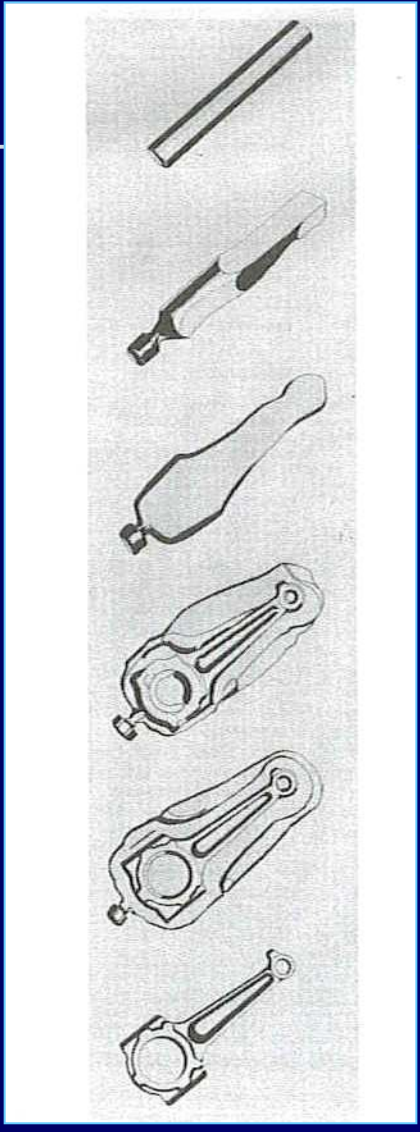


The ***flash*** serves two purposes:

- Acts as a '***safety value***' for excess metal.
- Builds up ***high pressure*** to ensure that the metal fills all recesses of the die cavity.

Remark: *It is necessary to achieve complete filling of the forging cavity without generating* ***excessive pressures*** *against the die that may cause it to fracture.*

Example: *Die set and forging steps for the manufacturing of an automobile engine connecting rod*



- ***Preforming*** of a round piece in an open die arrangement.
- Rough shape is formed using a block die.
- The finishing die is used to bring the part to final tolerances and surface finish.
- Removal of flash (excess metal).

Steering knuckle

Rail

Flange

http://www.hirschvogel.de/en/produktionsverfahren/warmumformung.php

See simulation

Closed-die design

Usually the deformation in closed-die forging is very complex and the design of the intermediate steps to make a final precision part requires considerable experience and skill.

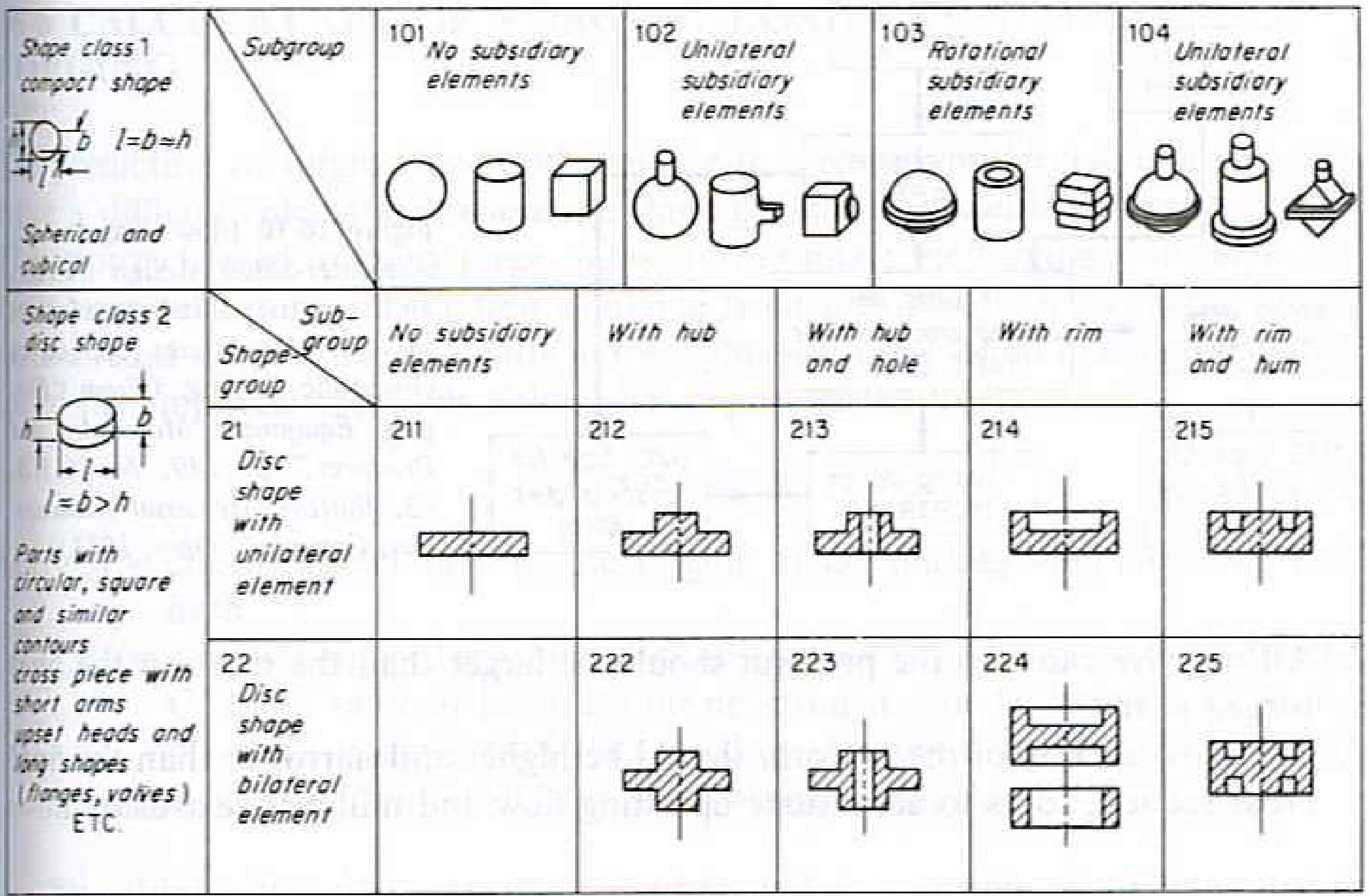
The design of a part for production by closed-die forging involves the prediction of

- workpiece volume and weight
- number of preforming steps and their configuration
- flash dimensions in preforming and finishing dies

the load and energy requirement for each forging operation, for example; the flow stress of the materials, the fictional condition, the flow of the material in order to develop the optimum geometry for the dies.

Shape classification

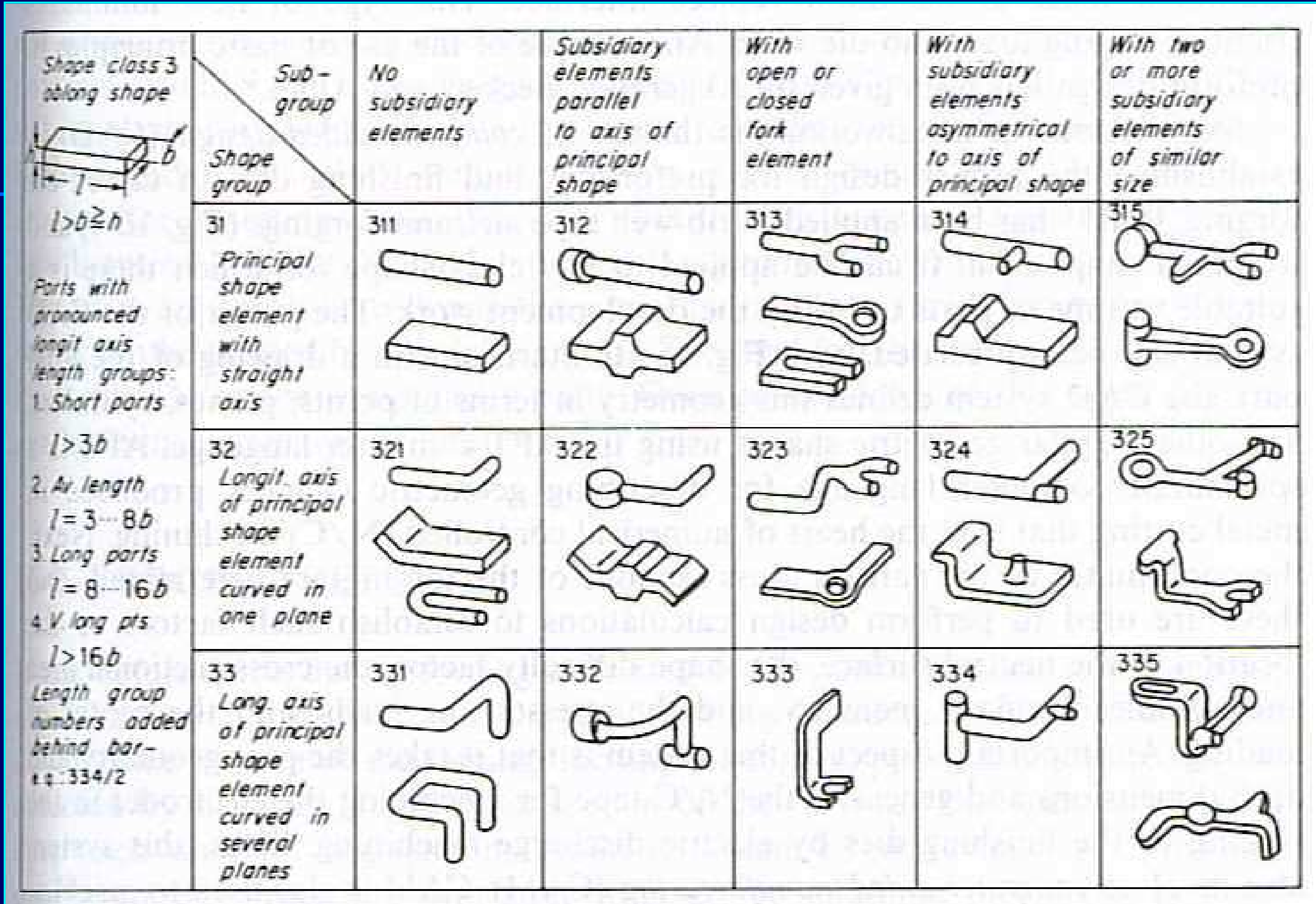
•The ***degree of difficulty*** increases as the geometry moves down and toward the right.



