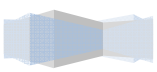
Module 41

Preferred orientation

Lecture 41

Preferred orientation



Keywords : Anisotropy, its origin, texture, effect of texture on properties of materials, texture hardening, pole figures, representation of crystallographic texture, methods of determining pole figure, factors that control preferred orientation, sheet formability, effect of texture on creep and magnetic properties

Introduction

Metals are crystalline. Crystals have different properties along different directions. Cubic crystals having the highest degree of symmetry has three independent elastic constants although only two are needed for an isotropic material. The only true isotropic crystal is that of tungsten. It is BCC. This is only for general curiosity. We rarely use single crystal. Most metals are made of a large number of tiny crystals. If these are randomly arranged the aggregate is likely to exhibit isotropic behavior. However often it is difficult to obtain a perfectly random orientation. It needs precise control of composition and several processing parameters to get such a structure. The absence of perfect random orientation is responsible for the anisotropic behavior of most of the commercial metals and alloys. The main source of anisotropy is the preferred arrangement of the various constituents present in the alloy. The purpose of this module is to explain the following aspects of preferred orientation:

- Origin of texture or preferred orientation in material
- Effect of texture on the properties and performance of engineering materials
- Evaluation of textures in materials
- Texture control
- Texture: good or bad?

Origin of anisotropy:

Crystalline structure is primarily responsible for the anisotropic behavior of engineering material. Cubic crystal having the highest symmetry has 3 independent elastic constants (stiffness or compliance). If there is a definite relation between the three as given in slide 1 it can be said to be isotropic. Tungsten having BCC structure fulfills this criterion. Therefore it is isotropic.

Most engineering materials are polycrystalline. If these are randomly arranged the overall properties are likely to be independent of direction. This is why we only need to specify Young's modulus and Poisson ratio the two elastic constants for most of the cases. However the way metals or alloy are cast and subsequently processed often it does not ensure perfectly random orientation of its constituents. For example even the solidification of pure metal in an ingot although starts with the nucleation of a large number of tiny randomly arranged crystals at the mold wall only a few of these having favorable orientation grow against the direction of heat

flow giving rise to large columnar grains. In the case of metals having BCC or FCC structure [100] axis happens to be the preferred direction of growth.

Anisotropy

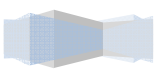
Crystals have limited symmetry elements. Even cubic crystals have different properties along different directions. Three elastic constants. Isotropic crystal: 2 elastic constants (W).

C: Stiffness $C_{44} = \frac{1}{2}(C_{11} - C_{12})$

S: Compliance $S_{44} = 2(S_{11} - S_{12})$

Poly-crystals: random orientation: isotropic. However orientation is rarely random.

Slide 1



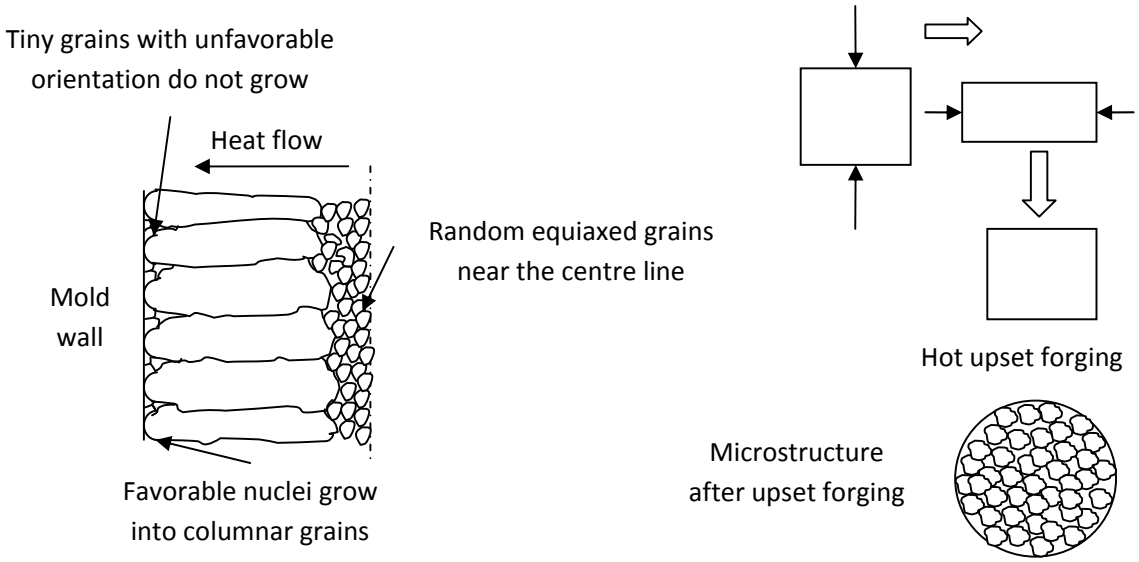


Fig 1: Columnar grains develop in a metal ingot as a result of the constraint imposed by heat flow through the mold wall. A few of the tiny grains that form along the wall grow into large columnar grains. [100] is often the direction of growth. Towards the end of solidification homogeneous nucleation along the centre line may result in random equiaxed grains. Cast metals are anisotropic because of the preferred orientation of the grains. Microstructure of cast metal can be converted into homogeneous equiaxed grains by upset forging. The sketch at the top right shows that by changing the direction of applied stress how large deformation can be given with little change in the shape and size of the casting. Large plastic deformation above the re-crystallization temperature helps develop homogeneous structure consisting of randomly oriented grains. Such a structure is expected to be isotropic.

Figure 1 illustrates with the help of a set of sketches the origin of preferred orientation of grains in a cast metal. The existence of columnar grains in a large part of the ingot makes it anisotropic. Upset forging where the ingot is subjected to large plastic deformation at a high temperature from all directions by turn may help develop a structure consisting of randomly oriented grains so that it becomes isotropic. Apart from hot upset forging most of the other deformation processes are likely to favor preferred orientation of grains and other micro-constituents.

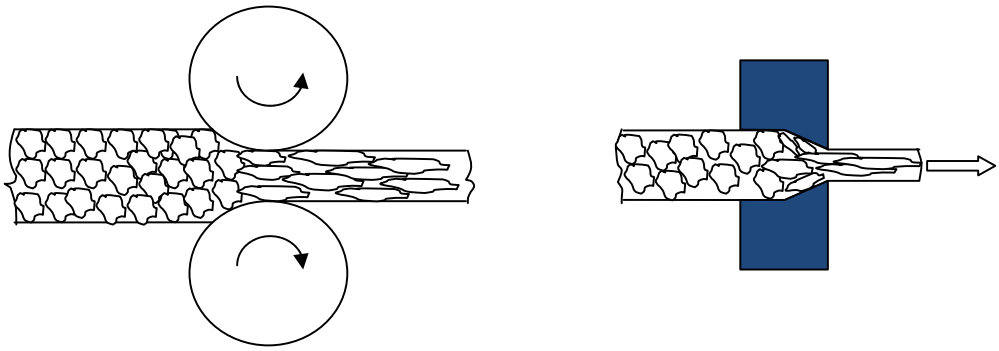


Fig 2: Shows schematic representation of the deformation of grains during rolling and wire drawing. During rolling a grain is pressed by a pair of rolls so that it transforms into a thin plate. Its length increases but its width remains nearly unaltered. The length increases at the cost of its height. During wire drawing a rod is pulled through a die. A grain is therefore subjected to radial pressure. As a result its length increases at the cost of its cross sectional area perpendicular to the direction of drawing. In short rolling transform nearly spherical grains into plates whereas wire drawing transforms grains into fibers. The drawing axis is often referred to as the fiber axis. Wire drawing is done at room temperature. Therefore it is a cold working process for steel, Cu or Al. However, rolling is done both at room and high temperatures. During hot rolling deformed grains get replaced by strain free re-crystallized grains. These are equiaxed. Therefore examination of grain structure of hot rolled steel may not reveal the direction of rolling. However steel has inclusions that get aligned and deformed in the direction of rolling. The shape and distribution of inclusions in hot rolled plates or sections clearly reveals the direction of deformation. The alignment of inclusions is mainly responsible for the anisotropic behavior of hot rolled plates. In the case of cold work both deformation and the alignment of inclusions or micro-constituents contribute towards anisotropy.

