MECHANICAL METALLURGY

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DEFORMATION:

Change in dimension or form of matter under the action of applied forces.

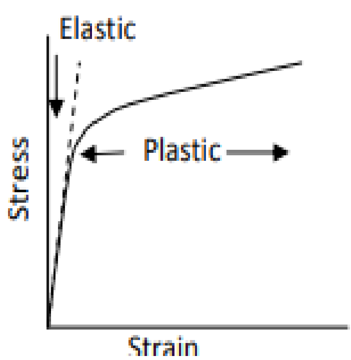
Deformation is caused either by the mechanical action of external forces or by various physical and physico chemical forces (for example, change in volume of separate crystallites in phase transformations or as a result of temperature gradient)

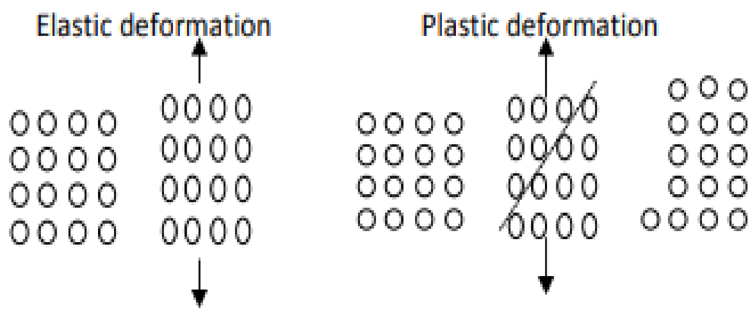
The process of deformation comprises the following consecutive stage

(1) Elastic deformation

(2) Plastic deformation

(3) Fracture

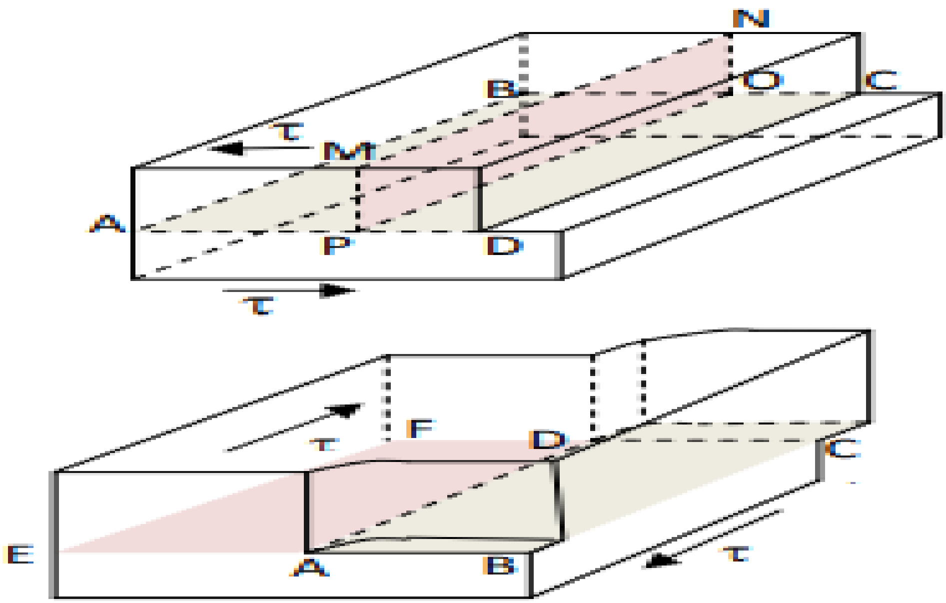




Elastic deformation is often defined as deformation which completely disappears as soon as the action of external forces ceases. Elastic deformation does not cause any noticeable changes in the structure of metals.

The application of a load elastically displaces atoms to a slight extent, relative to each other, or twists blocks of the crystal .Tensile load applied to a mono crystal increase the interatomic spacing while compressive loads tend to reduce it. Due the forces of attraction or repulsion, the atoms return to their equilibrium position as soon as the load is removed. So that the initial form and size of the crystal are restored

It should be noted, however, that the elastic deformation of polycrystalline metals, especially at higher temperatures, causes so called viscous flow and after the removal of the external forces, deformation doesn't disappear completely even in the case of relatively small loads.



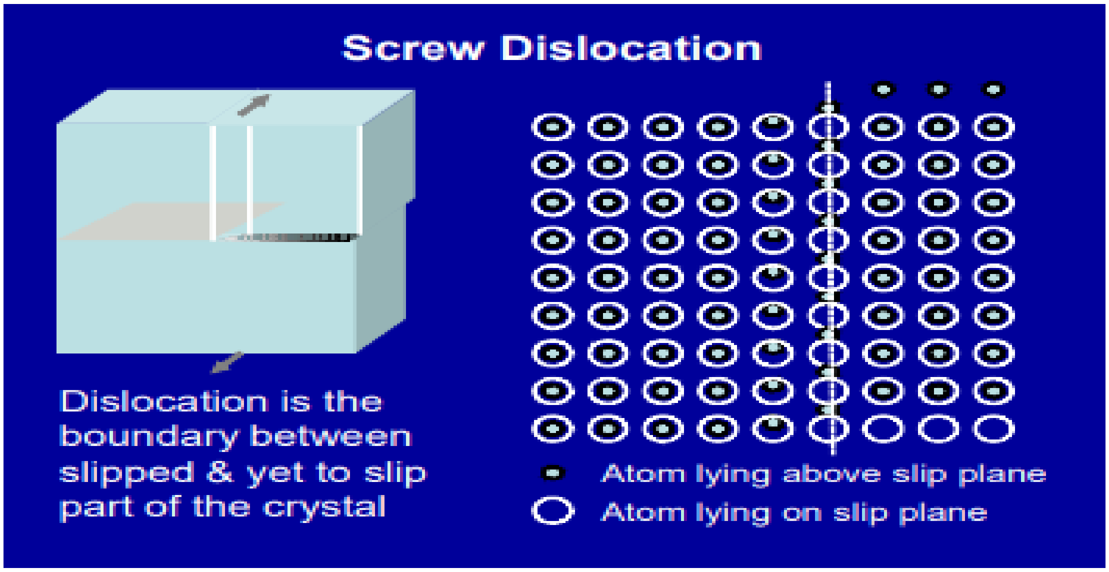
At stresses exceeding the elastic limit (the maximum stress that can be applied without producing a measurable permanent deformation or set after removing the stress)

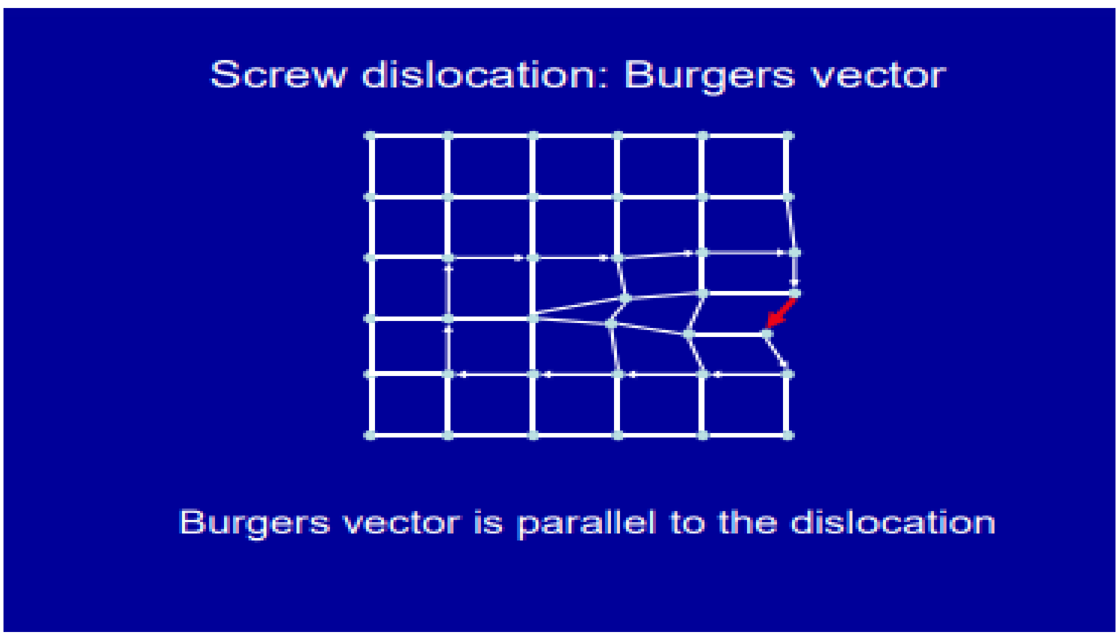
Plastic deformation is observed. Plastic deformation is associated with displacements of the atoms within the grains and causes permanent changes in shape of the specimen. Plastic deformation in crystal occurs in two ways -- By slip

--By twinning

(And also martensitic transformation)

	Edge	Screw
Burgers vector	Normal to dislocation	Parallel to dislocation
Atomic arrangement	Extra half plane	Atoms arranged along a helix
Glide plane	Unique	Multiple
Point defect interaction	Strong	Weak
Stress field	Hydrostatic + shear	Only shear
Strain energy	More than screw	Less than edge





All the above mechanism shares a common characteristic. They involve plane shear deformation. In slip shear is accomplished by dislocation glide in the slip plane.

In mechanical twinning, shear is accomplished in the twinning plane by the formation of twinned crystal

The crystal structure of the twinned crystal (T) is same as the parent crystal (A)

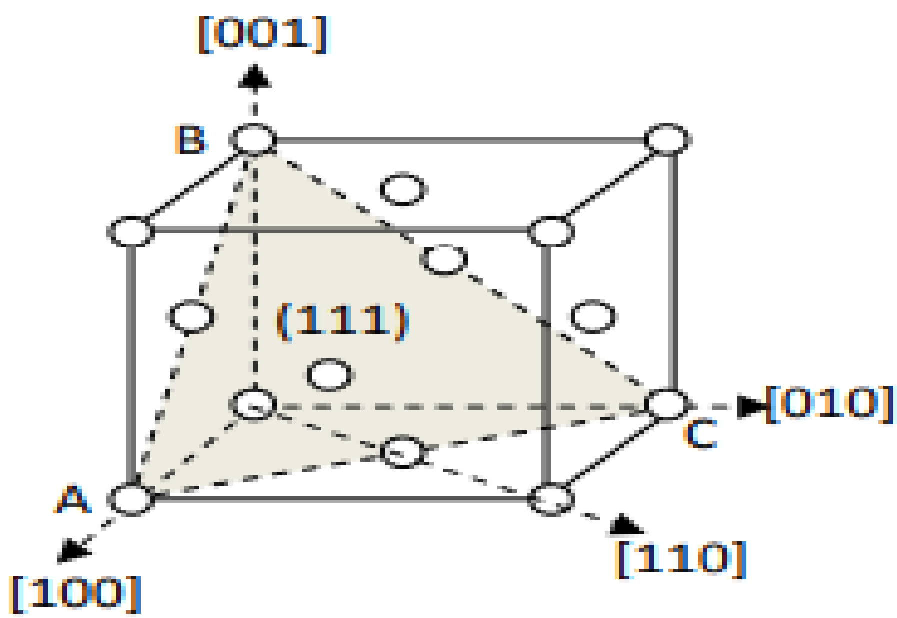
Martensitic transformation is characterized by large shear strain in the habit plane. In this case, contrary to mechanical twinning there is also a structural change taking place. The martensitic crystal (M) has different crystal structure from the parent metal.