Shape class 1 compact shape $l=b\approx h$ 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 $l=b>h$ Parts with circular, square and similar contours cross piece with short arms upset heads and long shapes (flanges, valves) ETC.	Sub-group / Shape-group	No subsidiary elements	With hub	With hub and hole	With rim	With rim and hum
	21 Disc shape with unilateral element	211	212	213	214	215
	22 Disc shape with bilateral element		222	223	224	225

• Simple parts are symmetry shape, or parts with ***circular, square and similar contours***.

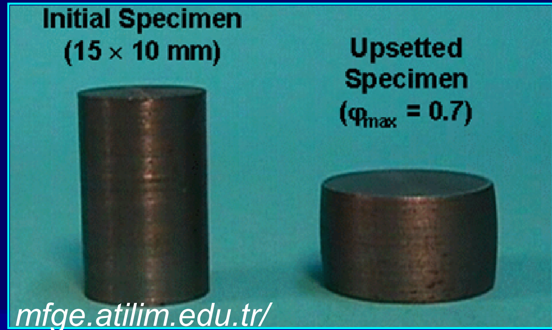
Shape classification



Shape class 3 oblong shape	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
$l > b \geqq h$ Parts with pronounced longit. axis length groups: 1. Short parts	31 Principal shape element with straight axis	311	312	313	314	315
$l > 3b$ 2. Av. length $l = 3 \cdots 8b$ 3. Long parts $l = 8 \cdots 16b$ 4. V. long pts $l > 16b$	32 Longit. axis of principal shape element curved in one plane	321	322	323	324	325
Length group numbers added behind bar– e.g.: 334/2	33 Long. axis of principal shape element curved in several planes	331	332	333	334	335

• More ***complicated parts*** have ***pronounced longitudinal axis*** and are curved in several planes.

Preform design is the most difficult and critical step in forging design. Proper preform design assures defect-free flow, complete die fill, and minimum flash loss.

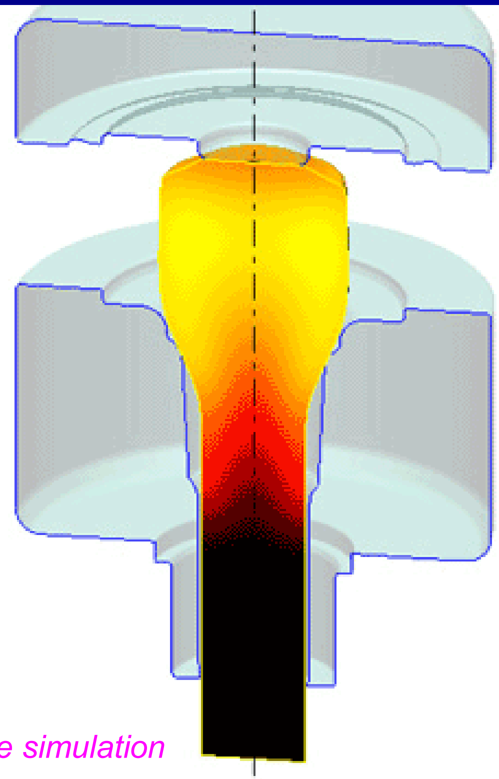


Upsetting

- Metal flow consists only of two basic types
- *extrusion* (flow parallel to the direction of the die motion)
- *upsetting* (flow perpendicular to the direction of the die motion).

- However both types of ***metal flow*** occur simultaneously.

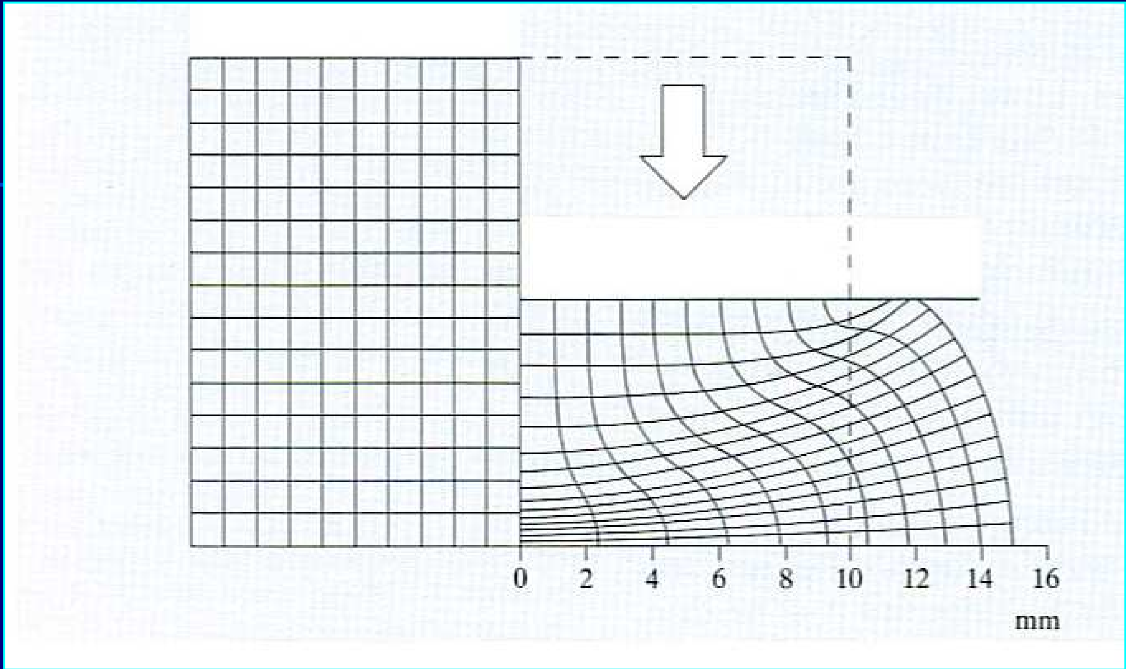
- We need to identify the neutral surface since metal flows away from the neutral surface in a direction perpendicular to the die motion.