Origin of anisotropy

Crystallographic anisotropy: texture

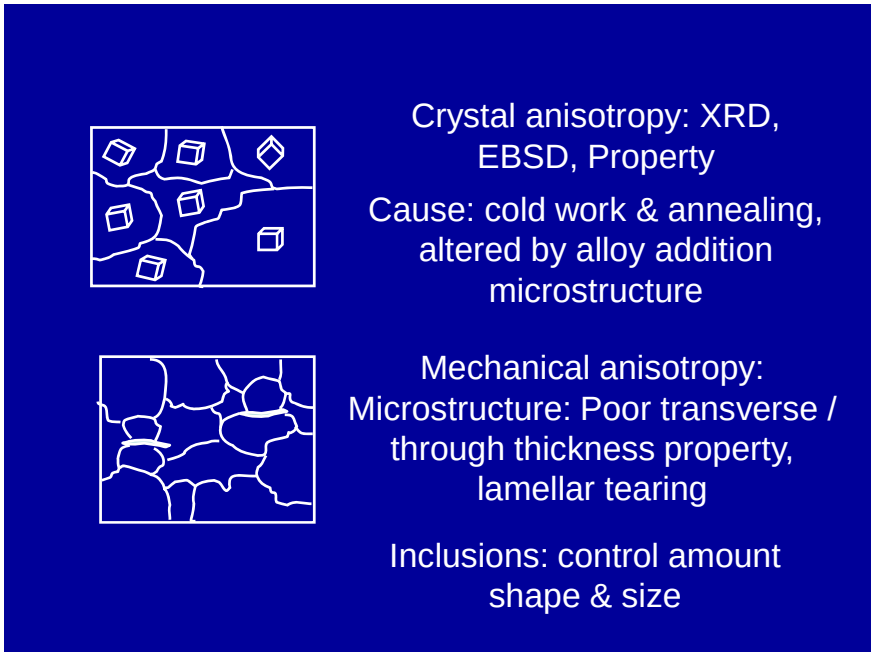
Mechanical anisotropy: inclusion shape: MnS

Crystal	Drawing	Rolling
FCC	[111] [100]	{100}<112> - {351}<112>
BCC	[110]	{112}<110> - {100}<011>
HCP	[210]	{0001}<1000>

Slide 2

Metals are known for its ductility. It can be deformed into any shape. This is true not only for the external shape of the metal but also for the individual grains within it. Therefore the shape of the grain, the distribution of precipitates and inclusions although may indicate the existence of anisotropy but it cannot give any idea about the orientation of individual grains. The external shapes of grains may look similar there their orientations might be different. This can only be evaluated from X-ray or Electron Back Scatter Diffraction (EBSD) patterns.

Slide 2 gives the orientations of grains in cold drawn wires or rolled sheets of metals. In the case of wire all the grains tend to align themselves in such a way that a specific crystallographic axis in each of these point along the axis of the wire. This is known as the fiber axis. Note that the indices of fiber axis depend on crystal structure. For example in the case of FCC structure the fiber axis is either [100] or [111], where as in the case of BCC it is [110]. These directions are normal to the close packed planes. (In FCC (111) planes have the highest packing density, and (100) has the second highest packing density.) A wire has an axi-symmetric geometry. It might be enough to specify its fiber axis. However in the case of a rolled sheet you need to specify the indices of the crystal planes in individual grains that are parallel to the rolled face and the indices of the directions of individual grains along the direction of rolling. For example in the case of low carbon steel which primarily consists of ferrite grains having BCC structure the top surface (rolled face) of each of the grains is either (110) or (100) where as the rolling direction is [110]. The texture that develops depends on the five independent slip systems that contribute to the deformation of individual grains.

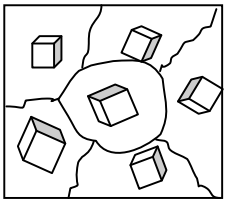


Slide 2

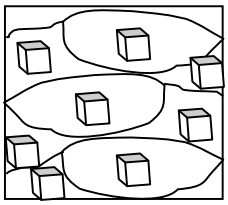
Slide 2 suggests that a polycrystalline material may exhibit anisotropic behavior because of the following two factors:

- Crystal anisotropy due to preferred orientation of individual grains
- Mechanical anisotropy due the preferred alignment of micro-constituents like inclusions

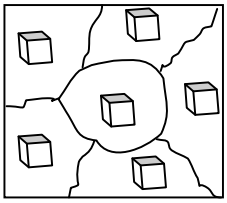
Slide 2 also suggests methods for the detection of anisotropy. Apart from direct determination of the orientation of grains measurement of the properties such as strength, ductility, magnetic permeability (for ferromagnetic material) or the elastic modulus along different directions could also be used.



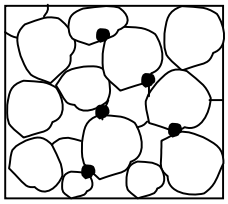
(a) Equiaxed grains having random orientation



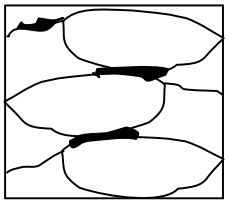
(b) Elongated grains having similar orientation



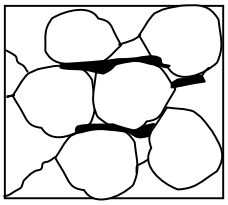
(c) Equiaxed grains having similar orientation



(d) Equiaxed grains having randomly distributed globular second phase



(e) Elongated grains and elongated second phase



(a) Equiaxed grains having elongated second phase

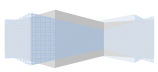
Fig 3: Shows a set of diagrams to explain the origin of anisotropy. Random grain orientation and random distribution of globular second phase (precipitate or inclusions: shown as dark filled in regions) is necessary for isotropic behavior: illustration (a) and (d). Aligned or elongated grains often denote preferred orientation: look at sketch (b) each grain has similar orientation. You get such a structure in directionally solidified casting or cold rolled parts. The presence of inclusions, second phase precipitates along dendritic channels in cast alloys or between elongated grains in cold worked parts (see sketch (e)) is also responsible for anisotropy. Such a microstructure gives poor through thickness strength, toughness and ductility. The presence of equiaxed grains does not ensure isotropy. Look at the sketch (c) the grains are equiaxed but all of these have identical orientation. Nucleation of strain free grains during re-crystallization is often controlled by the presence of inclusions or precipitates. This often controls the orientation of grains. Annealing of cold rolled parts cannot alter the shape and distribution of inclusions or segregations that are left behind even after deformation processing. Look at the sketch (e). The grains of cold rolled parts appear to be equiaxed but the inclusions retain their shape. This is responsible for its anisotropic behavior.