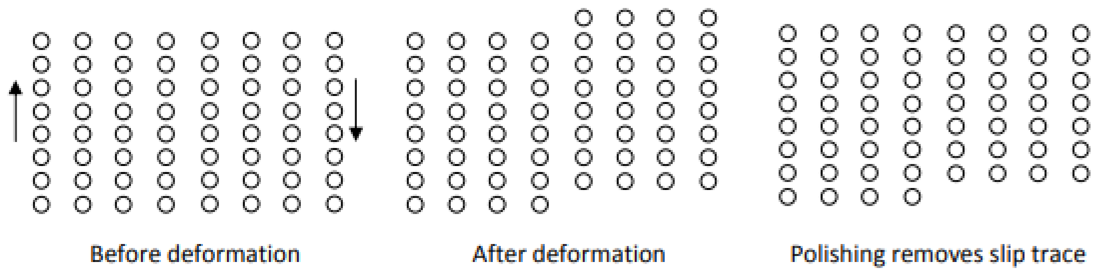
Slip Vs Twin:

Slip:

Has specific plane and direction , no orientation change , displacement is same for all planes , quiet, no serration on stress strain plots , relatively slow takes milliseconds

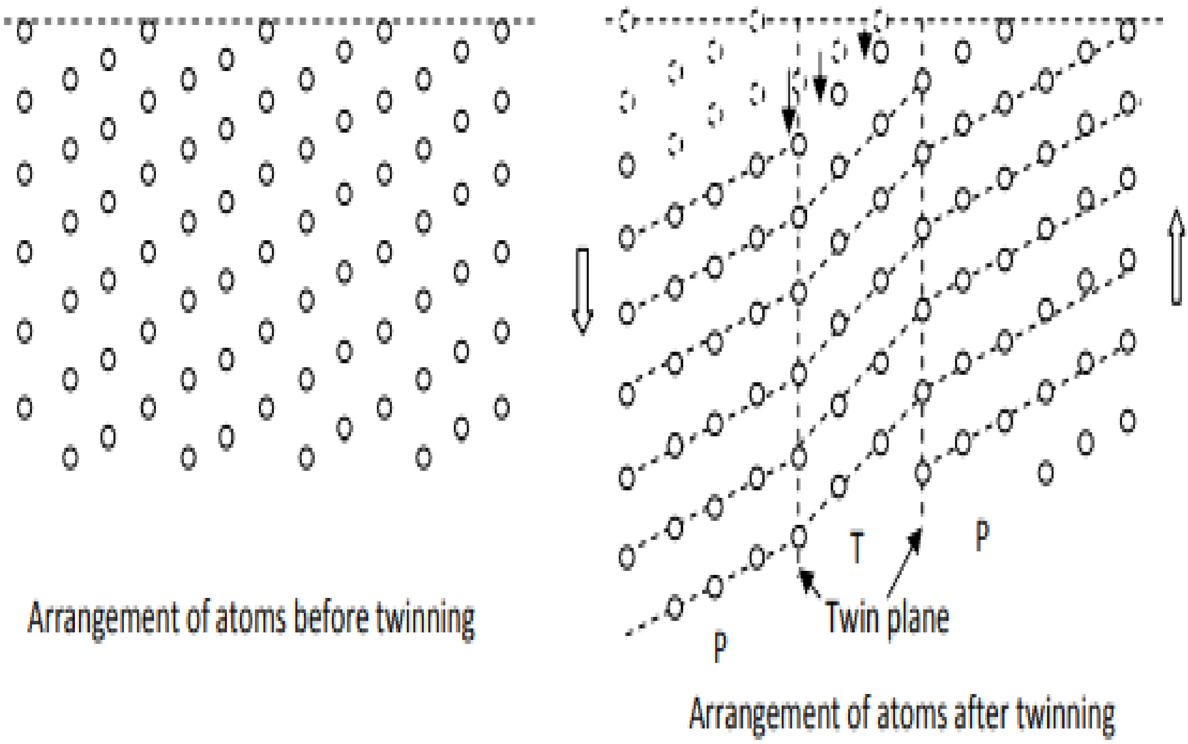
Crystal lattice	Slip plane	Slip Direction	No. of slip system
FCC	{111}	<110>	12
HCP	{0001}	$<2\bar{1}\bar{1}0>$	3
BCC	{110} {112} {123}	<111>	48

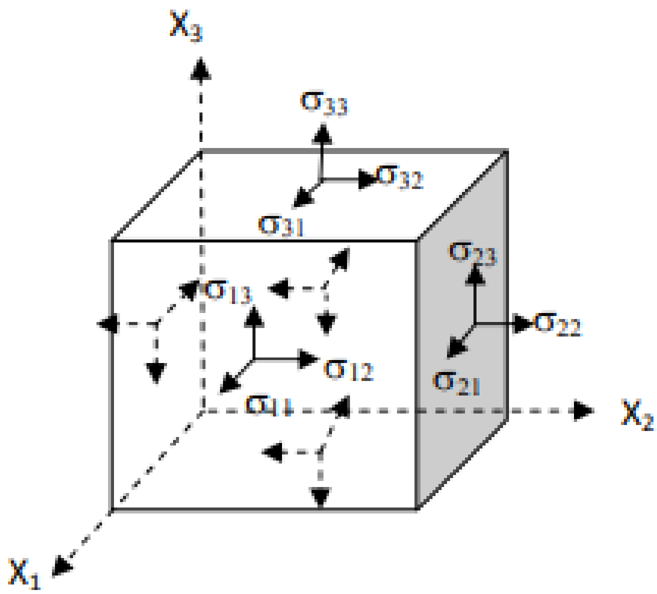




Twin:

Has specific plane and direction, orientation change, displacement is proportional to its distance from twin planes, noisy (tin cry), and shows serration on stress strain plots, very fast: takes microseconds





Invariants of a tensor:

$$\begin{pmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{pmatrix}$$

First invariant:

J_1 sum of diagonal values

Sum of normal values

Sum of eigen values

Sum of principal stresses

Second invariant:

J_2 sum of principal minors

$$\begin{vmatrix} \sigma_{yy} & \tau_{yz} \\ \tau_{zy} & \sigma_{zz} \end{vmatrix} + \begin{vmatrix} \sigma_{xx} & \tau_{xz} \\ \tau_{zx} & \sigma_{zz} \end{vmatrix} + \begin{vmatrix} \sigma_{xx} & \tau_{xy} \\ \tau_{yx} & \sigma_{yy} \end{vmatrix}$$

Third invariant:

J_3 Determinant of the matrix

Product of eigen values

Product of principal stresses

A stress tensor can be divided into a hydrostatic or mean stress tensor σ_m , which involves only pure tension or compression and deviator stress tensor σ_d which represents the shear stresses in the total state of stress.

In direct analogy with the situation for strain the hydrostatic component of the stress tensor produces only elastic volume changes and doesn't cause plastic deformation

Yield stress of the metal is independent of hydrostatic stress because the stress deviator involves shearing stress. It is important in causing plastic deformation

Total stress = Hydrostatic stress + Stress deviator

$$\sigma_m = \frac{\sigma_{xx} + \sigma_{yy} + \sigma_{zz}}{3}$$

$$\begin{pmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{pmatrix} = \begin{pmatrix} \sigma_m & 0 & 0 \\ 0 & \sigma_m & 0 \\ 0 & 0 & \sigma_m \end{pmatrix} + \begin{pmatrix} \sigma_{xx} - \sigma_m & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} - \sigma_m & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} - \sigma_m \end{pmatrix}$$

Hydrostatic stress tensor + Deviatoric stress tensor

(Volume change) (Shape change)

Now J_1 & J_2 of deviatoric stress tensor

$J_1 = (\sigma_{xx} - \sigma_m) + (\sigma_{yy} - \sigma_m) + (\sigma_{zz} - \sigma_m) = 0$

$$J_2 = \begin{vmatrix} \sigma_{yy} - \sigma_m & \tau_{yz} \\ \tau_{zy} & \sigma_{zz} - \sigma_m \end{vmatrix} + \begin{vmatrix} \sigma_{xx} - \sigma_m & \tau_{xz} \\ \tau_{zx} & \sigma_{zz} - \sigma_m \end{vmatrix} + \begin{vmatrix} \sigma_{xx} - \sigma_m & \tau_{xy} \\ \tau_{yx} & \sigma_{yy} - \sigma_m \end{vmatrix}$$

$$= \frac{1}{6}\left(\left(\sigma_{xx} - \sigma_{yy}\right)^2 + \left(\sigma_{yy} - \sigma_{zz}\right)^2 + \left(\sigma_{zz} - \sigma_{xx}\right)^2 + 6\left(\tau_{xy}{}^2 + \tau_{yz}{}^2 + \tau_{zx}{}^2\right)\right)$$

Von Mises' or Distortion Energy criterion

Von Mises' proposed that yielding would occur when the second invariant of the stress deviator J_2 exceeds some critical value (let's say "k")

$$\frac{1}{6}\left(\left(\sigma_{xx}-\sigma_{yy}\right)^2+\left(\sigma_{yy}-\sigma_{zz}\right)^2+\left(\sigma_{zz}-\sigma_{xx}\right)^2+6\left(\tau_{xy}{}^2+\tau_{yz}{}^2+\tau_{zx}{}^2\right)\right)= k\text{............}(1)$$

For principal stresses (zero shears)

$$\frac{1}{6}\left(\left(\sigma_1-\sigma_2\right)^2+\left(\sigma_2-\sigma_3\right)^2+\left(\sigma_3-\sigma_1\right)^2\right)=k \text{ ....}(2)$$

For the case of uniaxial (say on x-axis) tension yield point is $\sigma_1=\sigma_0$

Hence

$$\frac{1}{6}\left(\left(\sigma_0-0\right)^2+\left(0-0\right)^2+\left(0-\sigma_0\right)^2\right)=k$$

$$\Rightarrow \frac{2\sigma_0{}^2}{6}=k \text{ ....}(3)$$

Substituting the value of" k" from equation 3 in equation 1

$$\frac{1}{6}\left(\left(\sigma_{xx}-\sigma_{yy}\right)^2+\left(\sigma_{yy}-\sigma_{zz}\right)^2+\left(\sigma_{zz}-\sigma_{xx}\right)^2+6\left(\tau_{xy}{}^2+\tau_{yz}{}^2+\tau_{zx}{}^2\right)\right)=\frac{2\sigma_0{}^2}{6}$$

$$\Rightarrow \sigma_0=\frac{1}{\sqrt{2}}\left(\left(\sigma_{xx}-\sigma_{yy}\right)^2+\left(\sigma_{yy}-\sigma_{zz}\right)^2+\left(\sigma_{zz}-\sigma_{xx}\right)^2+6\left(\tau_{xy}{}^2+\tau_{yz}{}^2+\tau_{zx}{}^2\right)\right)^{\frac{1}{2}}$$

Maximum shear stress or tresca criterion

$$\tau_{\max}=\frac{\sigma_1-\sigma_3}{2} \text{ .... }(1)$$

This yield criterion assumes that yielding occurs when the maximum shear stress reaches the value of the shear stress in the uniaxial tension test

So,

$\frac{\sigma_0 - 0}{2}$ Is the limiting value …… (2)