See simulation

http://www.qform3d.com/images/elecrups/elecrups2.gif

Metal flow in forging



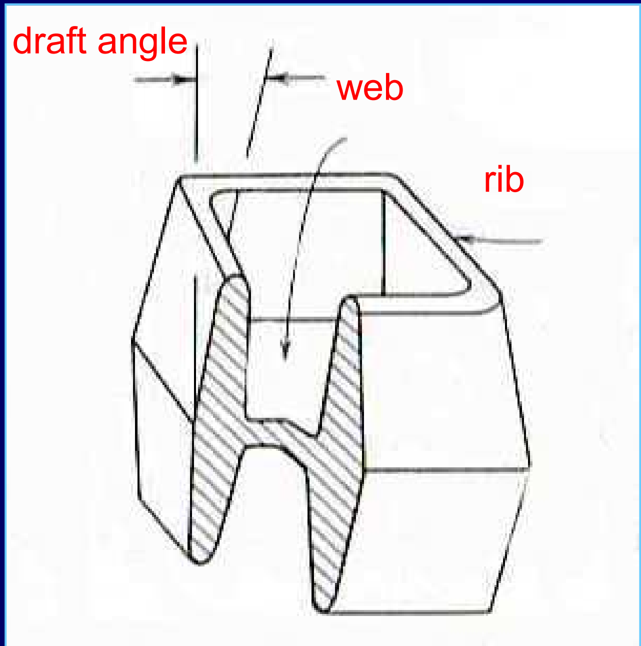
Finite element analysis of upsetting an aluminium cylinder

- ***Finite element analysis*** was originally developed to model the ***elastic deformation of complex structures*** but recently has been extended to cover large plastic deformation under ***real stress system.***

- It is a numerical modelling technique that involves ***splitting the whole of a body into a series of simple geometrical elements*** that are joined together at points (nodes) where both ***equilibrium*** (lower bound) and compatibility (upper bound) requirement are established.

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.

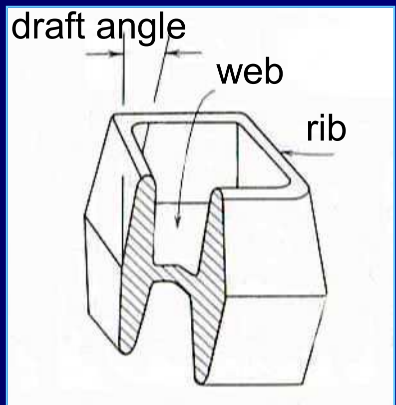


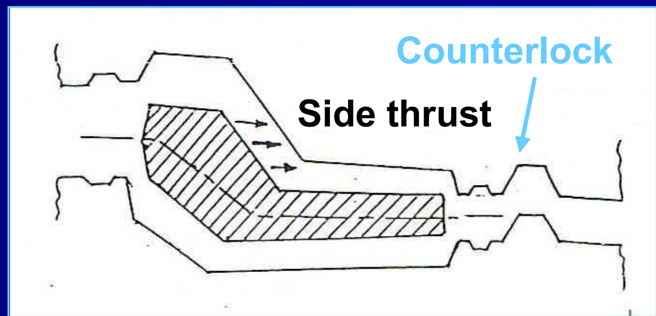
Some typical nomenclature

- 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 blocklike) 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.





www.nitrex.com

Forging die

Die materials

Required properties

- Thermal shock resistance
- Thermal fatigue resistance
- High temperature strength
- High wear resistance
- Hgh 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 are nitriding or chromium plating are required to improve die life)

Note:

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 materials

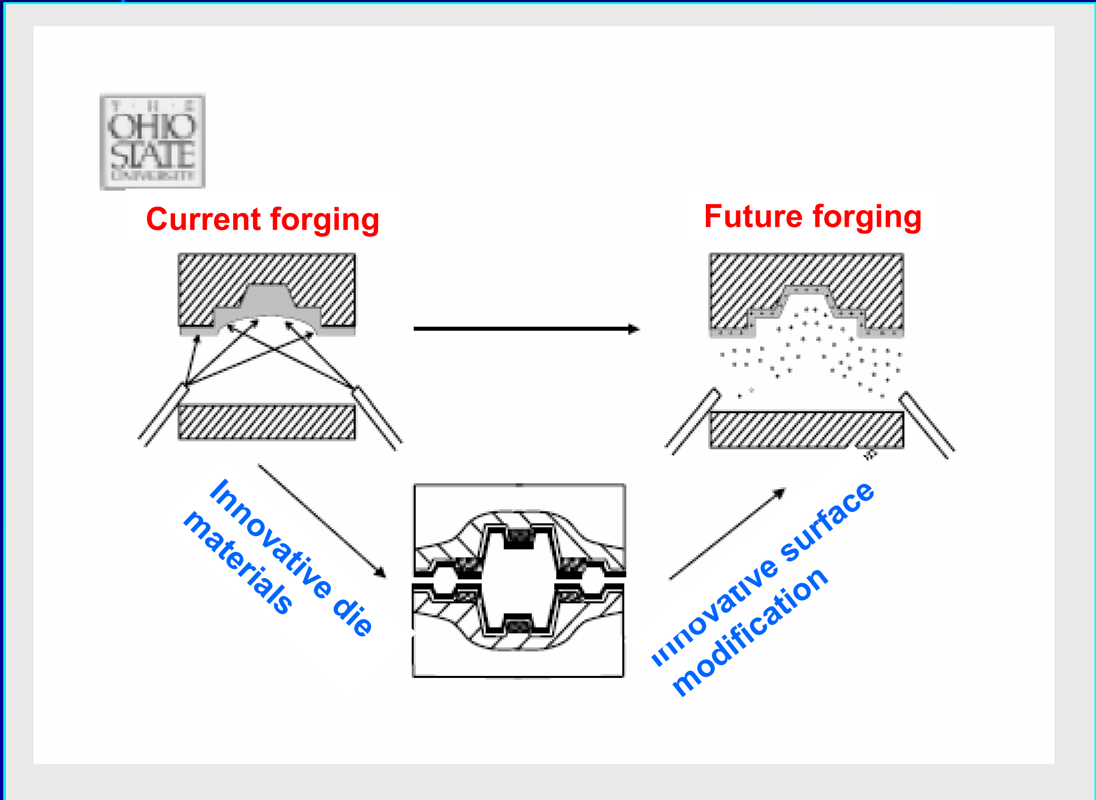
Common steels used for forging dies

Forging materials	Steels		Copper and copper alloys		Light alloys	
	DIN	AISI	DIN	AISI	DIN	AISI
Forging dies	C70 W2	-				
	C85 W2	-				
	60MnSi4	-	X30WCrV53	H21	X30WCrV53	-
	40CrMnMo7	-	X38CrMoV51	H11	X38CrMoV51	H11
			X32CrMoV33	H10		
Die inserts	55NiCrMoV6	6F2			55NiCrMoV6	
	56NiCrMoV7	6F3			56NiCrMoV7	6F2
	57NiCrMoV77	-	57NiCrMoV77	-	57NiCrMoV77	6F3
	35NiCrMo16	-				
	X38CrMoV51	H11	X30WCrV93	H21	X38CrMoV51	H11
	X32CrMoV33	H10	X32CrMoV33	H10	X32CrMoV33	H10
	X30WCrV53	-	X30WCrV52	-	X30WCrV53	-
	X37CrMoW51	H12				

Die materials

Die life can be increased by

1) Improving die materials such as using composite die or
2) Using surface coating or self-lubricating coatings



Ultra hard surface coatings

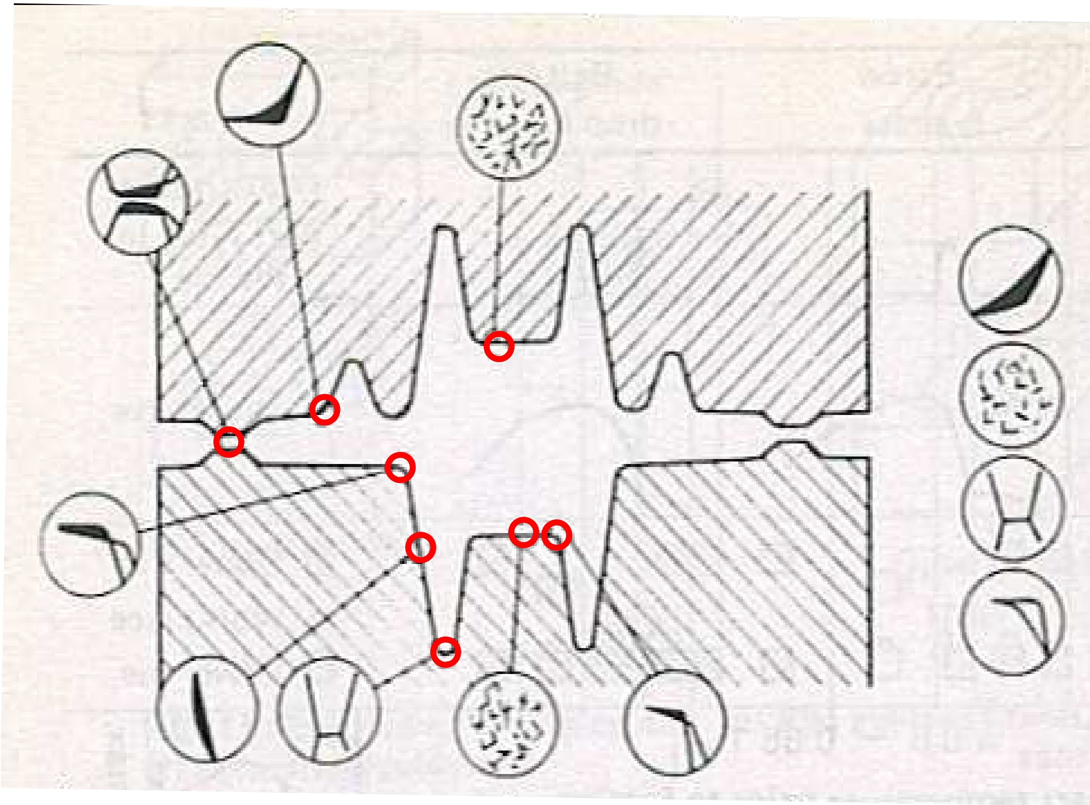
Ultra hard surface coating on die surface is used to