Figure 3 explains with the help of a set of sketches the origin of anisotropy in crystalline material. Apart from crystal structure, it depends a lot on the presence of second phase particles or inclusions and the various processing steps a component has to undergo before being put to use. The production of a perfectly isotropic material too can be a challenging task. For example to make cold rolled annealed steel sheet having isotropic behavior apart from the thermo mechanical processing parameters you may have to control the shape, size and

distribution of inclusions as well. Anisotropy is not necessarily bad. It can be beneficial for several applications. Let us now look at a few such examples.

Texture hardening:

Flow stress of a material is an important property. It is the stress at which large plastic deformation takes place. This occurs by slip. A metal consists of a number of crystals having different orientation. It would deform only if slip takes place in each of these. Slip occurs in a crystal when the resolved shear stress on specific slip system exceeds a critical value. The relation between applied and resolved shear stress was derived in module 9. It is also given in slide 3. The ratio of uniaxial applied stress (σ) to the resolved shear stress (τ) is known as the orientation factor (m). It is the reciprocal of the product $\cos\phi \cos\lambda$ where, ϕ is the angle between the load and the slip plane normal and λ is the angle between the load and the slip direction. A product of two independent variable is maximum when the two are equal ($\phi = \lambda = 45°$). Therefore the lowest value m can have is 2.0 whereas the highest value can be as high as infinity. The range depends on the availability of sufficient number of active slip system in each grain so that strain continuity is maintained. Most metals have either BCC or FCC structure having very high symmetry. There are various options to choose 5 independent slip systems to satisfy the continuity criterion. Therefore the range of m may not be wide in the case of metals having FCC or BCC structure. The average value of m for a polycrystalline aggregate consisting of randomly oriented FCC crystals is 3.1. It is also known as Taylor factor. As against these HCP structure can have a very wide range of values for m. This is because it has only a limited number of slip systems. The range of m (orientation factor) can be very wide in the case of ideal HCP structure. See slide 3.



Texture hardening

Potential application: dent resistant material.
Scope is limited for fcc / bcc metal.

$$\tau = \frac{P}{A}\cos\phi\cos\lambda$$

m = orientation factor

$$\frac{\sigma}{\tau} = \frac{1}{\cos\phi\cos\lambda} = m$$

m_{min} = 2.0

hcp: m: 2-infinity

fcc: m: limited range ~3.1 for random orientation

Textures in metal affect several other properties

Slide 3

The strengthening (or the resistance to plastic deformation) due to preferred orientation is a function of m the Taylor factor. The yield stress of a material under uniaxial loading is equal to m times the critical resolved shear stress $(\sigma_y = m\tau_{CRSS})$. Note that the critical resolved shear stress is the true material uniaxial tensile or compression test is a function of the crystallographic texture the material has. Depending on the magnitude of m it can vary widely. Polycrystalline metal having ideal HCP structure has a very high potential for texture hardening. A potential application is the development of dent resistant material.

Representation of crystallographic texture:

Stereographic projection is used to represent the orientation of a single crystal. Figure 4 (a) gives an example of such a projection. A tiny cube has been placed at its center. It has a shaded triangle to denote the orientation of its 111 plane. (001) is the plane of projection. Note the location of its four 111 type poles. A polycrystalline metal is an aggregate of a large number of grains. Each of these would have 4 such poles. If there are 1000 grains (crystals) / mm^3 there should be 4000 (111) poles. Figure 4 (b) shows a schematic representation of the locations of such a large number of (111) poles of a polycrystalline aggregate. A dot in this diagram denotes the location of one 111 plane. A uniform distribution means the absence of any texture or preferred orientation. Such diagrams are known as pole figures. These are used to represent the preferred orientation in crystalline materials.

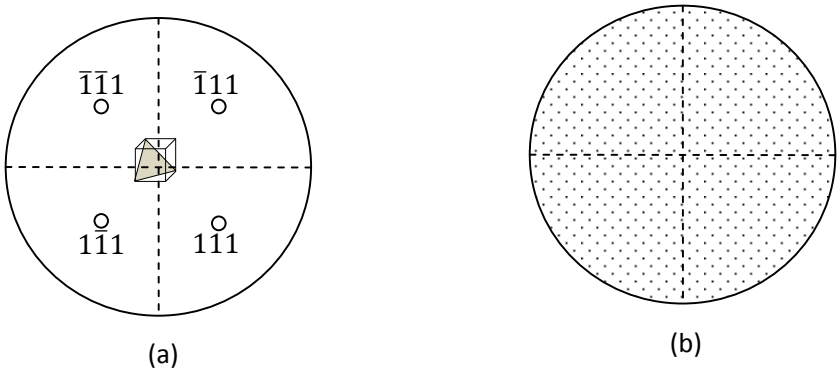


Fig 4: (a) Shows the orientation of (111) poles of a cubic crystal on a standard 001 projection. A cubic crystal has four 111 poles. Therefore the projection shows their locations with the help of 4 points. (b) Shows the locations of 111 poles of in a polycrystalline material. These are represented as dots as there are several grains having 4 such poles. Uniform distribution indicates random orientation. This type of representation of a particular pole in a polycrystalline material is known as pole figure.

How are pole figures generated?

Pole figure represents the distribution of poles (normal to a specific reflecting plane) on a standard projection. This can be constructed only if the orientations of all the crystals within the metal are known. The most common method is to track or record the diffracted beams emanating from a specific crystallographic plane of the metal when a monochromatic beam of X-ray or electron falls on it. Recall that diffraction occurs when the Bragg conditions are satisfied. This is represented as follows:

$$2d\ sin\theta = \lambda \qquad (1)$$

Note that d denotes inter planar spacing, θ is the angle of incidence and λ is the wave length of incident beam of X-ray. Let us consider only the diffracted beams from (111) planes of a FCC crystal. Inter- planar spacing of (111) planes are fixed. It is equal to $a/\sqrt{3}$ where 'a' denotes lattice parameter which is fixed. Since a monochromatic beam is used wave length too is constant. The angle of incidence (θ) is the only variable. The condition set by equation 1 can be satisfied only if the sample has a large number of crystals. You will get diffracted beams only from crystals whose (111) planes are favorably oriented. This is illustrated with the help of diagrams in Fig 5.