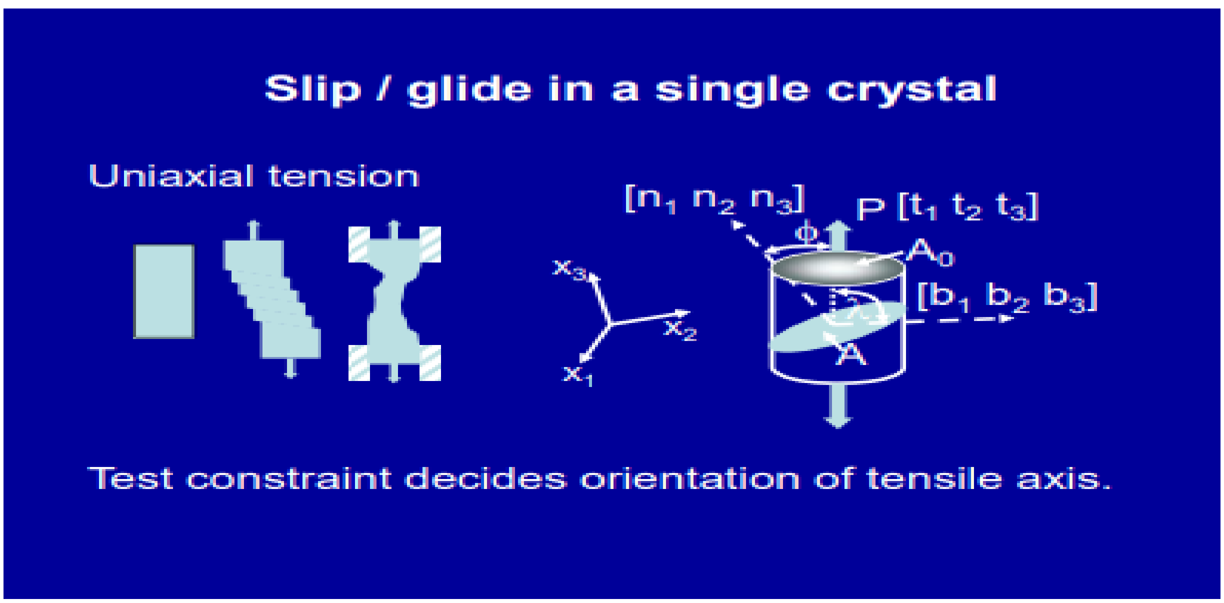
Equating 2 with 1

$$\frac{\sigma_1 - \sigma_3}{2} = \frac{\sigma_0 - 0}{2}$$

=> $\sigma_1 - \sigma_3 = \sigma_0$

We note that the maximum shear stress criterion is less complicated mathematically than the Von mises' criterion and for this reason it is often used in engineering design .However , the maximum shear strain criterion doesn't take into account the intermediate principal stress. It suffers from major difficulty that it is necessary to know in advance which the maximum and minimum principal stresses are

<u>Critically resolved shear stress:</u>



The above diagram shows the tensile axis $[t_1\ t_2\ t_3]$ is oriented with respect to the slip plane whose normal $[n_1\ n_2\ n_3]$subtends an angle ϕ with P and λ is the angle between P and slip direction $[b_1\ b_2\ b_3]$

A_0 denotes the cross sectional area of the crystal

The driving force for glide (slip) is the resolved stress acting along the slip direction on the slip plane.

The expression for this can be derived as follows

$$\text{Resoled shear stress } \tau = \frac{P\cos\lambda}{A} = \frac{P\cos\lambda}{A_0 / \cos\phi} = \frac{P}{A_0}\cos\lambda\cos\phi = \sigma \cos\lambda \cos\varphi$$

Equation (1) gives a relation between tensile and shear yield stress of a crystal .Note that Critically Resolved Shear Stress is a material property of the crystal.

This doesn't depend on the size, geometry and orientation of the crystal. However the tensile yield strength of the crystal depends on its orientation.

$$SF = cos\phi cos\lambda = \frac{(n_1t_1+n_2t_2+n_3t_3)}{\sqrt{n_1^2+n_2^2+n_3^2}} \frac{(b_1t_1+b_2t_2+b_3t_3)}{\sqrt{b_1^2+b_2^2+b_3^2}\ \sqrt{(n_1^2+n_2^2+n_3^2)}} \qquad (8)$$

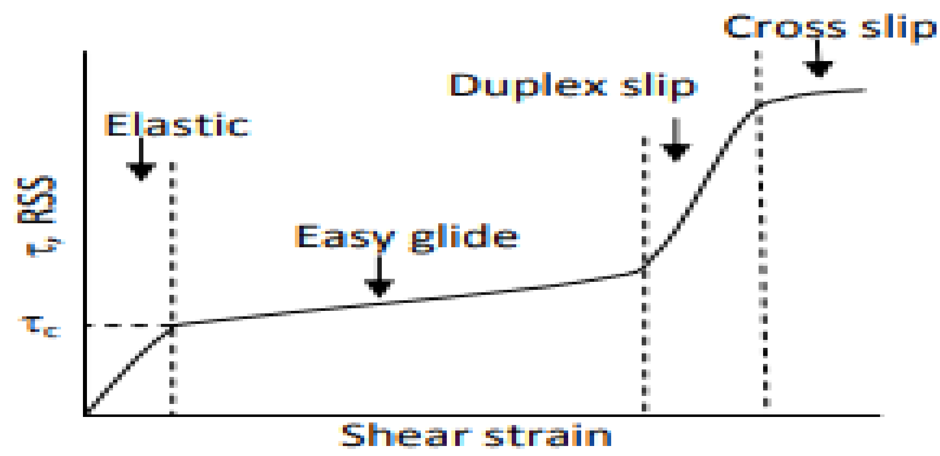
Estimation of Schmid factor for a given tensile axis for different slip system

t1	t2	t3							
1	2	3							
h	k	l	u	v	w	cos f	cos l	m	
1	1	1	-1	1	0	0.926	0.189	0.175	
1	1	1	-1	0	1	0.926	0.378	0.35	
1	1	1	0	-1	1	0.926	0.189	0.175	
-1	1	1	1	1	0	0.617	0.567	0.35	
-1	1	1	1	0	1	0.617	0.756	0.467	
-1	1	1	0	-1	1	0.617	0.189	0.117	
-1	-1	1	0	1	1	0	0.945	0	
-1	-1	1	1	0	1	0	0.756	0	
-1	-1	1	-1	1	0	0	0.189	0	
1	-1	1	1	1	0	0.309	0.567	0.175	
1	-1	1	-1	0	1	0.309	0.378	0.117	
1	-1	1	0	-1	1	0.309	0.189	0.058	

Slide 3: A table showing the magnitudes of SF (denoted by m) for FCC crystal when the tensile axis is [123]. (hkl) are the indices of slip plane whereas [uvw] are the indices of slip direction. Note that the magnitude of m is the highest for the slip system $(\bar{1}11)\{101\}$. The equation 8 has been used to find SF.

The term $\cos\lambda\cos\varphi$ represents the orientation relationship of the slip system with respect to the tensile axis

It is commonly known as Schmid's factor .It can have a maximum value of 0.5.



The above figure shows a plot between resolved shear stress Vs resolved shear strain

It has several distinct stages .Glide occurs when $\tau > \tau_c$

Initially when slip takes place on a single system there is little work hardening .This is known as the period of easy glide.

With deformation tensile axis would rotate .The orientation factor would change so does the resolved shear stress

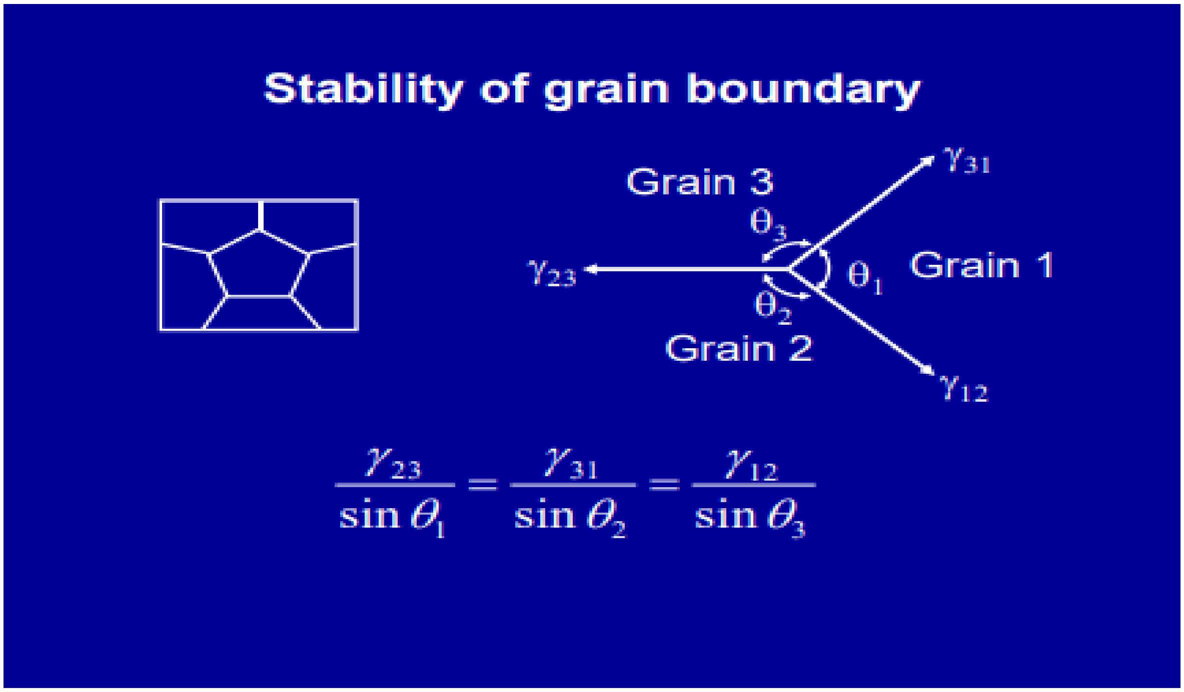
When the orientation factor on another slip system becomes equally favorable slide occurs simultaneously on the two slip systems .This stage is known as duplex slip .As a result strain hardening rate becomes much higher.

At a later stage when as a result of changing orientation factor several other slip planes become operative there is strain softening (the slope of the stress strain plot decreases .This stage is known as cross slip.

<u>Deformation of polycrystalline material</u>

Metals we use are rarely made of single crystal .They consist of numerous (grains) crystals arranged at random .This means that the orientation of a particular grain is independent of its neighbors .These are separated by boundaries .Across boundary there is no relation between the atomic arrays .However when deformations occur there must be continuity along the boundaries .This is possible if all the components of deformations of all the grains are identical.

A minimum of five independent slip systems must be operative for polycrystalline solid to exhibit ductility and maintain grain boundary integrity



STRENGTHENING MECHANISMS

Material strength can be increased by hindering dislocation, which is responsible for plastic deformation. The strengthening mechanisms are, therefore, related to the interaction between the dislocations and various obstacles present in the microstructure of the material.

Among the obstacles to dislocation glide are the atomic bonds of the crystal lattice, other dislocations, intersititial or substitutional solute atoms, grain boundaries and precipitates or second phase particles etc.

So different ways to hinder dislocation motion or strengthening mechanisms

In single phase materials

→Grain size reduction

→Solid solution strengthening

→Strain hardening

In multi phase materials

→Precipitation strengthening

→Dispersion strengthening

→Fiber strengthening

→martensite strengthening

STRENGTHENING BY GRAIN SIZE REDUCTION

It is based on the fact that dislocations will experience hindrances while trying to move from a grain into the next grain because of abrupt change in orientation planes.

Hindrances can be two types: Forcible change in slip direction and discontinuous slip plane.

Smaller the grain size, often a dislocation encounters a hindrance. Yield strength of the material will be increased.