- Improve die life.
- Reduce energy input.
- Reduce die-related uptime and downtime.
- Reduce particulate emission from lubricants.

http://www.eere.energy.gov/industry/supporting_industries/pdfs/innovative_die_materials.pdf

Die failures

Different types of die failure



Wear (abrasion)

Thermal fatigue

Mechanical fatigue

Permanent deformation

- Different parts of dies are liable to permanent deformation and wear resulting from ***mechanical and thermal fatigue***.
- ***Important factors:*** shape of the forging, die materials, how the workpiece is heated, coating of die surface, the operating temperature (should not exceed the annealing temperature).

Calculation of forging loads

The ***total energy*** required for deformation process;

$$U_{total} = U_{ideal} + U_{friction} + U_{redundant}$$

Note: *redundant work = work that does not contribute to shape change of the workpiece*

Efficiency of a given deformation process η is

$$\eta = \frac{U_{ideal}}{U_{total}}$$

Note: η *= 0.3-0.6 for extrusion*
= 0.75-0.95 for rolling
= 0.10-0.20 for closed die forging

The calculation for forging load can be divided into three cases according to friction:

- ***In the absence of friction***
- ***Low friction condition (lower bound analysis or sliding condition)***
- ***High friction condition (sticky friction condition)***

1) In the absence of friction

By assuming that there is no friction at die-workpiece interface, the forging load is therefore the ***compressive force*** (*P*) acting on a round metal bar.

Then

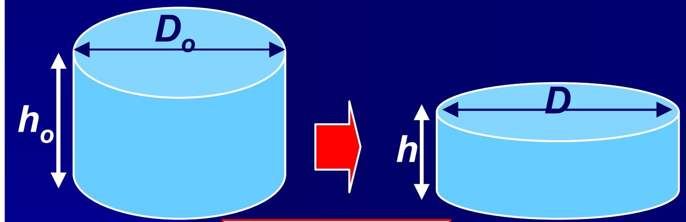
$$P = \sigma_o A \qquad \text{....Eq. 4}$$

Where **P** is the compressive force

σ_o is the yield stress of the metal

A is the cross sectional area of the metal.

And the ***compressive stress*** (***p***) *produced by this force* ***P*** can be obtained from



$$D_o^2 h = D^2 h$$

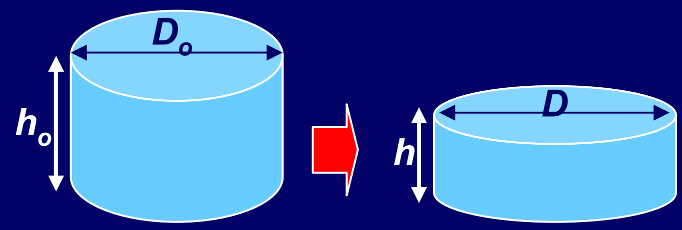
$$p = \frac{4Ph}{\pi D^2} \rightarrow \frac{4Ph}{\pi D_o^2 h_o} = \frac{4\sigma_o A h}{\pi D_o^2 h_o} \qquad \text{....Eq. 5}$$

Note: from volume constant

Where **h** is the instantaneous height of the metal bar during forging

h_o is the original height of the metal bar

D_o is the original diameter of the metal bar.



We have ***engineering strain*** in compression,

$$e = \frac{\Delta h}{h_o} = \frac{h - h_o}{h_o} \qquad \text{....Eq. 6}$$

And ***true strain*** in compression,

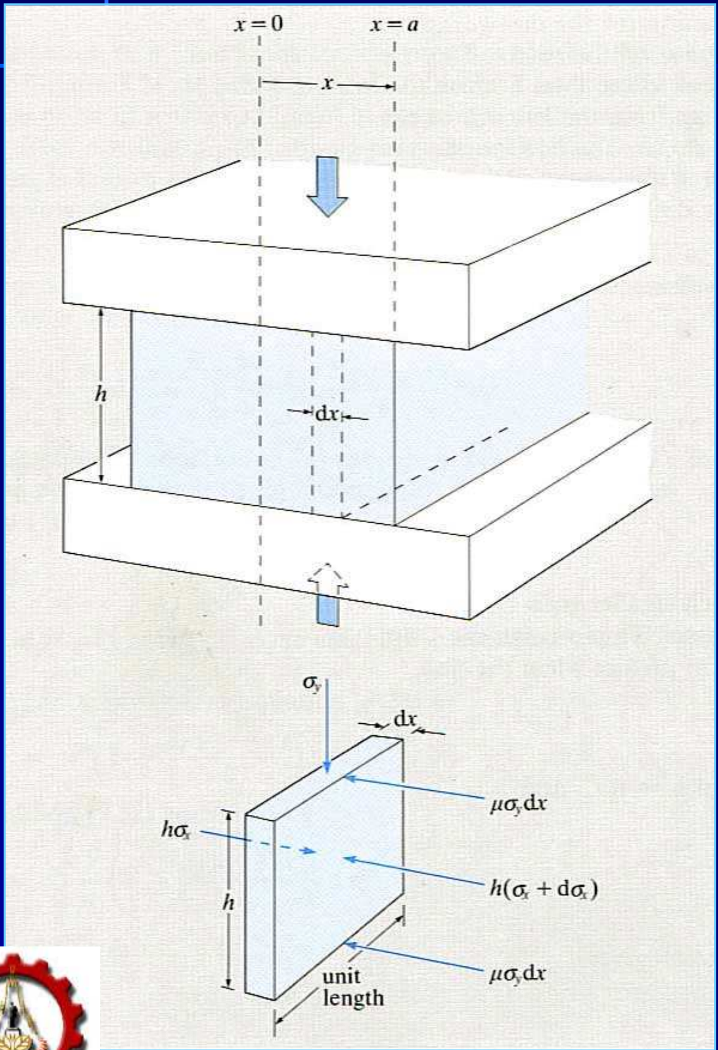
$$\varepsilon = \int_{h_o}^{h} \frac{dh}{h} = \ln\frac{h}{h_o} = -\ln\frac{h_o}{h} \qquad \text{....Eq. 7}$$

The relationship between e and ε is

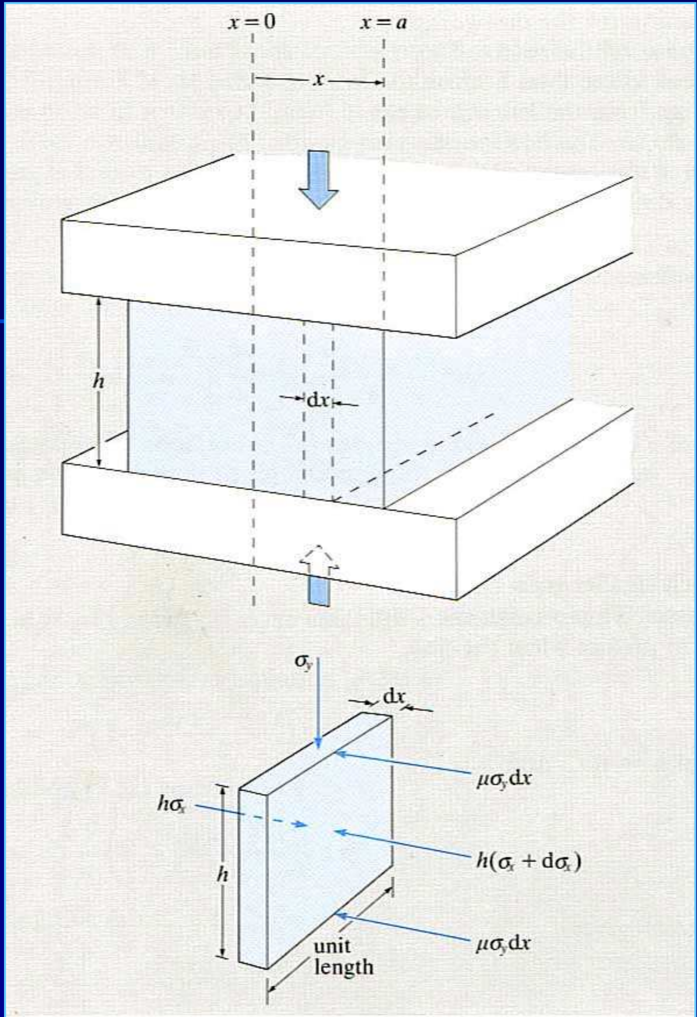
$$\varepsilon = \ln(e+1) \qquad \text{....Eq. 8}$$

2) Low friction condition (Lower bound analysis)

By considering the equilibrium of forces acting on the workpiece at any instant of deformation.