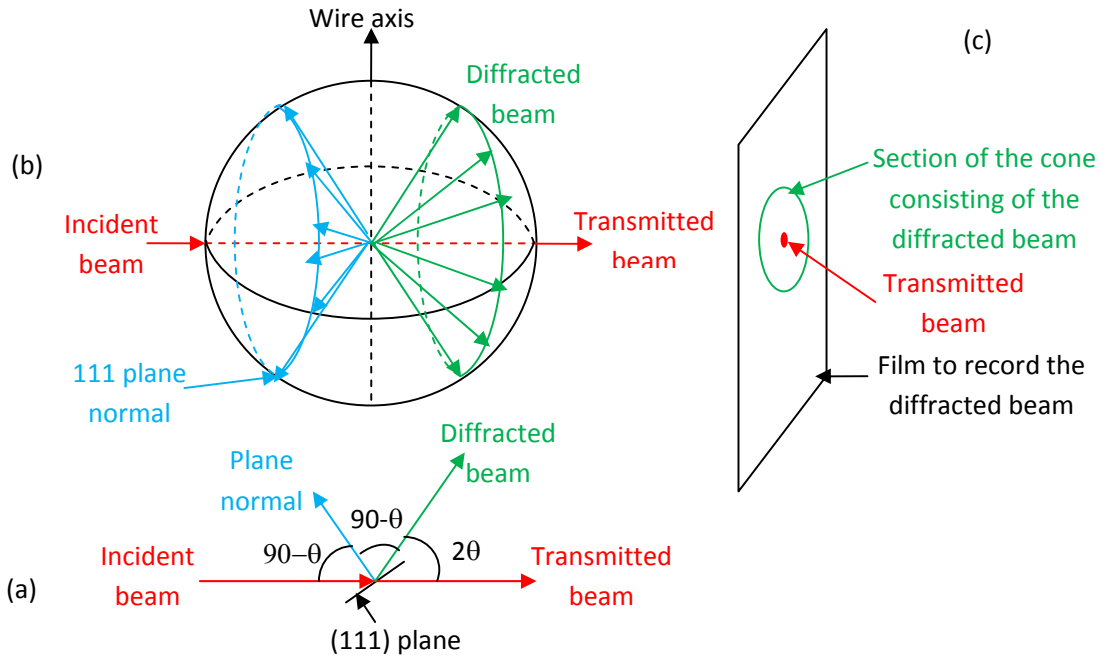


Fig 5: Shows the directions of diffracted beams originating from a wire sample where grains are randomly oriented. (a) Shows the Bragg condition under which there will be a diffracted beam from (111) plane. The crystal is assumed to be FCC. (b) Shows a 3-D view of the setup used to record the diffraction pattern. A sample consisting of a large number tiny crystal is located at the centre of the reference sphere. Note that the blue lines denote the orientations of the (111) plane normal that satisfy the Bragg condition. These lie on a cone whose semi apex angle is (90-θ). This intersects the reference sphere along the blue circle. The corresponding diffracted beams would lie on a cone whose semi apex angle is 2θ. These are shown as green arrows. This intersects the reference sphere along the green circle. (c) Shows the orientation of the film to record the diffraction pattern. It is perpendicular to the axis of the cone made of diffracted beams represented by green arrows. It is located at a short distance from the center of the reference sphere. Therefore the diffraction pattern would be a circle as shown.

Figure 5 explains with the help of a set of diagrams why a continuous diffraction ring on the film is expected if the grains are randomly oriented. What would you expect if the (111) reflecting planes were preferentially oriented with respect to the wire axis? This is shown with the help of a set of sketches in fig 6. This suggests that the intensity of diffraction spots is a function of crystal orientation.

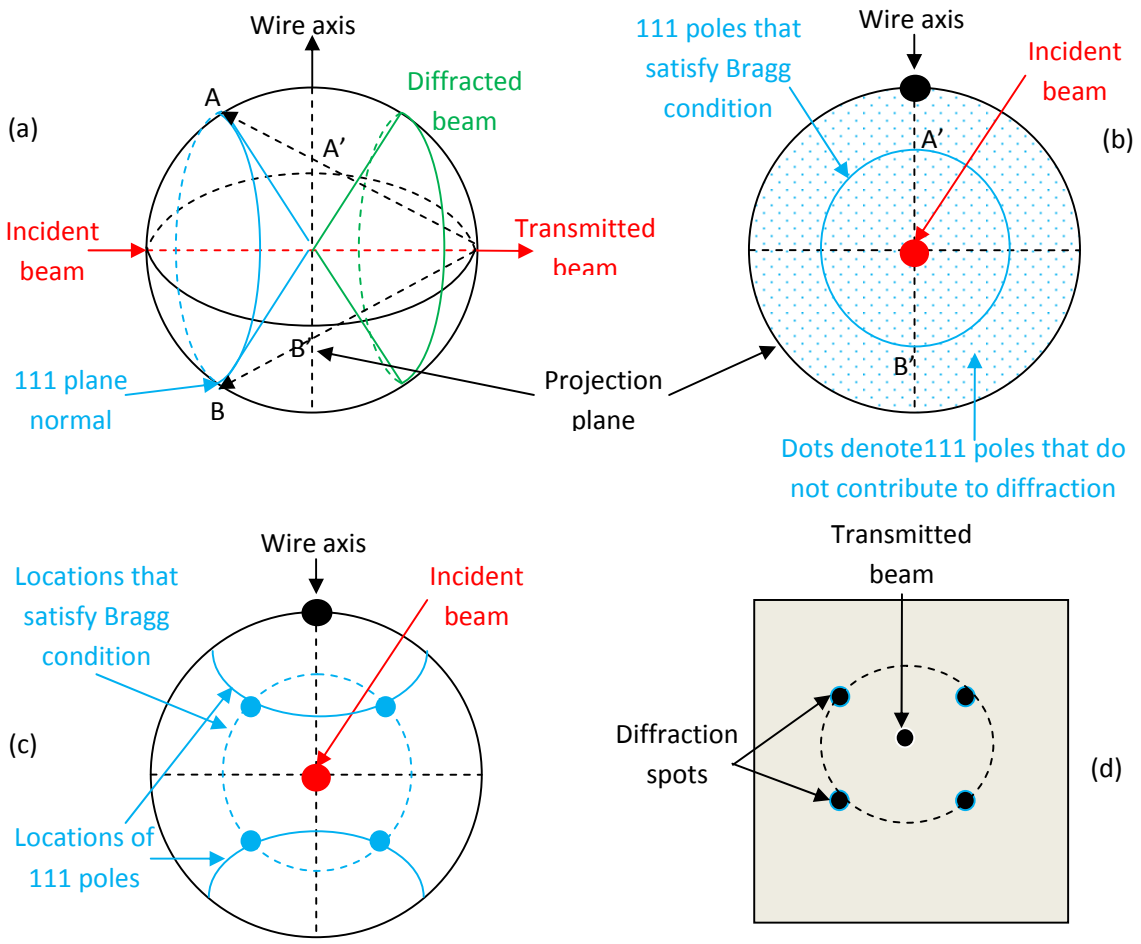
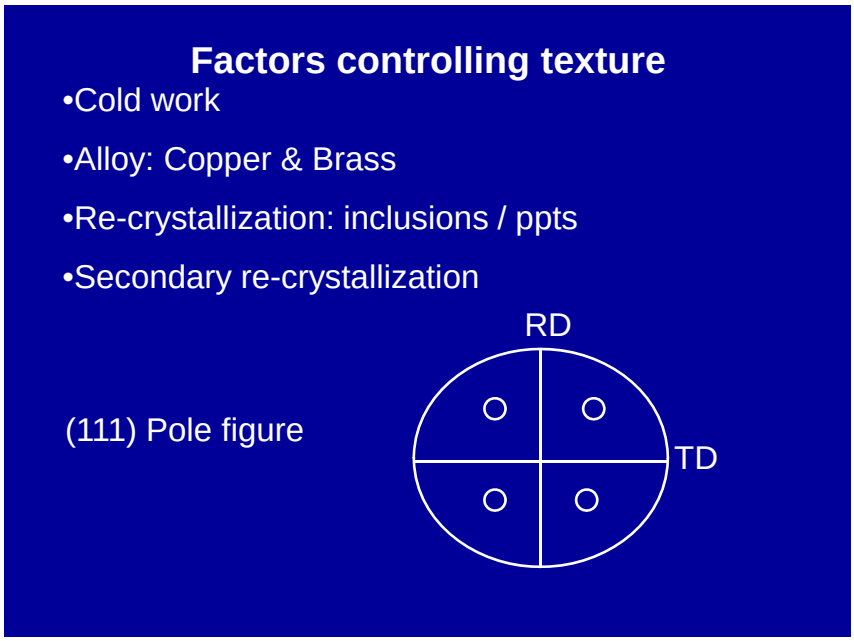