Yield strength is related to the grain size (diameter "d") as Hall–Petch relations

$$\sigma_y = \sigma_i + k\ d^{\frac{-1}{2}}$$

"k" locking parameter

"σ_i" overall resistance of the lattice to dislocation motion

Grain size can be tailored by controlled cooling or by plastic deformation followed by appropriate heat treatment.

Grain boundaries act as obstacles to dislocations and hence, dislocations pile up at the grain boundaries.

Number of dislocations in the pile up

$$n = \frac{k\pi\tau_s L}{Gb}$$

G Shear modulus b Burger's vector τ_s Average resolved shear stress

SOLID SOLUTION STRENGTHENING

Impure foreign atoms in a single phase material produces lattice strains which can anchor dislocations

Solute atoms introduce lattice strain as their size is different from the host atoms.

A larger substituitional solute atom will impose a compressive stress while a smaller interstitial atom will cause tensile stresses in the lattice.

Interstitial atoms are often bigger than the interstitial space they occupy, resulting in a compressive field.

Effectiveness of the strengthening depends on two factors.

→Size difference

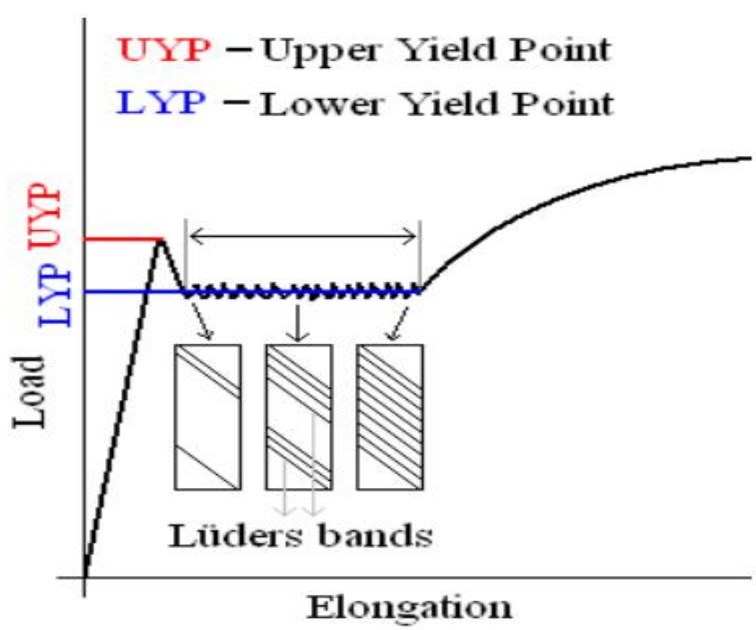
→Volume fraction of the solute

Dislocations have strain field at their core due to lattice distortion

Solute atom with a tensile strain field will diffuse to the dislocation core to nullify part of the compressive strain field of the dislocation to reduce the strain energy.

This hinders the motion of the dislocation and hence, the strength increases

YIELD POINT PHENOMENON



Localized, heterogeneous type of transition from elastic to plastic deformation marked by abrupt elastic-plastic transition

It characterizes that material needs higher stress to initiate plastic flow than to continue it.

The bands are called Lüders bands /Hartmann lines / stretcher strains and generally are approximately 45^0 to the tensile axes.

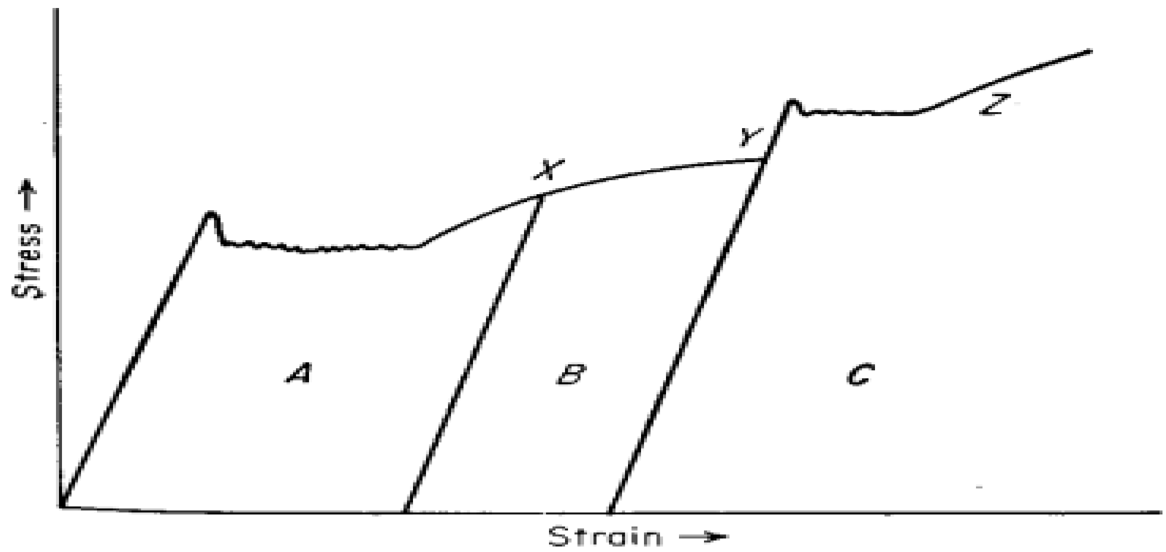
Occurrence of Yield point is associated with presence of small amounts of interstitial or substitutional impurities.

It's been found that either unlocking of dislocations by a high stress for the case of strong pinning or generation of new dislocations are the reasons for the Yield point phenomenon.

Magnitude of the Yield point effect will depend on energy of interaction between solute atoms and dislocations and on the concentration of solute atoms at the dislocations.

STRAIN AGEING

Strain ageing is a type of behavior usually associated with the yield point phenomenon in which the strength of a metal is increased and the ductility is decreased on heating at a relatively low temperature after cold working.



The above figure shows the effect of strain ageing on the flow curve of low-carbon steel.

Region A of figure shows the stress-strain curve for a low –carbon steel strained plastically through the yield point elongation to a strain corresponding to point X. The specimen is then unloaded and released without appreciable delay or any heat treatment (region B)

Note that on reloading the yield point doesn't occur, since the dislocations have been torn away from the atmosphere of carbon and nitrogen atoms.

Consider now that the specimen is strained to point Y and unloaded .If it is reloaded after ageing for several hours at an ageing temperature like 400K, the yield point will reappear.

Moreover, the yield point will be increased by the ageing treatment from Y to Z.

The reappearance of the yield point is due to the diffusion of carbon and nitrogen atoms to the dislocations during the ageing period to form new atmospheres of interstitials anchoring the dislocations

To control strain ageing , it is usually desirable to lower the amount of carbon and nitrogen in solution by adding elements which will take part of the interstitials out of the solutions by forming stable carbides or nitrides e.g. Al, V , Ti

While a certain amount of control over strain ageing cab be achieved, there is no commercial low carbon steel which is completely no-strain ageing. The usual industrial solution to this problem is to deform the metal to the point X by roller leveling or a skin pass rolling operation and use it immediately before it can age. The local plastic deformation by rolling produces sufficient fresh dislocations so that subsequent plastic flow occurs without a yield point.

FIBER STRENGTHENING

A second phase in the form of fiber can be introduced into matrix in fiber form too.

Requisite for fiber strengthening

Fiber material: High strength high modulus

Matrix material: ductile and non reactive with the fiber material

E.g. fiber material Al_2O_3, boron, graphite etc

Matrix material: metals, Polymer

Mechanism of strengthening is different from other methods.

Higher Modulus fiber carry load, ductile matrix distributes the load to fibers

Interface between matrix and fibers thus play an important role.

Strengthening analysis involves application of continuum not dislocation concepts as in other methods of strengthening.

To achieve any benefit from the presence of fibers, critical fiber volume this must be exceeded for fiber strengthening to occur

$$f_{critical} = \frac{\sigma_{mu} - \sigma_m'}{\sigma_{fu} - \sigma_m'}$$

Where σ_{mu} strength of the strain hardened matrix

σ_m' Flow stress of the matrix at a strain equal to the fiber breaking stress

σ_{fu} Ultimate tensile strength of the fiber

Minimum volume fraction of fiber which must be exceeded to have real reinforcement

$$f_{\min} = \frac{\sigma_{mu} - \sigma_m{}'}{\sigma_{fu} + \sigma_{mu} - \sigma_m{}'}$$

MARTENSITE STRENGTHENING

This strengthening method is based on the formation of martensitic phase from the retained high temperature phase at temperatures lower than the equilibrium invariant transformation temperature.

Martensite forms as a result of shearing of lattices.

Martensite platelets grow at very high sped i.e. activation energy for growth is less. Thus volume fraction of martensite exist is controlled by its nucleation rate.

Martensite platelets attain their shape by two successive shear displacements contained in boundaries coherent with the parent phase. The first displacement is a homogeneous shear throughout the plate which occurs parallel to a specific plane in the parent phase known as the habit plane. The second displacement, the lesser of the two, can take place by one of two mechanisms slip as in Fe-C martensite or twinning as in Fe-N martensite

Martensite formation occurs in many systems like Fe-C , Fe-Ni, Fe-Ni-Cu, Cu-Zn and even pure metals like Li, Zr and Co. However, only the alloys based on Fe and C show a pronounced strengthening effect.

High strength of martensite is attributed to its typical crystal structure i.e. effective barrier to slip are provided by the fine twin structure or high dislocation density.

In Fe –C system carbon atoms are also involved in strengthening. Super saturated carbon atoms strain the ferrite lattice and this strain can be relieved by redistribution of carbon atoms by diffusion at room temperature .One result is that a strong binding is set up between dislocation and carbon atoms.\

This hinders the motion of dislocation, thus increasing the strength.

This strengthening mechanism is one of the most common processes used in engineering materials. The name basically arises from the phase martensite that forms in steel when they are quenched from the solutionizing temperature.