- For example, if we consider the effect of friction on an upset forging operation in ***plane strain condition*** (rigid-plastic behaviour, *see Fig*).
- To calculate the ***total forming load***, we have to determine the local stresses needed to deform each element of a workpiece of height ***h*** and width ***2a***.
- In ***plane strain condition***, as the workpiece is reduced in height, it expands laterally and all deformation is confined in the ***x-y*** plane. This lateral expansion causes frictional forces to act in opposition to the movement.
- Assuming that there is no ***redundant work*** and the material exhibits ***rigid-plastic behaviour***, and all stress on the body are compressive.



- Consider the force acting on a vertical element of unit length and width ***dx***. The element is at some distance ***x*** from the central '***no-slip***' point, in this case to the right.

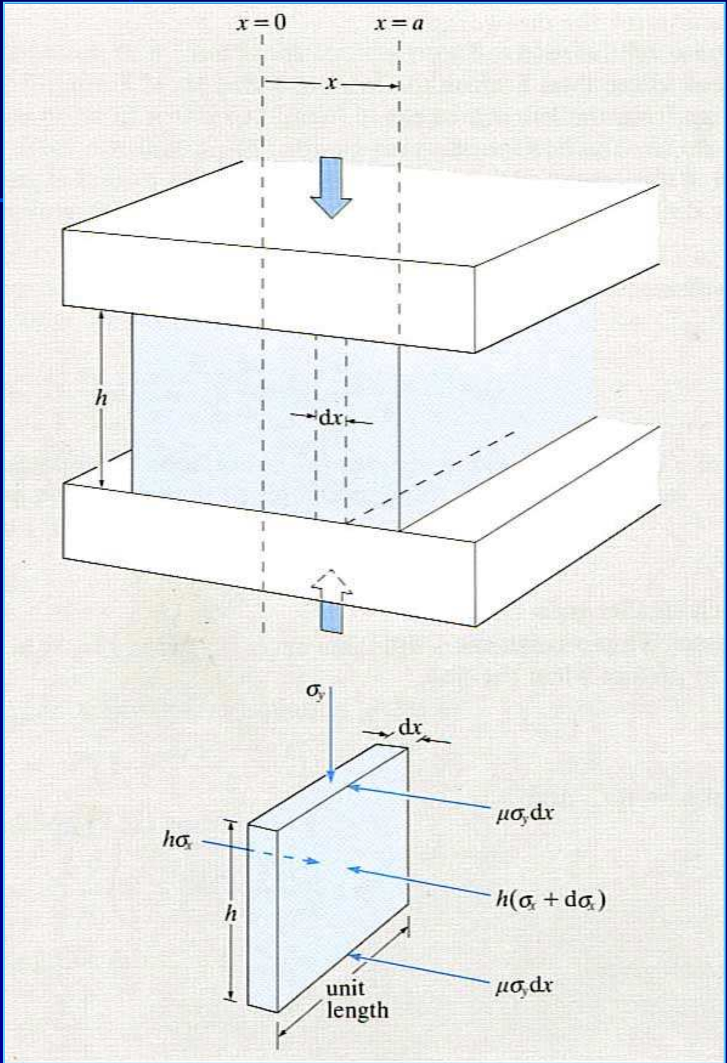
- The ***vertical force*** acting on the element is

$$\boxed{stress \times area = \sigma_y dx}$$

….Eq. 9

- If the coefficient of friction for the die-workpiece interface is μ, the magnitude of the friction force will be $\mu\sigma_y dx$. The frictional force acts at both ends of the element so the total horizontal force from the right is $2\mu\sigma_y dx$.

- Acting on the left will be the force $\sigma_x h$ and from the right the force $(\sigma_x + d\sigma_x)h$. The horizontal compressive stress σ_x varies from a maximum at the centre of the workpiece to zero at the edge and changes by $d\sigma_x$ across the element width ***dx***.



Balancing the horizontal forces acting on the element:

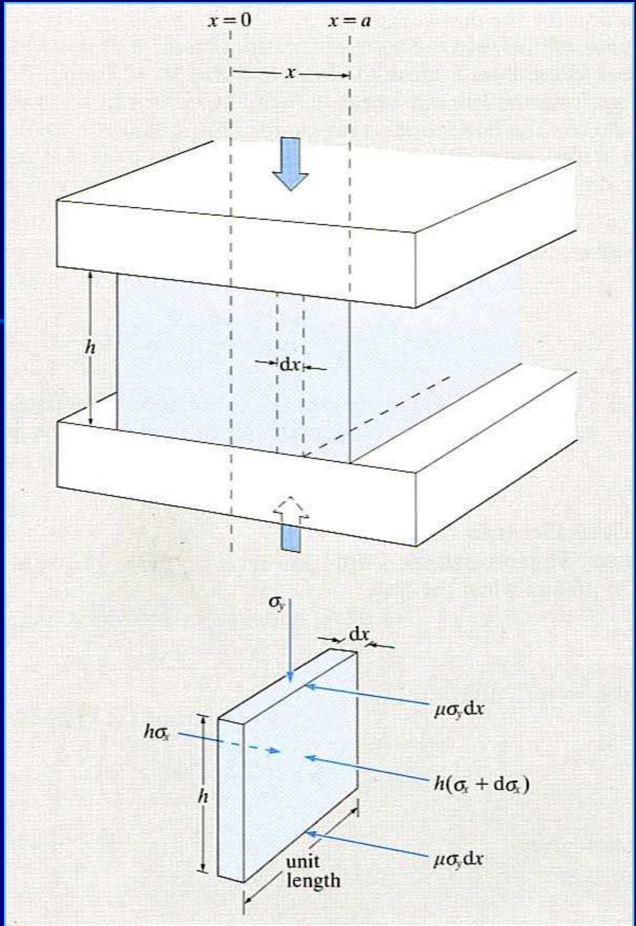
$$h(\sigma_x + d\sigma_x) + 2\mu\sigma_y dx = h\sigma_x \qquad \text{....Eq. 10}$$

Rearranging, we have

$$2\mu\sigma_y dx = -hd\sigma_x \qquad \text{....Eq. 11}$$

and therefore

$$\frac{d\sigma_x}{\sigma_y} = -\frac{2\mu}{h}dx \qquad \text{....Eq. 12}$$



As the frictional force $\mu\sigma_y$ is usually much smaller than both σ_x and σ_y, which are principal stresses. Thus we can use them in the ***yield criterion*** when the slab will yield

$$\sigma_y - \sigma_x = \frac{2}{\sqrt{3}}\sigma_o = \sigma_o' \qquad \text{….Eq. 13}$$

Where σ'_o is the yield stress in plane strain.