Fig 6: (a) Shows a 3-D setup to record the diffraction pattern of a wire sample placed at the centre of a reference sphere. The surface of the blue cone is generated by the normal to the (111) planes satisfying the Bragg condition for diffraction. The red dashed lines denote the incident and the transmitted beams. The surface of the green cone consists of the diffracted beams from (111) planes that are favorably oriented. (b) Gives the stereographic projection of the reference sphere in (a). Look at the pair of black dashed lines with arrow heads originating from a point on the sphere in (a). It joins the point from where the projection has been taken to a point on the blue circle representing the locations of the (111) poles on the reference sphere. The two points in (a) are marked as A and B. The locations of these two poles on the plane of projection are A' and B'. The vertical dashed line marked as the wire axis in (a) is a great circle or a plane. This explains the relation between the two diagrams (a) and (b). The latter is the stereographic projection of the former. The blue small circle denotes the locations of (111) that satisfy the Bragg condition. The uniform distribution of blue dots indicates that (111) poles are uniformly distributed. (c) Shows what happens when (111) plane normal from all the grains subtend a definite angle with the wire axis. The two firm blue lines denoting the locations of (111) poles intersect the blue dashed circle at four points. (d) Shows that diffraction pattern should consist of only four spots.

Factors that control preferred orientation:

The origin of crystal texture lies in the way a material is made. It develops right from the solidification stage itself. The presence of columnar grains in a cast structure is an indication of preferred orientation. However it may get altered during subsequent processing. Depending on the processing route an engineering material may have perfectly random to perfectly aligned structure. Apart from conventional casting or cold work preferred orientation (or texture) can also develop during directional solidification, electro-deposition and zone refining. Recall that zone refining is a method of purification of metal. A thin molten zone is formed at one end of a bar made of commercially pure metal and it is made to move along its length until it reaches its other end. Impurities get partitioned into the molten pool. The purity increases with the number of times the process is repeated. It finally results in a solid having two distinct zones: one which is extremely pure and the other having all the impurities that were present in the initial stock. Slide 4 gives the factors that control texture in metals during deformation processing.

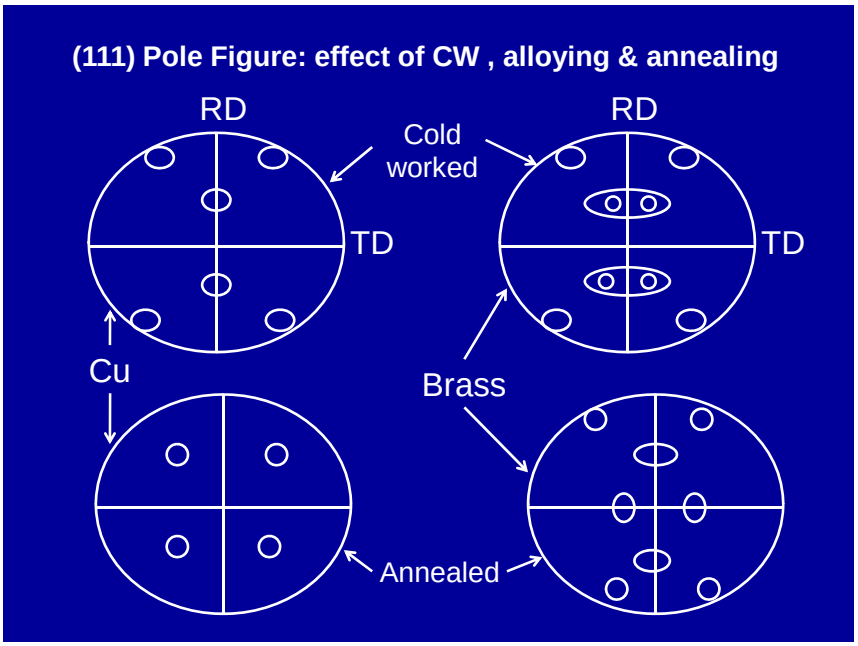


Slide 4

Cold work: During cold work the shape and the orientation of the grains keep changing. The magnitude of change is a function of the amount of cold work. For example in the case of wire drawing as the amount of reduction increases individual grains orient themselves in such a manner that a particular direction in all of them tend to become parallel to the direction of deformation or the wire axis. This is commonly known as its fiber axis. The physical property of the wire (elastic modulus for example) is likely to be same as that along its specific crystallographic axis. Figure 6(c) shows how the orientation of a particular direction gets concentrated within a specific region of the standard projection and fig 6(d) gives the nature of the diffraction pattern. The shape and the size of the diffraction spots describe the exact

orientation of the grains. A set four perfect dots (or spots) may represent that the wire axis is exactly [100], whereas the presence of four small arcs lying along the imaginary diffraction ring indicate that [100] directions in all the grains lie within a few degrees of the wire axis. In case of cold rolled sheet specifying the rolling direction may not be enough. You need to specify either the indices of the transverse direction or give the indices of the planes that are parallel to the rolled surface. Slide 4 gives a typical representation of (111) pole figure of a rolled sheet. This denotes that the rolling direction (RD) is [001] and the indices of crystal planes that are parallel to the rolled surface are (100). This is usually denoted as {001} <100>.

Alloy addition (Cu & Brass): Slide 5 gives the typical pole figure plots of cold rolled copper and brass. This shows that alloy addition can alter the nature of texture found after cold work. This is certainly not unexpected. The origin of texture is associated with the micro-mechanism of deformation. Alloy addition affects stacking fault energy. Alpha brass has lower stacking fault energy than that of pure copper. This makes cross slip difficult. As a result the set of slip planes contributing towards deformation are likely to be different. This affects the evolution of texture during cold work. The sketches shown are purely schematic. The actual pole figures may have a set of contours representing the intensity of diffraction pattern or the density of particular poles oriented along specific regions of the projection.