STRAIN HARDENING

Phenomenon where ductile metals become stronger and harder when they are deformed plastically is called strain hardening or work hardening

Increasing temperature lowers the rate of strain hardening

During plastic deformation, dislocation density increases .And thus their interaction with each other resulting in increase in yield stress

Dislocation density (ρ) and shear stress (τ) are related as follows

$$\tau = \tau_0 + A\rho^{\frac{1}{2}}$$

During strain hardening, in addition to mechanical properties physical properties also changes such as ;

A small decrease in density

An appreciable decrease in electrical conductivity

A small increase in thermal co-efficient of expansion

Increase in chemical reactivity (decrease in corrosion resistance)

Deleterious effects of cold work can be removed by heating the material to suitable temperatures, annealing. It restores the original properties into material. It consists of 3 stages

→Recovery

→Recrystallization

→Grain growth

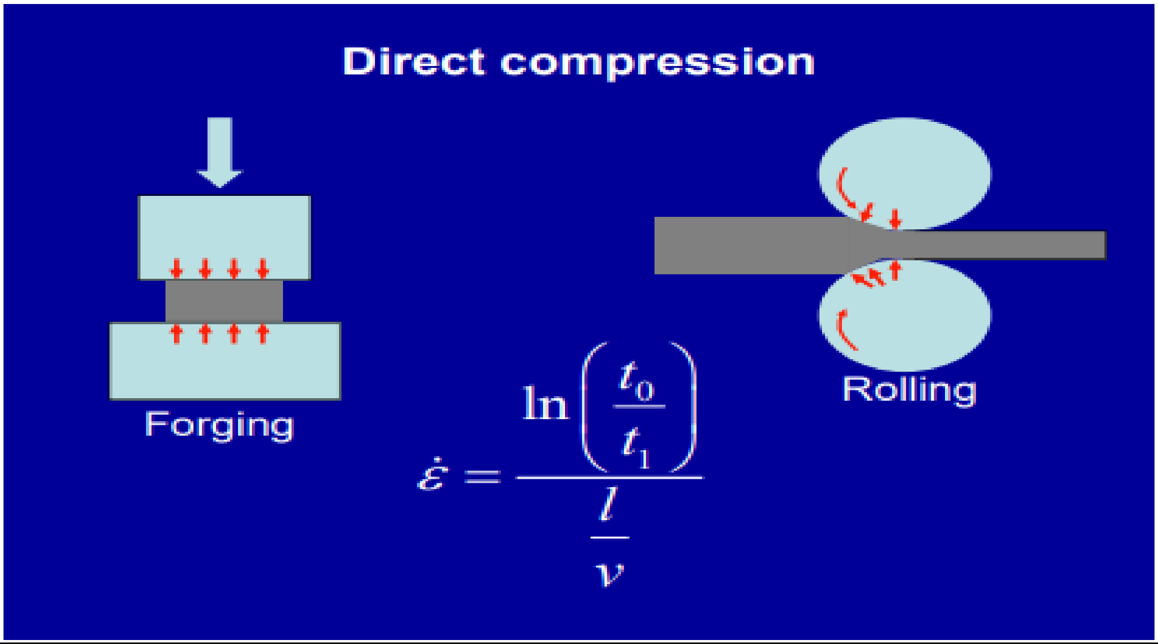
In industry, alternate cycles of strain hardening are to deform most metals to a very great extent

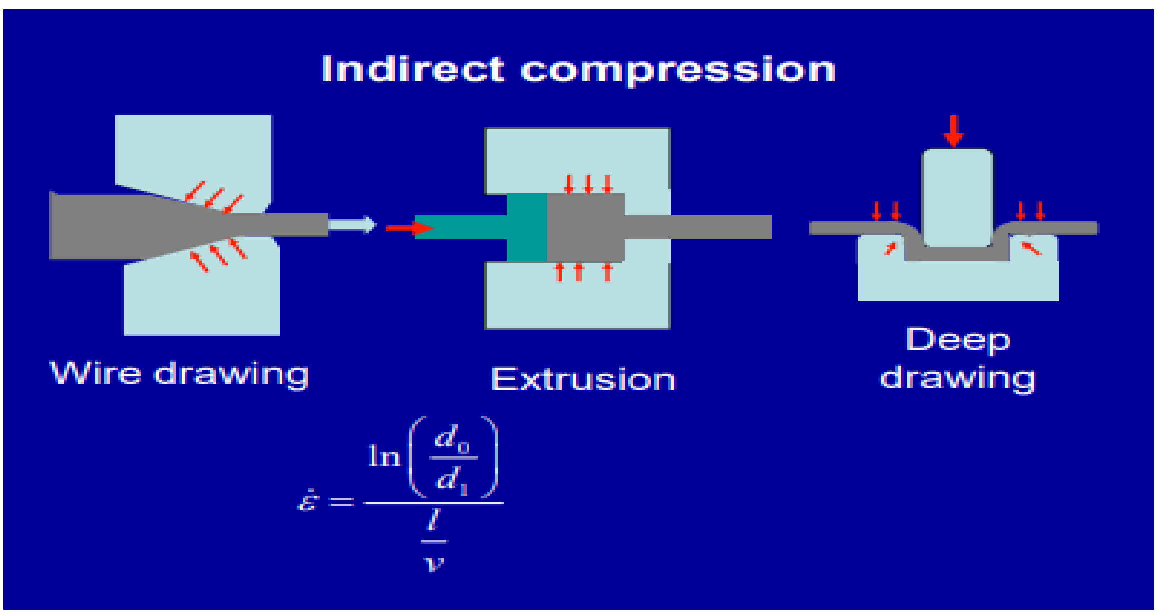
<u>Bauschinger effect:</u>

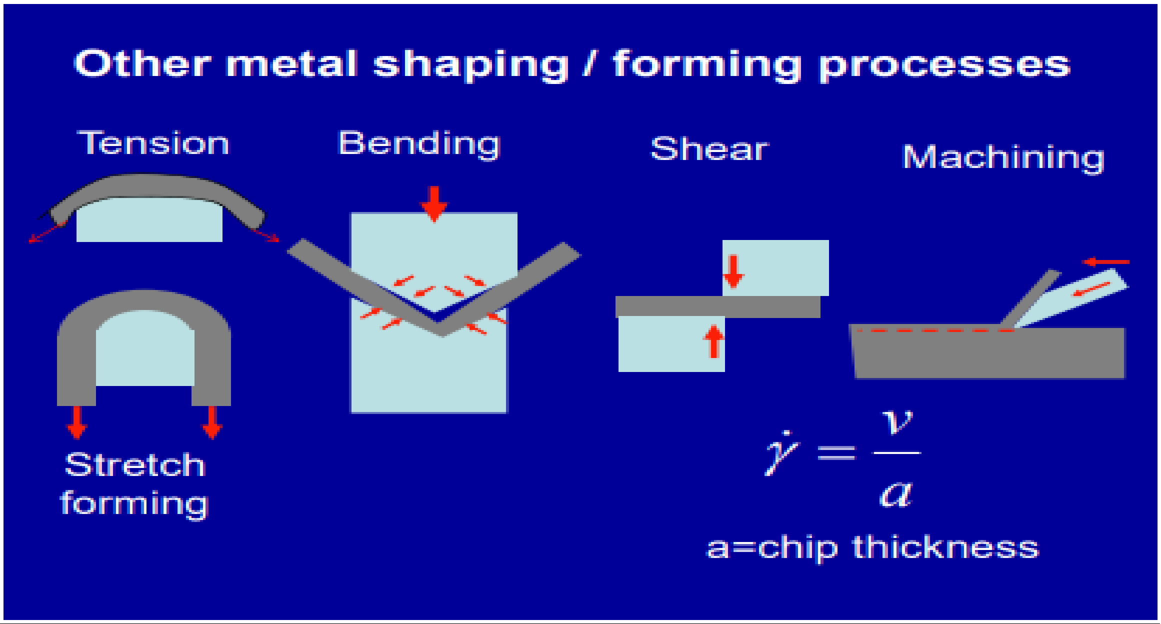
The lowering of yield stress when deformation in one direction is followed by deformation in the opposite direction is called Bauschinger effect.

The crystal is strained to point “O”, unloaded, and then reloaded in the direction opposite to the original slip direction. On reloading the crystal yields at a lower shear stress than when it was first loaded. This is because the back stress developed as a result of dislocations piling up at barriers during the first loading cycle is aiding the dislocation movement hen the direction of slip is reversed . And also when the slip direction is reversed dislocation of opposite sign could be created at the same sources that produced the dislocations responsible for strain in the first slip direction

UNIT -4


Direct compression
Forging
Rolling
$\dot{\varepsilon} = \frac{\ln\left(\frac{t_0}{t_1}\right)}{\frac{l}{v}}$


Indirect compression
Wire drawing
Extrusion
Deep drawing
$\dot{\varepsilon} = \frac{\ln\left(\frac{d_0}{d_1}\right)}{\frac{l}{v}}$



Metals are known for its ductility. It can be formed into useful shapes by deformation processing

There are several ways by which metals can be deformed into various shapes. The processes are often referred to as metal working .Deformation takes place under the influence of applied stress depending on the way the stress is applied to the work piece and its nature, metal working processes can be classified into different categories

These are (i) Direct compression

(ii) Indirect compression

(iii)Tension

(iv)Bending

(v)Shearing

Direct compression

Force is applied to the surface of the work piece and the metal flows at right angles to the direction of compression

E.g. forging & rolling

Indirect compression processes include wire drawing, tube drawing, extrusion and deep drawing of a cup

The primary applied forces are frequently tensile but the indirect compressive forces developed by the reaction of the work piece with the die reach high values. Therefore the metal flows under the action of a combined stress state which includes high compressive forces in at least one of the principal direction.

Tension

The best example of a tension type forming process is stretch forming, where a metal sheet is wrapped to the contour of a die under the application of tensile forces.

Bending

Bending involves the application of bending moments to the sheet.

Shearing

It involves the application of shearing forces of sufficient magnitude to rupture the metal in the plane of the shear.

In most of the metal working processes, the dimension of the work piece increases along one or two direction at the cost of the other

During rolling the length increases at the cost of its thickness whereas in wiredrawing its length increases at the cost of its cross section.

The ability of a metal to deform depends on its flow stress which is a function of strain rate temperature and its microstructure.

It is always easier to shape the metal at high temperatures because it can flow easily at low stresses. The flow stress remains unchanged with deformation. However at lower temperature the flow stress is high. It needs higher stresses to deform and it keeps increasing with strain because of strain hardening. The temperature at which there is such a change in its deformation behavior is known as recrystallization temperature.

Deformation above this temperature is known as hot working whereas that below it is called cold working

A rough estimate of the re crystallization temperature is around o.5 T_m where T_m is the melting point of metal in Kelvin

Effect of cold working on the structure and properties of metals

-Change in grain shape /size

-Development of texture

-Increase in dislocation density

-loss of ductility

-Increase in strength

-increase in residual stress

-crystal structure remains unaltered

-corrosion resistance decreases

Effect of hot working on the structure and properties of metals

-Change in product shape/size with little change in grain shape and morphology

-Absence of texture

-Little change in dislocation density

-No loss of ductility /improve ductility of cast structure

-No significant increase in strength

-Little residual stress/stored energy

-Crystal structure remains unaltered

Recovery

Annealing relieves the stresses from cold working

Three stages

--recovery

--recrystallization

--grain growth

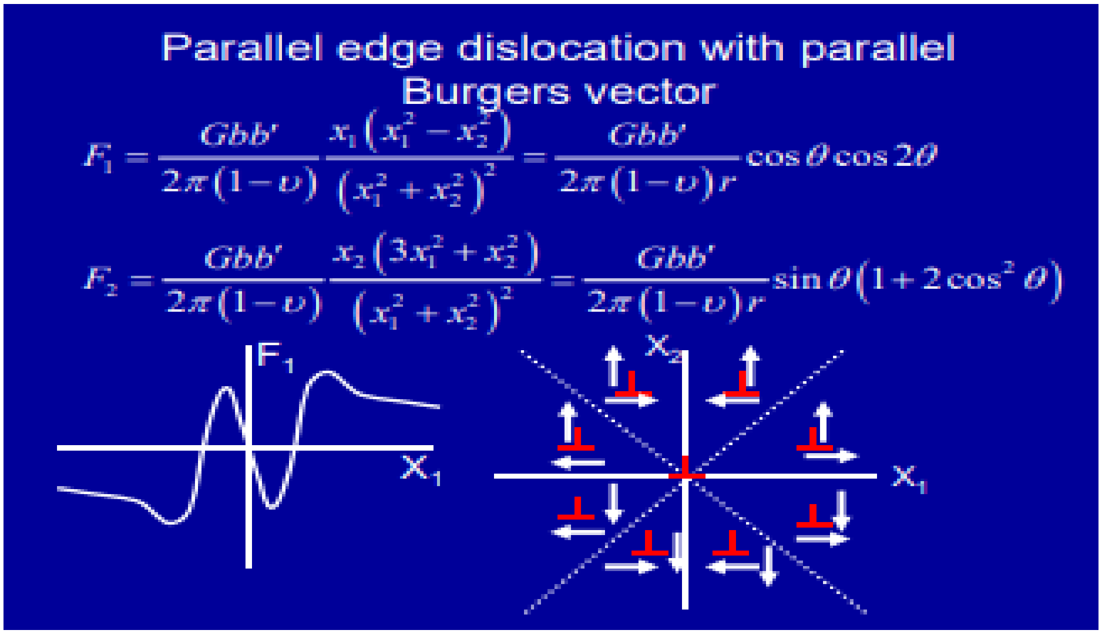
Recovery involves annihilation of point defects