Differentiation of the yield condition gives $d\sigma_y = d\sigma_x$, and substituting for $d\sigma_x$ in *Eq. 12* gives

$$\frac{d\sigma_y}{\sigma_y} = -\frac{2\mu}{h}dx \qquad \text{….Eq. 14}$$

Integrating both sides of this differential equation gives

$$\ln \sigma_y = -\frac{2\mu x}{h} + C_o \qquad \text{….Eq. 15}$$

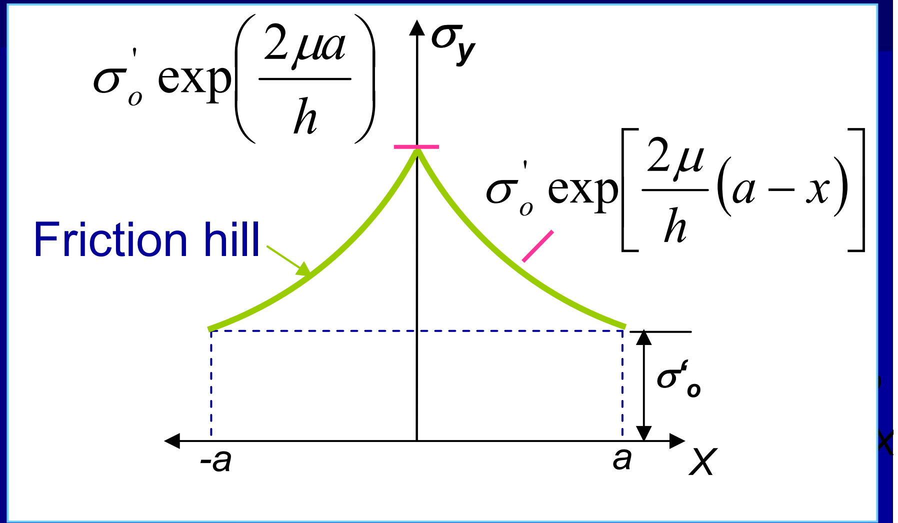
or

$$\sigma_y = C\exp\left(-\frac{2\mu x}{h}\right) \qquad \text{….Eq. 16}$$

where C_o is a constant of integration.

We can evaluate ***C*** by looking at the boundary conditions. At the edge of the workpiece where $x = a$, $\sigma_x = 0$ and from the ***yield criterion*** $\sigma_y - \sigma_x = \sigma'_o$, so $\sigma_y = \sigma'_o$ and therefore:

$$C \exp\left(-\frac{2\mu a}{h}\right) = \sigma'_o \quad \text{....Eq. 17}$$

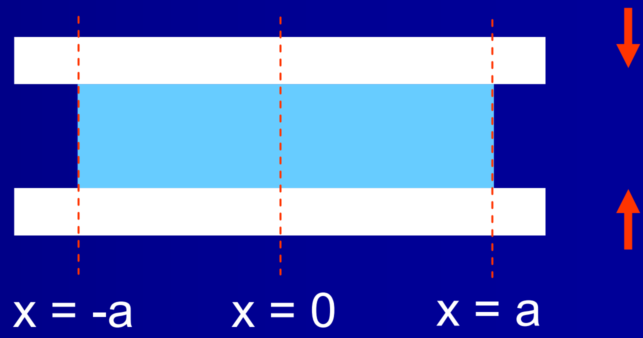


so

$$C = \sigma'_o \exp\left(\frac{2\mu a}{h}\right) \quad \text{....Eq. 18}$$

Using this in *Eq.16*, we find

$$\sigma_y = \sigma'_o \exp\left[\frac{2\mu}{h}(a-x)\right] \quad \text{....Eq. 19}$$



The total forging load, *P*, is given by

$$P = 2\bar{p}aw$$ ….*Eq. 20*

Where $\bar{p}$ is the average forming pressure across the workpiece
w is the width of the workpiece (in the plane of the paper).

This equals σ_y and can be estimated by integrating *Eq.19*:

$$\bar{p} = \int_o^a \frac{\sigma_y}{a}dx = \int_o^a \frac{\sigma_o'}{a}\exp\left[\frac{2\mu}{h}(a-x)\right]dx$$ ….*Eq. 21*

The integration in *Eq. 18* can be simplified if we make the following approximation to *Eq. 16*. The general series expansion for ***exp x*** is

$$\exp x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + ...$$ ….*Eq. 22*

Since μ is usually small (<1) we can approximate ***exp x*** as ***(1+x)*** for small ***x***.

Thus we can approximate *Eq.19* as

$$\sigma_y = \sigma'_o \left[1 + \frac{2\mu(a-x)}{h} \right] \qquad \text{....Eq. 23}$$

and *Eq.21* becomes

$$\bar{p} = \int_0^a \frac{\sigma'_o}{a} \left[1 + \frac{2\mu(a-x)}{h} \right] dx \qquad \text{....Eq. 24}$$

Integrating this gives:

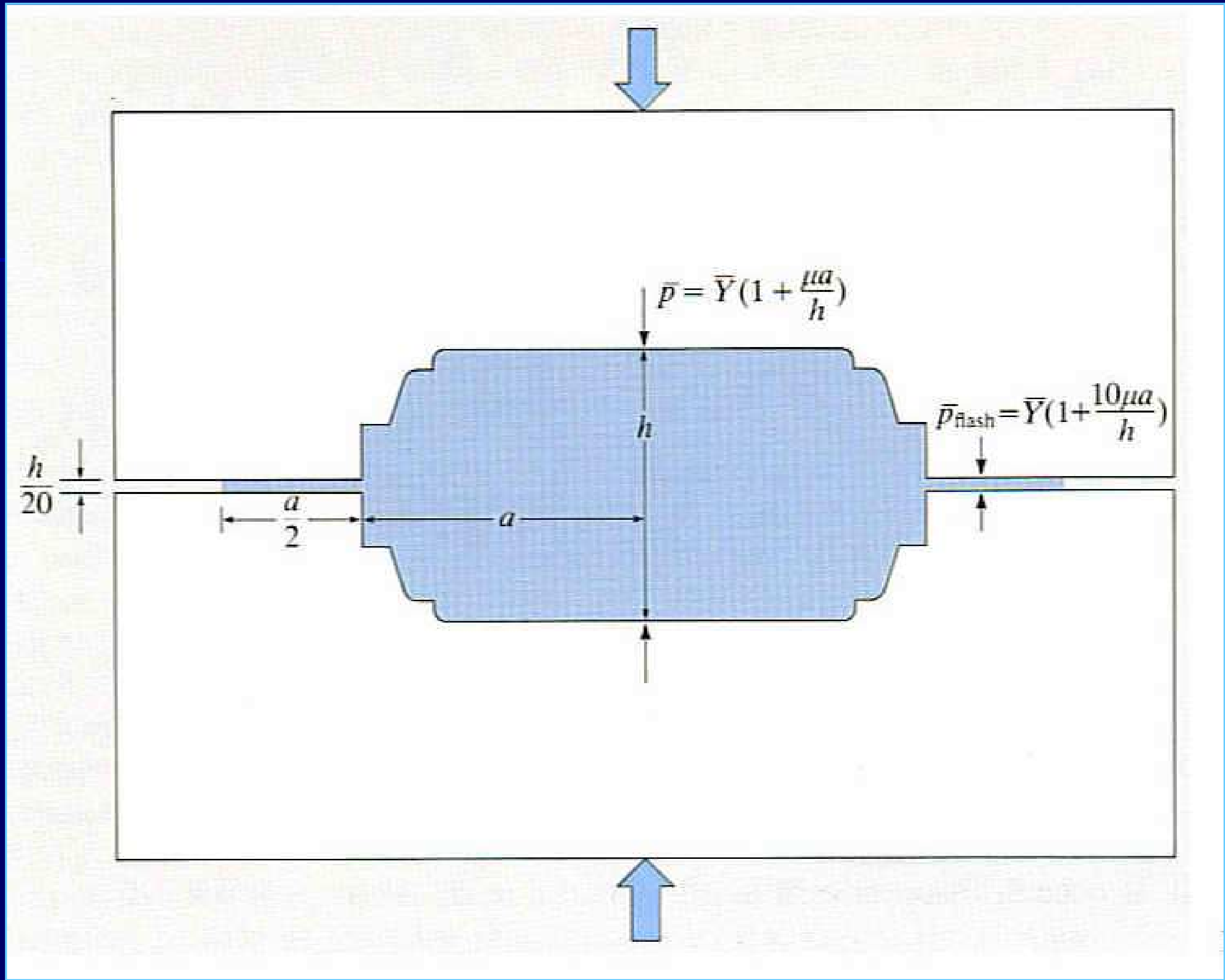
$$\bar{p} = \frac{\sigma'_o}{a} \left[x + \frac{2\mu a x}{h} - \frac{\mu x^2}{h} \right]_0^a \qquad \text{....Eq. 25}$$

So that the average axial tooling pressure, $\bar{p}$, is

$$\bar{p} = \sigma'_o \left(1 + \frac{\mu a}{h} \right) \qquad \text{....Eq. 26}$$

We can see that as the ratio ***a/h*** increases, the forming pressure $\bar{p}$ and hence the forming load rises rapidly.

Example:



The ***flash*** has high deformation resistance than in the die (due to much higher ***a/h*** ratio), therefore the material completely fills the cavity rather than being extruded ***sideward*** out of the die.