Slide 5

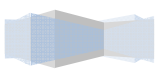
Annealing: On annealing cold worked grains are replaced by new strain free re-crystallized grains. The orientation of these depends on the amount of prior cold work and the presence of inclusions or tiny second phase particles. If there are no inclusions and the amount of cold work is less the orientation of re-crystallized grains is likely to be random. However in the presence of

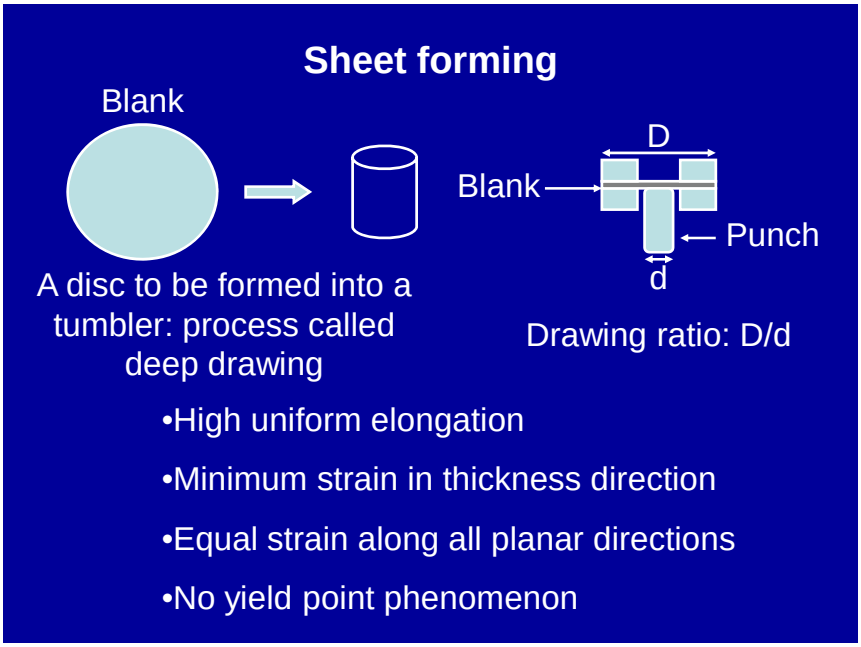
inclusions and high amount of cold work a texture that is totally different from that in cold worked metal may develop on annealing. Slide 5 shows the effect of annealing on the evolution of textures in Cu & brass. Often even if the annealing texture may be weak but on prolonged annealing only the grains that are preferentially oriented with respect to the inclusions continue to grow at the expense of the others. This is often referred to as secondary re-crystallization. A well known example secondary re-crystallization is the development of a very coarse grain structure having (110) [001] texture in iron silicon alloy.

Application: Preferred orientation or crystallographic texture in engineering material is not necessarily bad. There are applications where it might be beneficial. One of the most common examples is that of cold rolled grain oriented steel (CRGO) that are used as transformer core. It is subjected to repeated magnetization and demagnetization. Soft magnetic material is the ideal choice. [001] is the most preferred direction for easy magnetization or demagnetization. (110)[001] is the preferred texture. This develops easily as a result of secondary re-crystallization in iron-silicon alloy. However if you are looking for a soft magnetic material for a rotor in a motor this may not be the ideal choice. The direction of magnetization would keep changing periodically. Therefore a soft magnetic material having isotropic behavior would be preferable. Cold rolled non-oriented (CRNO) steel sheets are the best choice. Let us now look at two examples where evolution of preferred texture has significantly improved the performance of engineering materials.

- Sheet forming: Development of deep drawing quality steel
- High temperature material: Development of directionally solidified super-alloy

Deep drawing: This is one of the most common sheet forming techniques. It transforms a disc made of a thin metal sheet into a tumbler. This is illustrated with the help of a set of sketches in slide 6. Let D be the diameter of the disc to be formed into a one end closed hollow cylinder of diameter d. D/d is known as the drawing ratio. The maximum permissible value of this ratio is a measure of the deep drawing ability of the steel. It is known as limiting drawing ratio (LDR). Components like LPG cylinders, cold drink containers are made from deep drawing quality steel. High LDR means good deep draw-ability.





Slide 6

Slide 6 also gives a list of factors that could ensure high yield (or minimum rejection) and surface quality of the deep drawn product. The first three is in some way connected with the crystallographic texture present within the sheet whereas the last one is associated with the yield point phenomenon in low carbon steel.

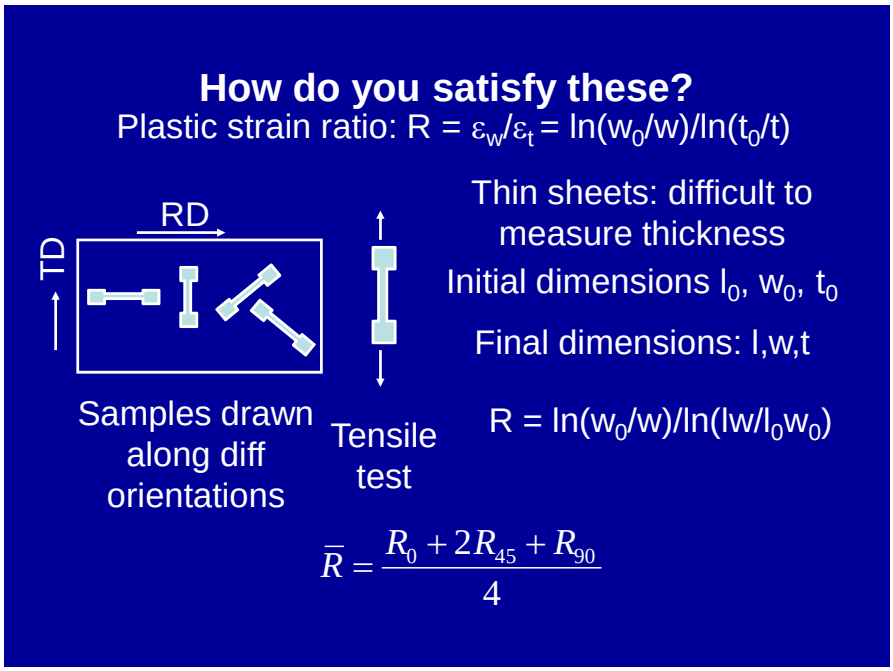
High uniform elongation: Slide 6 shows with the help of a sketch how a disc shaped blank is placed between a pair of guides while a punch pushes it within a die. As the blank gets pushed into the die cavity material must flow uniformly from all directions. A measure of this ability is the uniform ductility of the material. This is the strain beyond which local deformation or necking sets in. You may recall that the flow stress (σ) of a material is given by $\sigma = k\varepsilon^n$ where ε is the true strain, k denotes the stress at ε = 1 and n is a measure of true uniform strain. A high n means high uniform strain or high resistance to localized deformation.

High plastic strain ratio: Good sheet formability also means that during deep drawing the reduction in thickness (t) should be as low as possible in comparison to the reduction along its width (w). This is best described by a parameter called plastic strain ratio. This is defined as follows:

$$R = \frac{\varepsilon_w}{\varepsilon_t} = \ln\left(\frac{w_0}{w}\right) / \ln\left(\frac{t_0}{t}\right) \qquad (2)$$

In equation 2, w_0 and t_0 denote the initial width and thickness of the tensile test specimen. Both w and t denote the width and the thickness of the test specimen at peak stress (this corresponds to its UTS). However the reduction in thickness often may be more difficult to measure as it may be very small. Therefore often it is estimated from uniform elongation. The expression which is more convenient to estimate R is given in slide 7. This is derived on the

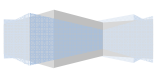
basis of the assumption that the volume remains constant during deformation. Note that l_0 denotes initial length and l is the length just before necking or local deformation.