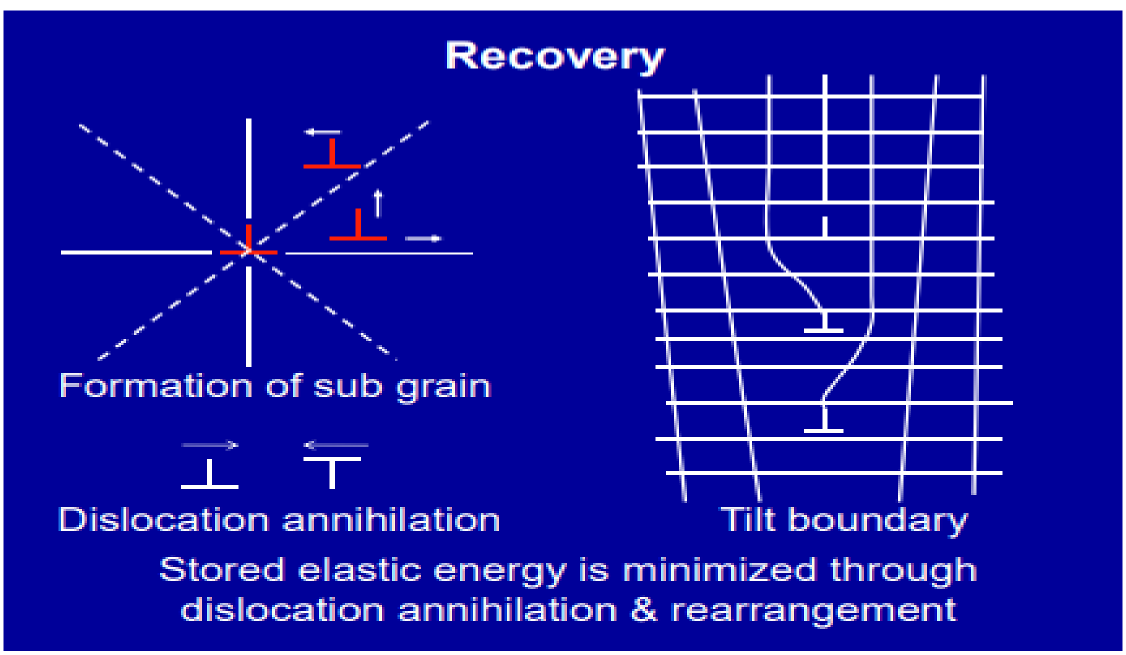
Driving force for recovery is decrease in stored energy from cold work

During recovery, physical properties of the cold worked material are restored without any observable change in microstructure

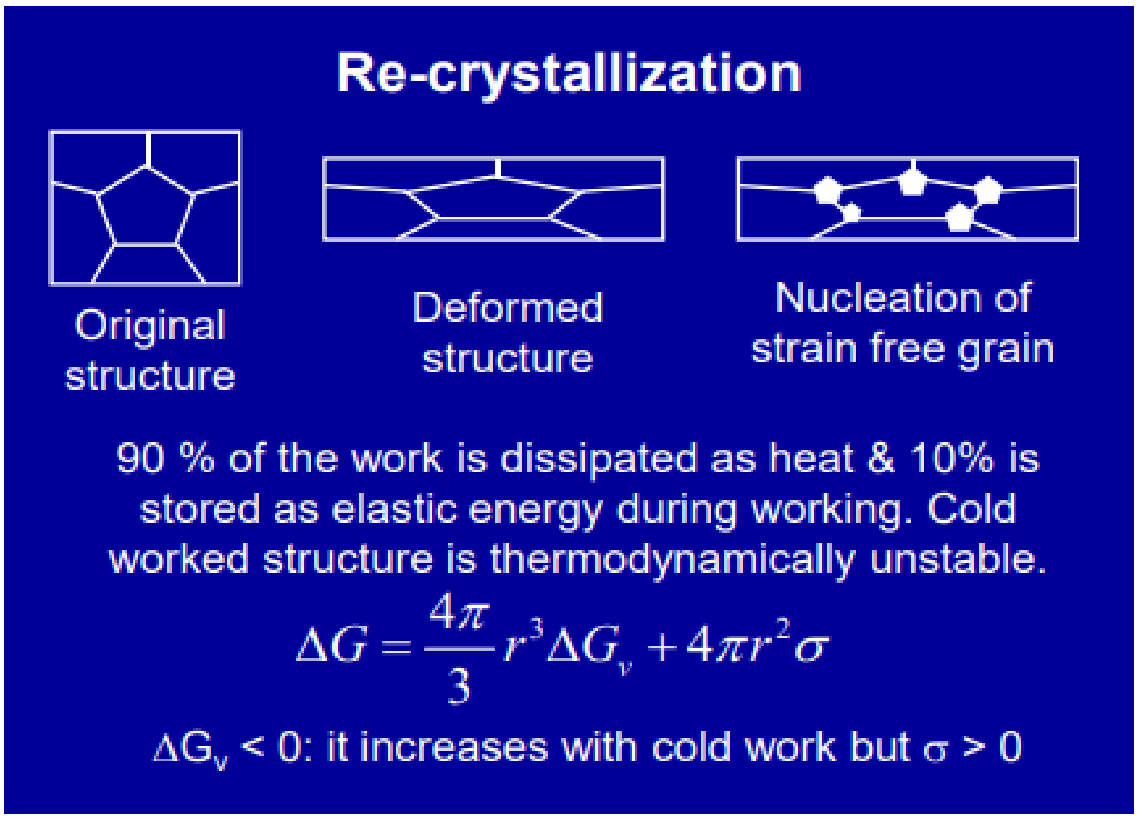
Recovery is the first stage of annealing which takes place at low temperatures of annealing

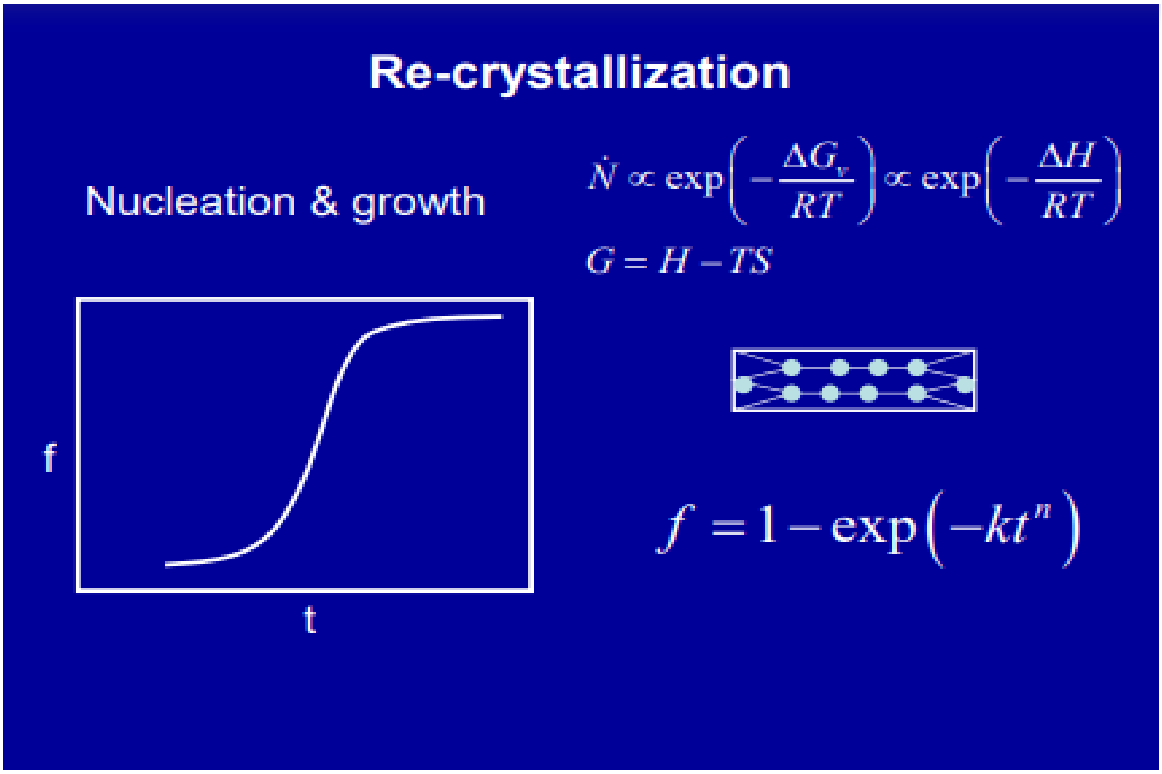
There is some reduction, though not substantial, in dislocation density as well apart from formation of dislocation configuration with low strain energies





Recrystallization





This stage follows recovery during annealing of cold worked metal .Driving force is stored energy during cold work

(90% of the cold work is dissipated as heat and 10% is stored as elastic energy during working & cold worked structure is thermodynamically unstable)

It involves replacement of cold worked structure by a new set of strain free approximately equi-axed grains to replace all deformed crystals

This process is characterized by recrystallization temperature which is defined as the temperature at which 50% of a material recrystallizes in 1 hour time

The recrystallization temperature is strongly dependent on the purity of material.

Pure metal recrystallizes around 0.3 T_m while impure material may recrystallize around 0.5-0.7T_m , where T_m is absolute melting temperature of the metal.

Recrystallization Laws

→A minimum amount of deformation is needed to cause recrystallization.

→Smaller the degree of deformation, higher will be the R_x temperature

→The finer is the initial grain size; lower will be the R_x temperature

→The larger the initial grain size, the greater degree of deformation is required to produce an equivalent R_x temperature.

→Greater the degree of deformation and lower the annealing temperature, the smaller will be the crystallized grain size

→The higher is the temperature of cold working, the less is the strain energy stored and thus R_x temperature is correspondingly higher.

→The R_x rate increases exponentially with temperature

Grain growth

Grain growth follows complete crystallization of the material is left at elevated temperature

Grain growth doesn't need to be preceded by recovery and recrystallization. It may occur in all polycrystalline material

In contrary to recovery and recrystallization driving force for this process is reduction in grain boundary energy

Larger grains grow at the expense of smaller grains

In practical applications: grain growth is not desirable

Incorporation of impurity atoms and insoluble second phase particles are effective in retarding grain growth

Grain growth is very strongly dependent on temperature.

ROLLING

The process of plastically deforming metal by passing it between rolls is known as rolling

Length increases (L)

Width remains the same (w)

Thickness is reduced (t)

-Only product with uniform cross section along the length can be produced

Angle of bite:

Determines the extent of reduction in thickness .It depends on the condition in which rolling is taking place i.e. hot or cold and surface roughness of rollers, diameter of the rolls.