3) High friction condition (sticky friction)

In the situation where the friction force is high, the stress acting on the metal is

$$\sigma_y = \sigma_o'\left(\frac{a-x}{h}-1\right) \qquad \text{….Eq. 27}$$

and the mean forging pressure is

$$\bar{p} = \sigma_o'\left(\frac{a}{2h}+1\right) \qquad \text{….Eq. 28}$$

Under these conditions, the forming load is dependent on the flow stress of the material and the geometry of the workpiece.

For example: if the ***a/h*** ratio is high, say ***a/h = 8,*** then $\bar{p} = 5\sigma_o'$. The local stress on the tooling can therefore be very high indeed and $5\sigma_o'$ is probably high enough to deform the tooling in most cold forming operation.

Solutions:

- reducing μ to ensure that sticking friction conditions do not apply.
- changing the workpiece geometry.
- reducing σ_o' by increasing the temperature.

In the case of ***sticky friction***, if we replace the force $\mu\sigma_y$ with $\bar{k}$ (the average shear stress of the material) in *Eq.14*

$$\frac{d\sigma_y}{\sigma_y} = -\frac{2\mu}{h}dx \qquad \text{….Eq. 14}$$

then we have

$$d\sigma_y = -\frac{2\bar{k}}{h}dx = -\frac{2\sigma_o}{\sqrt{3}}\frac{dx}{h} = -\sigma_o'\frac{dx}{h} \qquad \text{….Eq. 29}$$

Integrating

$$\sigma_y = -\sigma_o'\frac{x}{h} + C \qquad \text{….Eq. 30}$$

Since $\sigma_y = \sigma'_o$ at x = ***a***, then

$$C = \sigma_o' + \sigma_o'\frac{a}{h} \qquad \text{….Eq. 31}$$

Replacing ***C*** in *Eq. 30* we then have

$$\sigma_y = -\sigma_o'\frac{x}{h} + \sigma_o' + \sigma_o'\frac{a}{h} = \sigma_o'\left(\frac{a-x}{h} + 1\right)$$

Or *Eq. 27*

<u>Example:</u> *Dieter, page 574-575*

*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 150 mm dimension does not change, the deformation is plane strain. From *Eq.19*.

$$\sigma_y = \frac{2}{\sqrt{3}}\sigma_o \exp\left[\frac{2\mu}{h}(a-x)\right]$$

where

$$\sigma_o' = \frac{2}{\sqrt{3}}\sigma_o$$

At the centreline of the slab (***x*** = *0*)

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

Likewise, at <u>25</u> and <u>50</u> mm, the stress distribution will be <u>58.9</u> and <u>8.0</u> MPa respectively.

The mean forging load (in the sticky friction condition) from *Eq.28* is

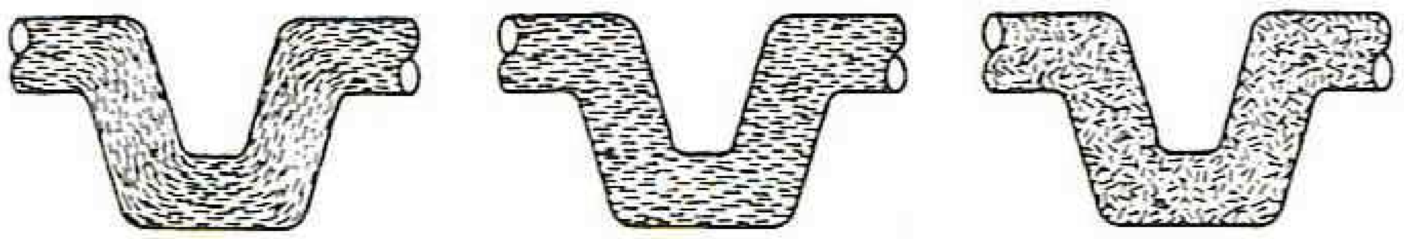
$$\bar{p} = \frac{2}{\sqrt{3}}\sigma_o\left(\frac{a}{2h}+1\right)$$

$$\bar{p} = \frac{2(6.9)}{\sqrt{3}}\left(\frac{50}{12.5}+1\right) = 39.8MPa$$

We calculate the forging load on the assumption that the stress distribution is based on 100 percent sticky friction. Then

The forging load is ***P*** = stress x area
= $(39.8\times10^{6})(100\times10^{-3})(150\times10^{-3})$
= 597 kN
= 61 tonnes.

Effect of forging on microstructure



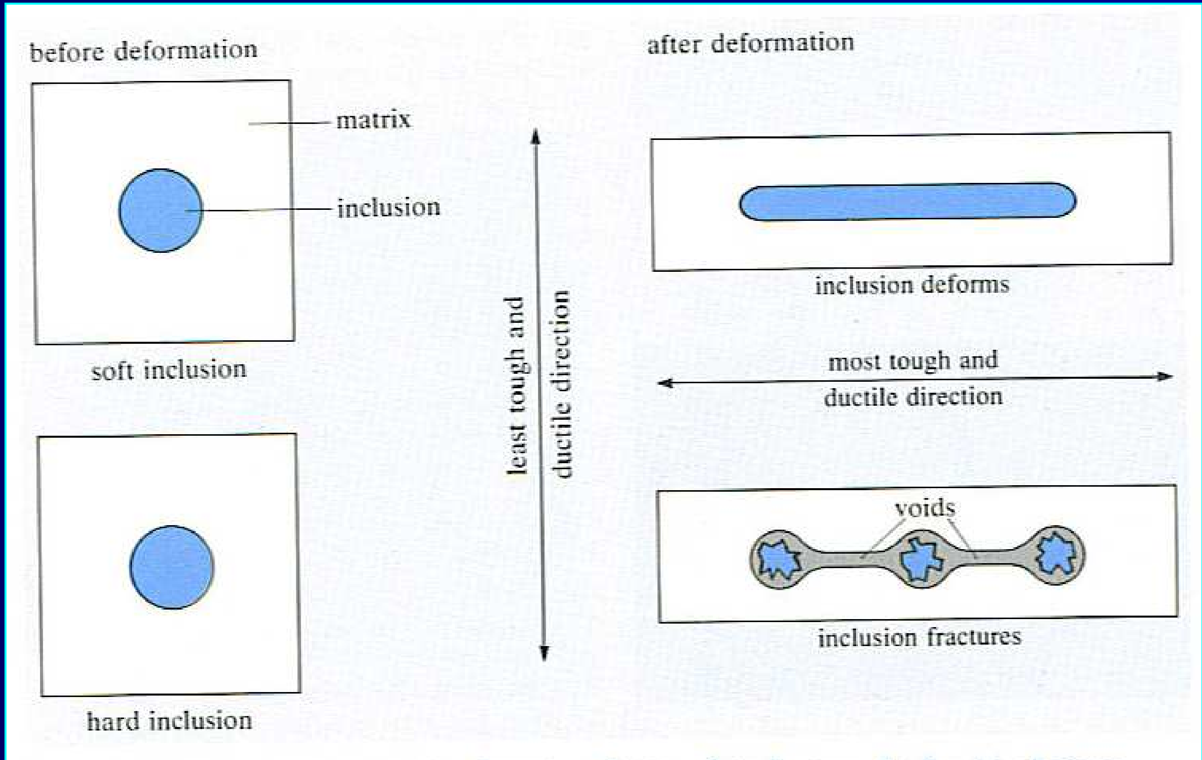
grain structure resulting from (a) forging, (b) machining and (c) casting.

- 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.

Forming textures

Redistribution of metal structures occurring during forming process involves two principle components; *1) redistribution of inclusions and 2) crystallographic orientation of the grains*

1) The redistribution of inclusions

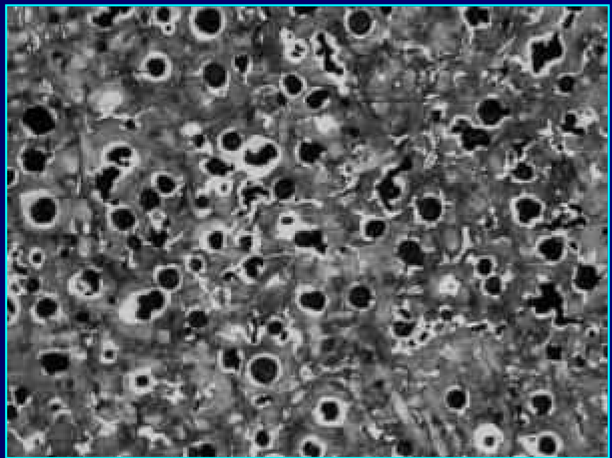


Redistribution during forming of
(a) soft inclusions
(b) hard inclusions

Forming textures

2) Crystallographic orientation of the grains

Castings



Cast iron structure

Mainly epitaxial, dendritic or equiaxed grains

Forgings

Fibre structure in forged steels

Redistribution of grains in the working directions

Residual stresses in forging

• The ***residual stress*** produced in forgings as a results of inhomogeneous deformation are generally small because the deformation is normally carried out well into the hot-working region.