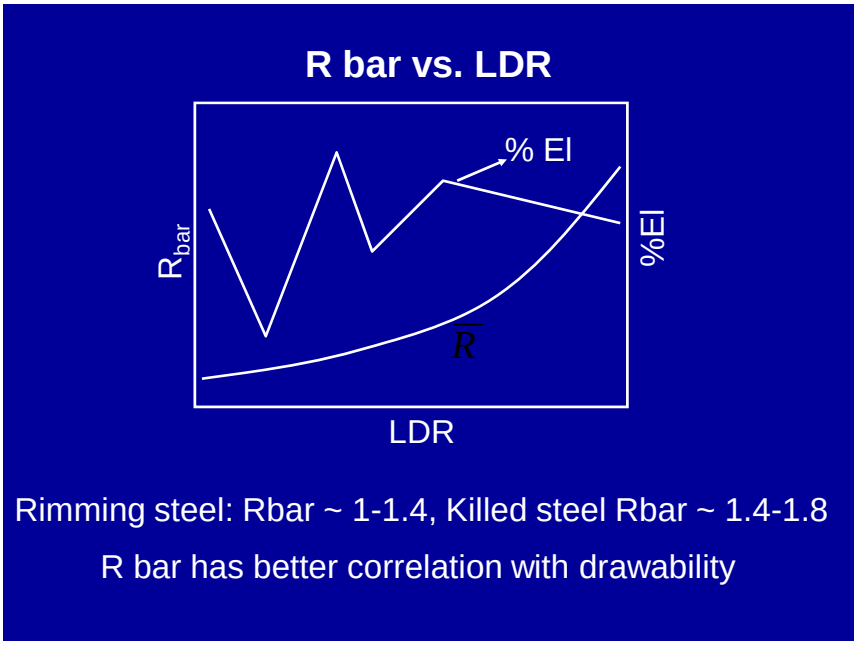


Slide 7

The plastic strain ratio also depends on the orientation of the test specimen. The sketch in Slide 7 gives how the specimens are made from a rolled sheet. R_0 represents the plastic strain ratio obtained from a specimen aligned along the rolling direction. R_{90} denotes the plastic strain ratio along the transverse direction. There are two possible ways you can make a specimen whose tensile axis subtends an angle of 45° with the rolling direction. R_{45} denotes the plastic strain ratio along these two directions. The average of the four is known as $\bar{R}$. Slide 7 gives the expression used to determine $\bar{R}$.

Slide 8 shows that the correlation between LDR and $\bar{R}$ is more dependable than that between LDR and % elongation. A high $\bar{R}$ means better deep drawability. This is of the order of 1-1.4 in the case of rimming steel whereas it is 1.4-1.8 in the case of Al killed steel. This is possibly due to the presence of tiny particles of AlN. There are steels having still higher $\bar{R}$ (~2). These are often referred to as extra deep drawing quality steel.



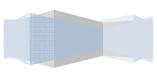


Slide 8

Planar isotropy: The material should have similar $\bar{R}$ along all planar directions. What happens if the material does not fulfill this criterion has been explained in fig 7. This leads to non-uniform planar deformation. This type of defect is known as earring. The magnitude of $\bar{R}$ is a function of the orientation of the specimen. Let the maximum and the minimum values of R be R_{max} and R_{min} respectively. The difference between the two is known as ΔR. This is given by $\Delta R = R_{max} - R_{min}$.

This defines the degree of planar isotropy. For planar isotropy ΔR = 0. This is what one should look for while selecting a material having good sheet formability. A high ΔR means high planar anisotropy. Such materials are susceptible to earring. The 3 most important criteria for good deep draw-ability are:

- High n: good uniform ductility (measure of stretch-ability)
- High $\bar{R}$: high through thickness strength
- Low ΔR: planar isotropy



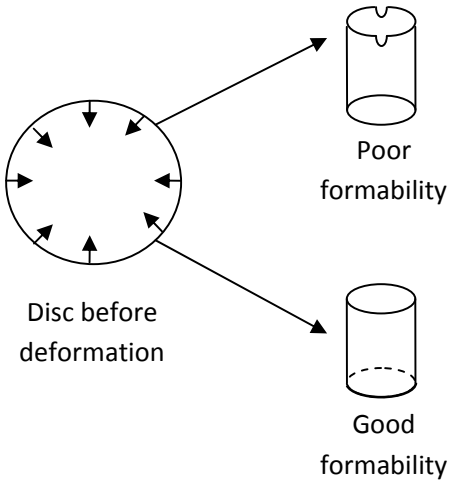
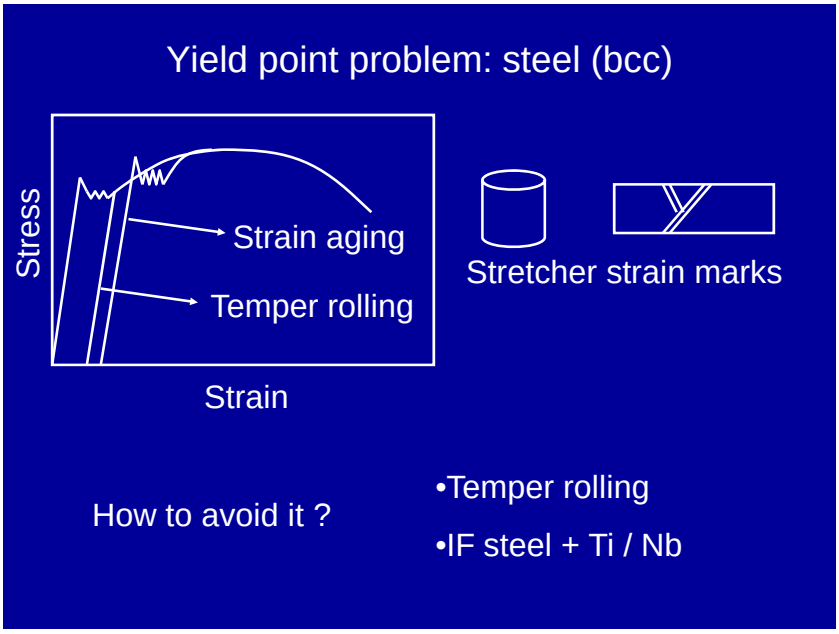


Fig 7: Shows the effect of planar isotropy on the shape of the final product. If planar ductility of the disc is identical along all directions on the plane, the top edge of the cylinder is uniform. If it is not so it results in an uneven top edge. This type of defect in the formed product is known as earring. If such a defect develops the top edge needs to be cropped. This is responsible for low yield. The main reason for its occurrence is the lack of planar isotropy.