Since the amount of mass entering the roll is equals to the amount of mass entering the roll is equal to the amount of mass exiting the roll

Initial length l_0 final length l_f

Initial width w_0 final width w_f

Initial thickness t_0 final thickness t_f

We can write

$\rho\, l_0\, w_0\, t_0 = \rho\, l_f\, w_f\, t_f$ $\rho \rightarrow$ Density

=> $l_0\, t_0 = l_f\, t_f$ $\because w_0 = w_f$

=> $l_f = l_0 \frac{t_0}{t_f}$

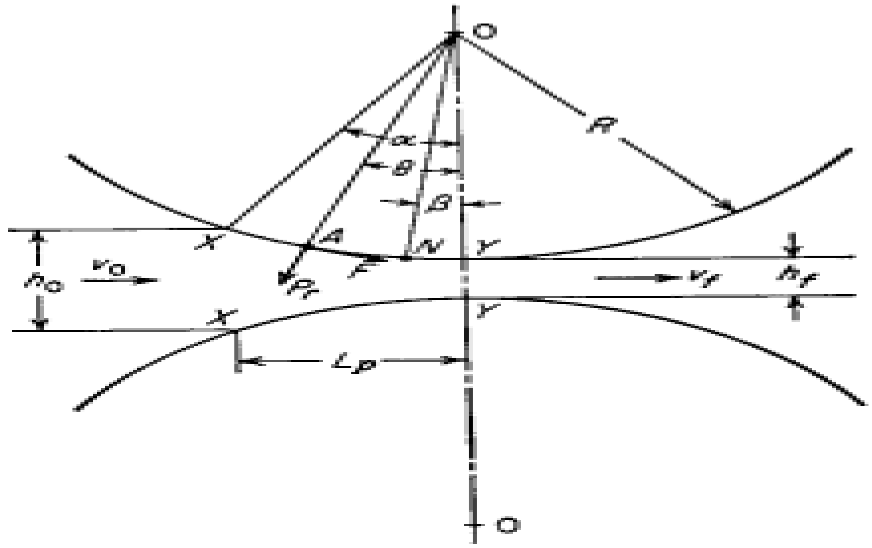
As reduction in thickness takes place in rolling $t_f < t_0$

Therefore $l_f > l_0$

That means speed of the material entering (v_0) the roll is less than the speed of the material exiting the roll (v_f)

Therefore the velocity of the sheet must steadily increase from entrance to exit

At one point along the surface of contact between the roll and the sheet is the surface velocity of the roll v_r equal to the velocity of the sheet. This point is called neutral point.



The direction of friction changes at neutral point N since the velocity of sheet entering the roll < surface velocity of roll up to neutral point and the velocity of sheet exiting after neutral point is greater than the surface velocity of the roll

For horizontal movement of the sheet from left to right the horizontal component of friction (F) must be greater than horizontal component of the normal force (P_r)

Therefore the limiting condition for unaided entry is

$$F \cos\alpha = P_r \sin\alpha$$

=> $\frac{F}{P_r} = \tan\alpha$

=> $\mu = \tan\alpha$

In $\triangle OAB$

$$\tan\alpha = \frac{AB}{OB} = \frac{\sqrt{R\Delta h}}{R - \frac{\Delta h}{2}} \approx \sqrt{\frac{R\Delta h}{R^2}} \approx \sqrt{\frac{\Delta h}{R}}$$

$\mu \geq \tan\alpha$ For unaided entry

Hence the maximum value of $\tan\alpha$ can be μ

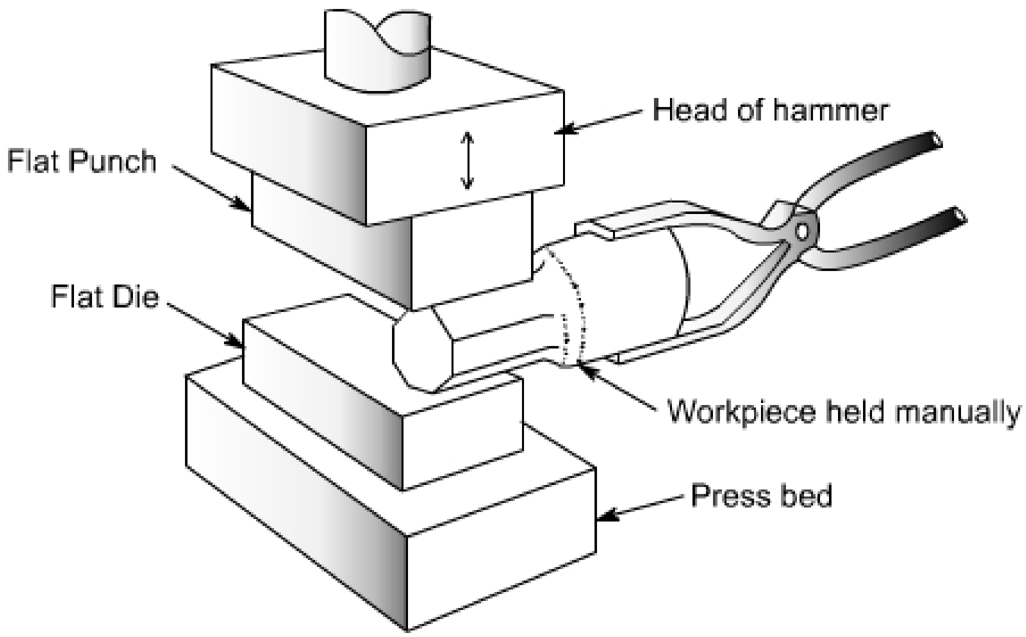
So $\sqrt{\frac{\Delta h_{\max}}{R}} = \mu$

=> $\Delta h_{\max} = \mu^2 R$

If the surface roughness is more , more draft is possible

More is the Dia of the roll more is the draft

FORGING



Forging is the working of metal into a useful shape by hammering or pressing

Most forging operations are carried out hot although certain metals may be cold forged

Two major classes of equipment are used for forging operations .The forging hammer or drop hammer, delivers rapid impact blows to the surface of the metal, while the forging press subjects to a slow speed compressible force.

The two broad categories of forging processes are open die forging and closed die forging

Open die forging is carried out between flat dies or dies of very simple shape

The process is used mostly for large objects or when the number of parts produced is small .Often open die forging is used to perform the work piece for closed die forging

In closed die forging the work piece is deformed between two die halves which carry the impression of the desired final shape. The work piece is deformed under high pressure in a closed cavity and thus precision forgings with close dimensional tolerances can be produced

The simplest open die forging operation is the upsetting of a cylindrical billet between two flat dies. As the metal flows laterally between the advancing die surfaces, there is less deformation at the die interfaces because of the friction forces than at mid height plane. Thus, the sides of the upset cylinder becomes barreled .As a general rule, metal will flow most easily towards the nearest free surface because this represents the lowest frictional path.

Forging operations

(1)Edging

(2) Fullering

(3)Drawing

(4)Swaging

(5)Piercing

(6)Punching

It is important to use enough metal in the forging billet so that the die cavity is completely filled

Because it is difficult to put just the right amount of metal in the correct places during fullering and edging, it is customary to use a slight excess of metal .When the dies come together for the finishing step, the excess metal squirts out of the cavity as a thin ribbon of metal called flash. In order to prevent the formation of a very wide flash, a ridge, known as the flash gutter is usually provided

The trick in designing the flash is to adjust its dimensions so that the extrusion of metal through the narrow flash opening is more difficult than the filling of the most intricate detail in the die .But, this must not be done in excess so as to create very high forging loads with attendant problems and problems of die wear and breakage.

Flashless forging

It is a closed die forging process in which the work volume is equal to die cavity volume with no allowance for flash. Excess material or inadequate material will lead to defective part. If billet size is less then underfilling takes place. Oversized billet leads to die damage or damage to the press.

Isothermal forging

In this process, the die is heated up to the same temperature of the billet. This helps in avoiding die chilling effect on work piece and lowering of flow stress. This process is suitable for complex parts to be mass produced

Coining

It is a special type of closed die forging .Complex impressions are imparted to both surfaces of the blank from the die. Forging load involved is very high as high as 6 times the normal load .Minting of coins is an example of this process.

Roll forging

In this process, the bar stock is reduced in cross section or undergoes change in cross section when it is passed through a pair of grooved rolls made of die steel. This process serves as the initial processing step for forging parts such as connecting rod, crank shaft etc.

PROPERTIES OF FORGED PRODUCTS

The formation of a grain structure in forged part 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 work piece often undergoes recrystallization therefore, provide finer grains compared to the cast dendritic structure resulting in improved mechanical properties

Redistribution of metal structures occurring during forming process involves two principal components (i) redistribution of inclusions (ii) crystallographic orientation of the grains

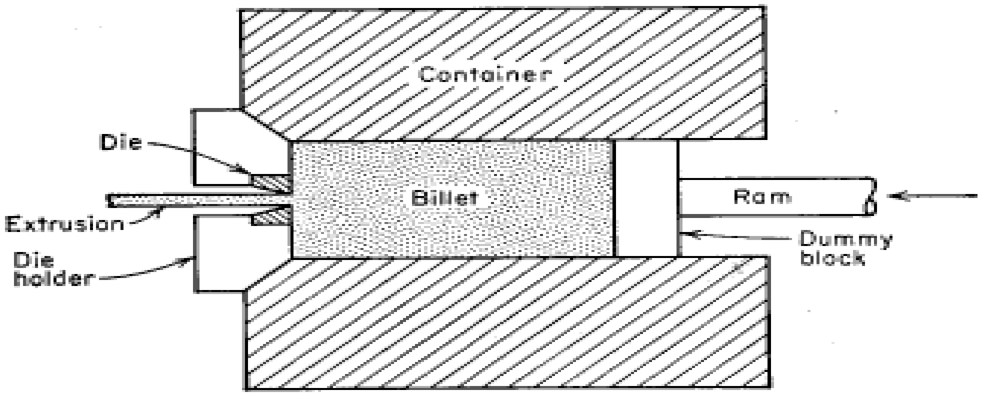
The residual stress produced in forgings as a result of inhomogeneous deformation is generally small because the deformation is normally carried out well into the hot working region

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

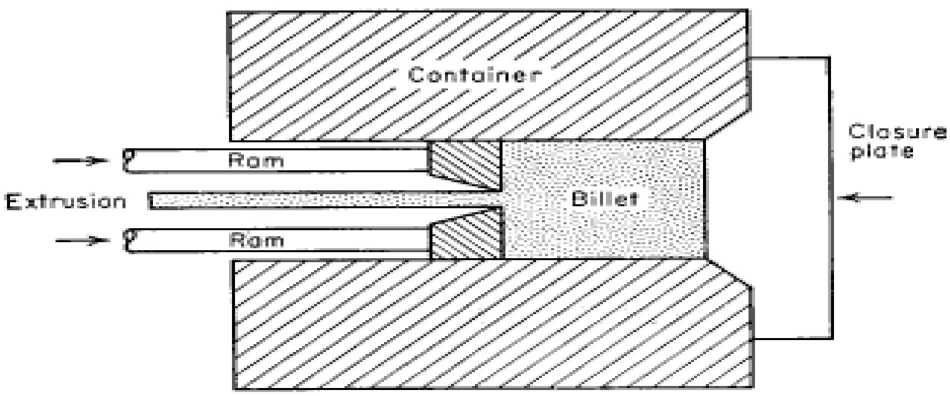
Large forgings therefore have to be slowly cooled from the working temperature

Examples: Burying the forging in ashes for a period of time or using a controlled cooling furnace

EXTRUSION



Direct extrusion



Indirect extrusion

Extrusion is a compressive deformation process in which a block of metal is squeezed through an orifice or die opening in order to obtain a reduction in diameter and increase in length of the metal block

The resultant product will have the desired cross section .Extrusion involves forming of axisymmetric parts. Dies of circular and non-circular cross section are used for extrusion.