• However, appreciable ***residual stresses and warping*** can occur on the quenching of steel forgings in heat treatment.

• Large forgings are subjected to the formation of ***small cracks, or flakes*** at the centre of the cross section. This is associated with the high hydrogen content usually present in steel ingots of large size, coupled with the presence of residual stresses.

• Large forgings therefore have to be ***slowly cooled*** from the working temperature. Examples: burying the forging in ashes for a period of time or using a controlled cooling furnace.

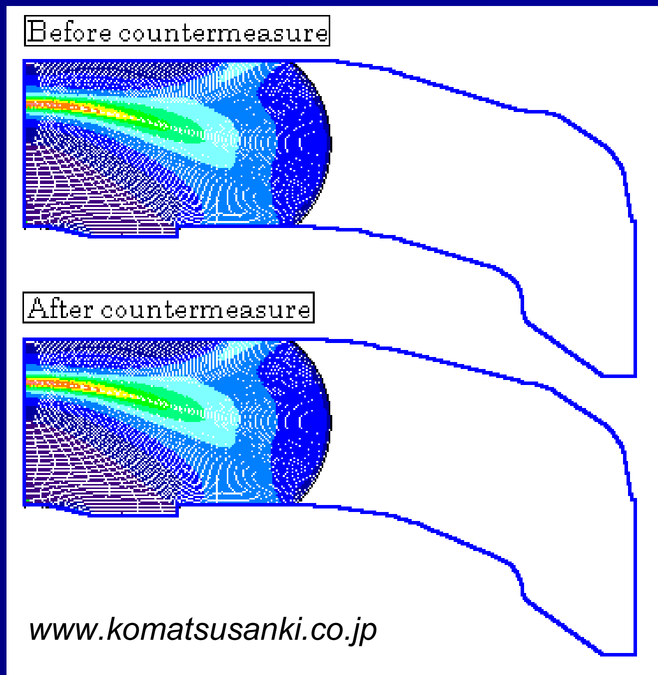
• Finite element analysis is used to predict residual stresses in forgings.

Typical forging defects

files.bnpmedia.com

Fluorescence penetrant reveals Forging laps

- Incomplete die filling.
- Die misalignment.
- Forging laps.
- Incomplete forging penetration- *should forge on the press.*
- Microstructural differences resulting in pronounced property variation.
- Hot shortness, due to high sulphur concentration in steel and nickel.



See simulation

Typical forging defects

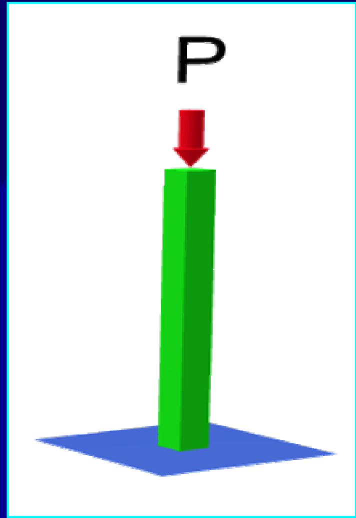
• Pitted surface, due to oxide scales occurring at high temperature stick on the dies.

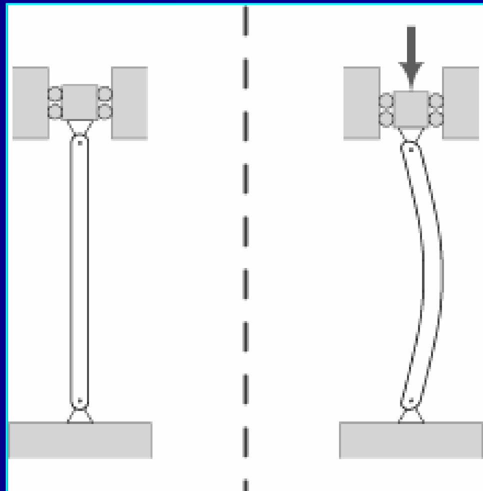
• Buckling, in upsetting forging. Subject to high compressive stress.

• Surface cracking, due to temperature differential between surface and centre, or excessive working of the surface at too low temperature.

• Microcracking, due to residual stress.

www.mece.ualberta.ca

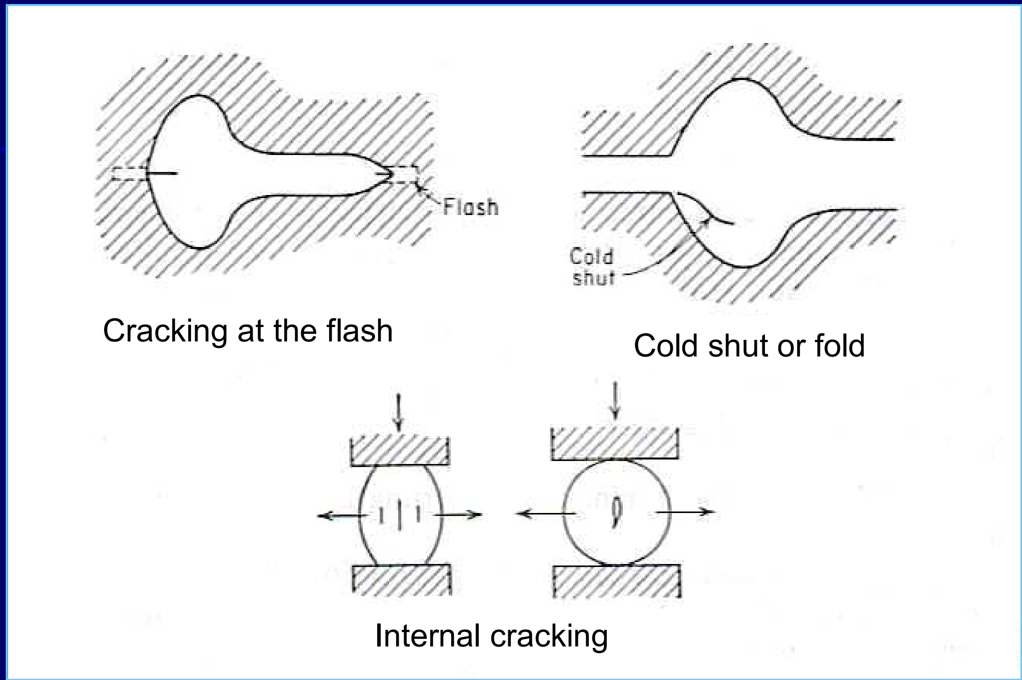




http://upload.wikimedia.org

Buckling

Typical forging defects



• ***Flash line crack***, *after trimming-occurs more often in thin workpieces. Therefore should increase the thickness of the flash.*

• ***Cold shut or fold*** *, due to flash or fin from prior forging steps is forced into the workpiece.*

• ***Internal cracking,*** due to secondary tensile stress.

Summary

• ***Mainly hot forging*** – Blacksmith, now using water power, steam, electricity, hydraulic machines.

• ***Heavy forging***

- Hydraulic press = slow, high force squeeze.
- Pieces up to 200 tonnes with forces up to 25,000 tonnes.
- Simple tools squeeze metal into shape (open-die forging).
- Sufficient deformation must be given to break up the '***as cast***' structure.
- Reheating is often needed to maintain sufficient temperature for hot working.
- Forging is costly but eliminates some as-cast defects
- Continuous '***grain flow***' in the direction of metal flow is revealed by etching.
- Impurities (inclusions and segregation) have become elongated and (unlike casting) gives superior properties in the direction of elongation.

References

- Dieter, G.E., ***Mechanical metallurgy***, 1988, SI metric edition, McGraw-Hill, ISBN 0-07-100406-8.
- Edwards, L. and Endean, M., ***Manufacturing with materials***, 1990, Butterworth Heinemann, ISBN 0-7506-2754-9.
- Beddoes, J. and Bibbly M.J., ***Principles of metal manufacturing process***, 1999, Arnold, ISBN 0-470-35241-8.
- Lange, K., ***Handbook of metal forming***, 1919, McGraw-Hill Book company, ISBN 0-07-036285-8.
- Lecture note, Sheffield University, 2003.
- Metal forming processes, Prof Manus.