Large hydrostatic stress in extrusion helps in the process by enhancing ductility of the material .Metals like aluminum, which are easily workable, can be extruded at room temperature. Other difficult to work metals usually hot extruded or warm extruded.

Difficult to form materials such as stainless steels, nickel alloys are extruded du to its inherent advantage, namely, no surface cracking due to reaction between billet and the extrusion container .Extrusion results in better grain structure, better accuracy and surface finish of the components .Less wastage of material in extrusion is another attractive feature of extrusion.

<u>Extrusion ratio</u>

It is the ratio of area of cross section of the billet to the are of cross section of the extrude

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

Another parameter used in extrusion is shape factor, ratio of perimeter to cross section of the part. An extruded rod has the lowest shape factor

<u>Extrusion is classified in general into 4 types</u>

Direct extrusion

Indirect extrusion

Impact extrusion

Hydrostatic extrusion

<u>Direct extrusion</u>, also called forward extrusion is a process in which billet moves along the same direction as the ram and punch do. Sliding of billet is against the stationary container of the wall.

Friction between the container and billet is high. As a result, greater forces are required .A dummy block of slightly lower diameter than billet diameter is used to prevent oxidation of the billet in hot extrusion.

Extrusion force, which is the force required for extrusion, in direct extrusion, varies with ram ravel as shown below

Initially the billet gets compressed to the size of the container before getting extruded .As a result the extrusion pressure or force increases steeply as shown.

Also initially static friction exist between billet and container

Once the billet starts getting extruded, its length inside the container is reduced .Friction between billet and container now starts reducing .Therefore extrusion pressure reduces.

The highest pressure at which extrusion starts is called breakthrough pressure .At the end of the extrusion , the small amount of material left in the container gets pulled into the die, making billet hollow at center . This is called pipe.

Beyond pipe formation, the extrusion pressure rapidly increases ,as the small size billet present offer high resistance .As the length of the billet is increased , corresponding extrusion pressure is also higher because of friction between container and billet .Therefore billet length beyond 5 times the dia are not preferred in direct extrusion.

<u>Indirect extrusion</u>

Indirect extrusion (backward extrusion) is a process in which punch moves opposite to that of the billet .Here there is no relative motion between container & the billet .Hence there is less friction ND HENCE reduced forces are required for indirect extrusion. For extruding solid piece, hollow punch is required. In hollow extrusion, the material gets forced through the annular space between the solid punch and the container. The variation of extrusion pressure in indirect extrusion is shown below.

As seen, extrusion pressure in indirect extrusion is lower than that for direct extrusion. Many components are manufactured by combining direct and indirect extrusions.

Hydrostatic extrusion

In hydrostatic extrusion container is filled with a fluid. Extrusion pressure is transmitted through the fluid to the billet. Friction is eliminated in this process because there is no contact between billet and container wall. Brittle materials can be extruded by this process

High brittle materials extruded into a pressure chamber. Greater reductions are possible by this method

Pressure involved in this process may be as high as 700MPa .Pressure is limited by the strength of the container, punch and die materials.

Normally this process is carried out at room temperature.

A couple of disadvantages of this process are

Leakage of pressurized oil

Uncontrolled speed of extrusion at exit, due to release of stored energy in the oil.

Impact extrusion

Hollow sections such as cups, toothpaste containers are made by impact extrusion. It is a variation of indirect extrusion .The punch is made to strike at high speed by impact load.

Tubes of small wall thickness can be produced .Usually metals like copper aluminum, lead are impact extruded.

Cold and hot extrusion

Cold extrusion could produce parts with good surface finish , high strength due to strain hardening , improved accuracy , high rate of production .However , the process requires higher pressure and tool are subjected to higher stresses .Proper lubrication is necessary for preventing seizure of tool and work piece

Hot extrusion can be employed for higher extrusion ratios. Inhomogeneous deformation can occur due to die wall chilling of the billet .Metal may get oxidized. The oxide layer can increase friction as well as the material flow. Glass is used as a lubricant for hot extrusion.

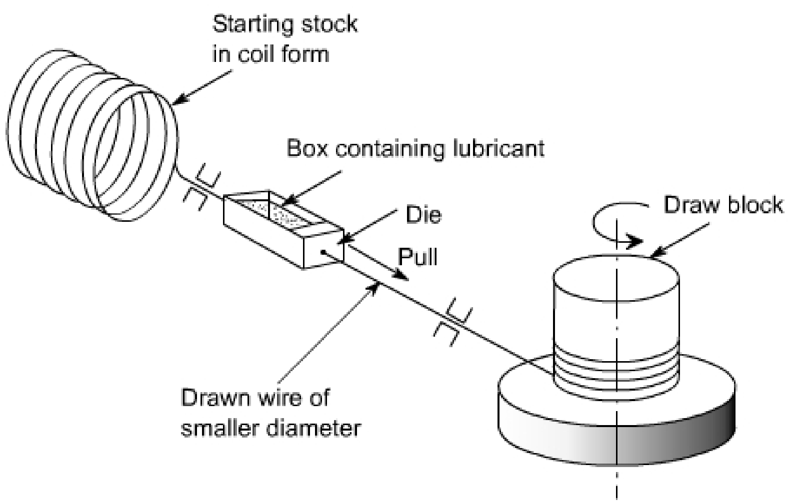
Manufacturing of seam less pipes

A solid rod is fed between two obliquely aligned, double –one shaped rolls which rotate it about its axis producing an axial hole.

His hole is then expanded and smoothened over a mandrel.

Further shaping and expansion of the tube done over a mandrel in various other types of special rolling mills

WIRE DRAWING



Bar or wire drawing is deformation process in which the work piece in the form of cylindrical bar or rod is pulled through a converging die. The stress applied is tensile.

However, the material is subjected to compressive stress within the die thereby deforming plastically.

A bar or rod is drawn in order to reduce its diameter. In general, drawing results in reduction in area of cross section.

Drawn rods are used as raw material for making bolts.

Wire drawing is used for producing wires e.g. electrical wires, cables, strings, welding electrodes, fencing etc.

Basic difference between bar drawing and wire drawing is the size of bar stock used for bar drawing is large.

Wire drawing is a continuous process.

A draw bench is used for drawing rods, bars and tubes because rods and bars cannot be coiled

The rod or bar is pointed by swaging operation and fed into the drawing die. The tip of the bar is clamped into the jaws of the draw head and the drawing operation is carried out continuously

The draw head is moved is using chain drive or hydraulic power pack. Draw speeds can be as 1500mm/sec.

In wire drawing a series of dies are used in tandem.

Usually drawing is drawn cold. Maximum reduction in cross sectional area per pass of drawing is restricted to 45%. Beyond this reduction, tensile stress may increase and surface finish may become poor.

Due to large stress involved in drawing the drawn wire gets strain hardened. Therefore, intermediate annealing is required before next stage of drawing.

The raw material for wire drawing is usually a hot rolled rod .The rod is coiled and fed into the die after subjected to acid pickling to remove oxides .Before drawing rod is lubricated.

In order to retain the lubricant of the surface, oxalate or sulphate coating is given to the rod. Soap solution or oil is used as lubricant.

The rod is dipped into the lubricant bath before feeding into the die

A bull block is used on the other end in order to wind the drawn wire.

Wire drawing is completed with multiple draw head and bull blocks, with maximum reduction in each step is limited to 35 to 40%

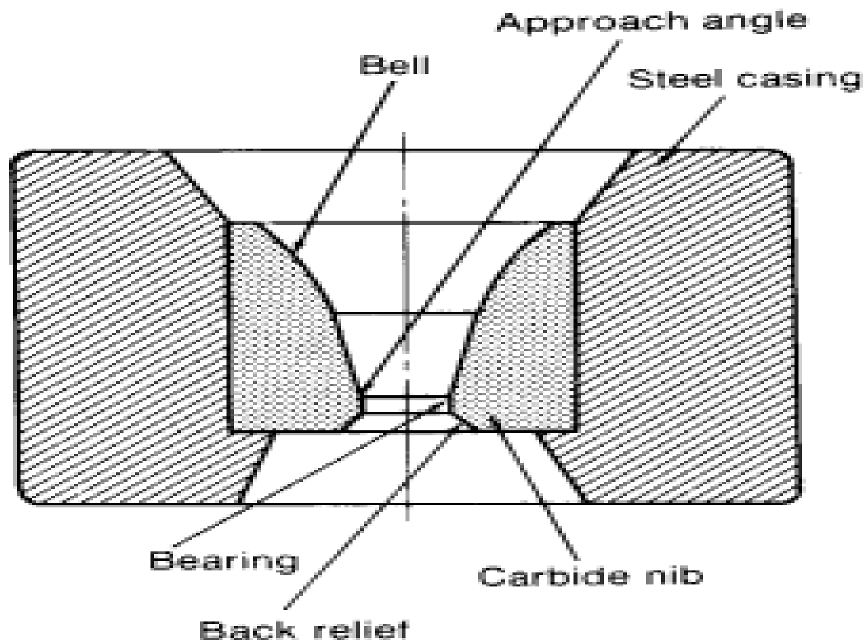
After each step of reduction, the wire diameter is reduced .Velocity of the wire and the length of the wire therefore will increase successively.

This requires that bull block be rotated at higher speeds after each reduction.

Drawing speeds can be as high as 30m/s.

Intermediate annealing is required before next step of drawing in order t improve the ductility of the wire.

Drawing die



Die for drawing may be made of tool steel, tungsten carbide or diamond. For drawing fine wires , diamond die is used.

Entrance has a bell assembly so as to facilitate the entry of lubricant along with the wire

Reduction in diameter takes place in the approach angle section.

Back relief provides space for expansion of the drawn wire.

Steel casing helps to hold the die.

<u>Deep drawing and sheet metal working</u>

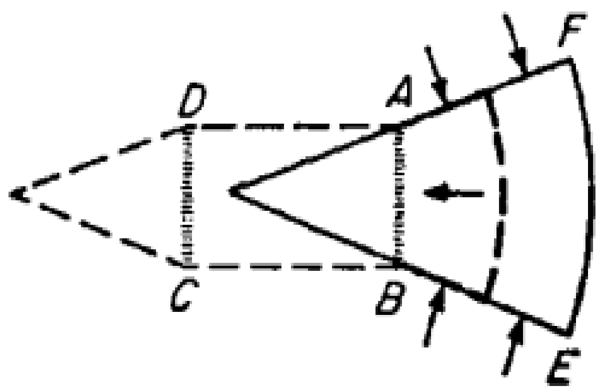
Metal sheets are shaped into bowls, cups, motor car panels etc by various processes.

In deep drawing a circular blank is pressed to the shape of a cup by a punch.

The radius of the blank decreases during the operation as the metal flows radially inwards and then turns the corner to become the wall of the cup.

In stretch forming, by contrast the outer part of the blank is prevented from moving by a clamp and the metal is deformed by tensile stretching.

Deep drawing is a true drawing operation



In the above figure which shows the deformation of a radial sector of the blank to form the wall of the cup ABCD. The drawing die in this case is provided by the neighboring sectors of the blank, along AE and BE, as they all move in & converge together

There is a danger of tensile necking failure here unless the blank is well lubricated to allow it to slide in freely.

There are many metallurgical problems in sheet metal working. We have already mentioned stretcher strains .Metals for deep drawing should be soft, ductile and without a great work hardening capacity e.g. very low carbon steel.

For stretch forming, on the hand work hardening is needed to suppress tensile necking.