In addition to these BCC metals such as steel must satisfy an additional requirement. This is associated with the yield point phenomenon. In the presence of interstitial solute elements BCC metals exhibit yield point elongation. This leads to the formation of local deformation bands called stretcher strains. This makes the product unacceptable. This is illustrated with the help of sketches in slide 9. The sketch on the left gives a typical stress strain plot of low carbon steel. The occurrence of sharp yield point and the substantial yield point elongation is responsible for the strain marks on the formed product. This phenomenon is due to the presence of interstitial carbon and nitrogen atoms in solid solution. In the presence of interstitial solute atoms the dislocations in BCC crystal are effectively pinned. The upper yield point is the stress at which these are unpinned. This suddenly produces a large number of mobile dislocations. Their subsequent movement results in significant yield point elongation until these are blocked by interactions between dislocations. Thereafter the stress starts increasing with strain. If the load is withdrawn after the yield point elongation and the sample is reloaded again it will not exhibit any yield point phenomenon. This suggests that cold worked steel does not show yield point phenomenon. However it may reappear after prolonged holding at room temperature or thermal exposure (100°-150°C).

How can we avoid the presence of sharp yield point in steel? Since this is associated with the presence of interstitial solute elements one of the possible ways could be complete removal of such elements. For example interstitial free (IF) steel do not exhibit yield point phenomenon. An alternative method could be to fix interstitial atoms as precipitates so that there are not enough atoms to pin the dislocations. An example is the addition of Ti or Nb. The two have very high affinity for carbon. Steels having such strong carbide formers do not have sharp yield point. The third option is prior cold work (~2%) little before the sheet forming operation. This is often known as temper rolling. However the waiting time (or the transit time) after such an operation should not be long as yield point may reappear due to the time dependent movement (diffusion) of interstitial atoms even at room temperature.

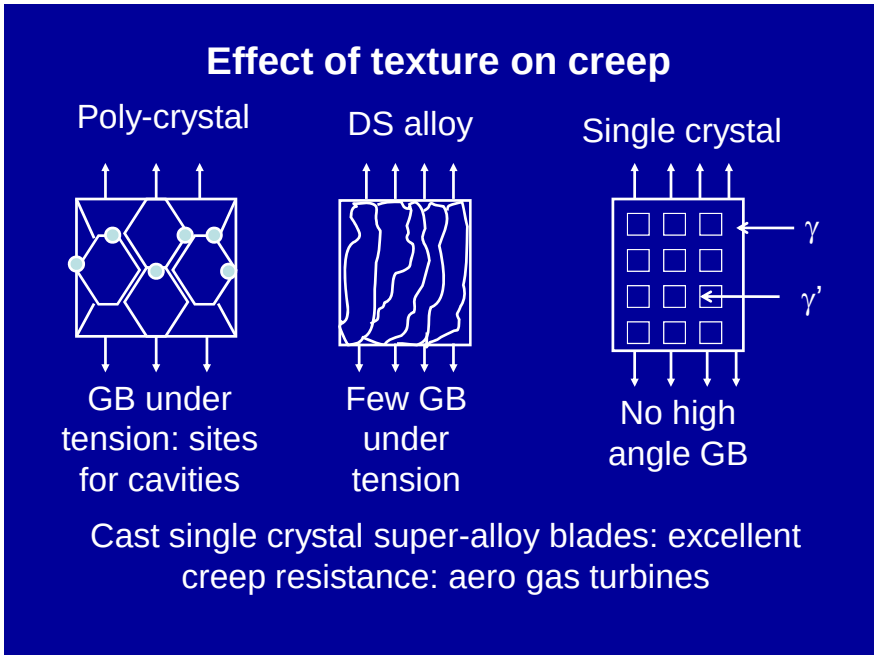


Slide 9

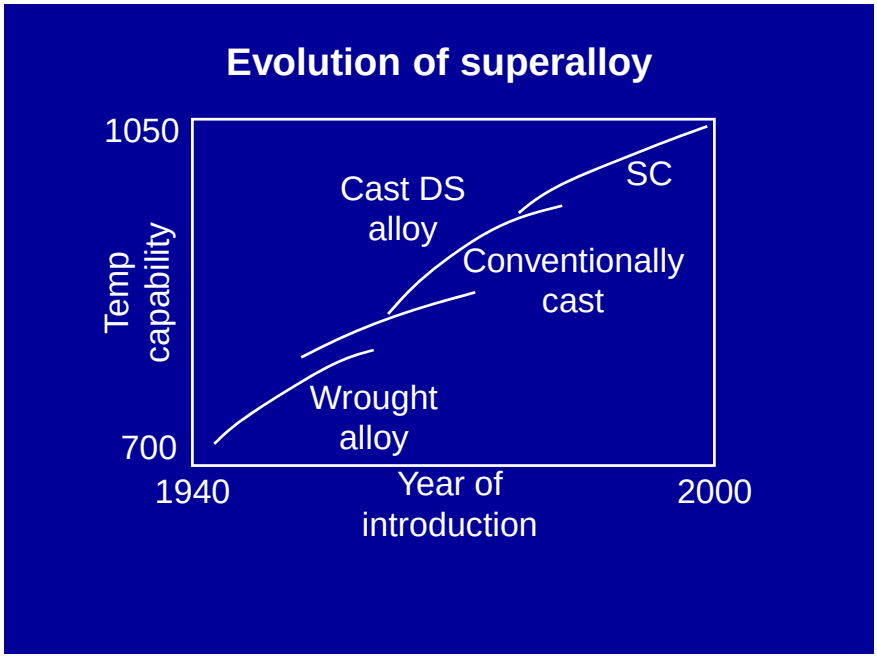
Effect of texture on creep: Time dependent deformation or creep is primarily responsible for the loss of load bearing capacity of high temperature engineering materials. There are several ways of improving the creep resistance. A few of these were discussed in module 40. The main focus however was on steel. This is made of several grains although the grain size may be relatively coarse. The bulk of creep failures originate from grain boundaries. Therefore one of the ways to improve the creep resistance is to make the grain boundaries stronger. Alloy addition that promotes formation of grain boundary precipitate is the most common option. An alternative approach is to control the nature and the orientation of grain boundaries within the alloy. What would happen if there is no grain boundary? This is illustrated in slide 10.

The sketch on the left shows that grain boundaries in polycrystalline metals perpendicular to the direction of loading are the most preferred sites for the nucleation of creep cavities. Therefore it has relatively poor creep resistance. The absence of such boundaries in directionally solidified alloys makes these more creep resistant. The absence of grain boundaries altogether as in single crystal can give still higher creep resistance. Currently single crystal super-alloy blades are the most popular material for gas turbine blades.

Creep resistant materials are extremely difficult to form because of its very high strength. These are used in as cast form. Precision or near net shape casting techniques are used to make these. This is based on investment casting or lost wax process. Molten alloy poured into ceramic molds is cooled slowly under a controlled thermal gradient. The solidification starts from one end and the solid liquid interface moves in the direction of the thermal gradient. Usually the cube axis is the most preferred direction of growth. It has relatively low elastic modulus. Apart from good rupture strength it gives very high thermal fatigue resistance too.



Slide 10



Slide 11

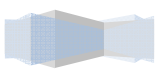
Slide 11 shows how the performance of Ni-base super-alloy since its inception in 1940s has improved over the years. This is represented in terms of the temperature capability of the alloy. Polycrystalline or wrought NiCr alloy having Ti/Al as the precipitation hardening elements was amongst the first to be used as aero gas turbine blades. In order to improve it temperature

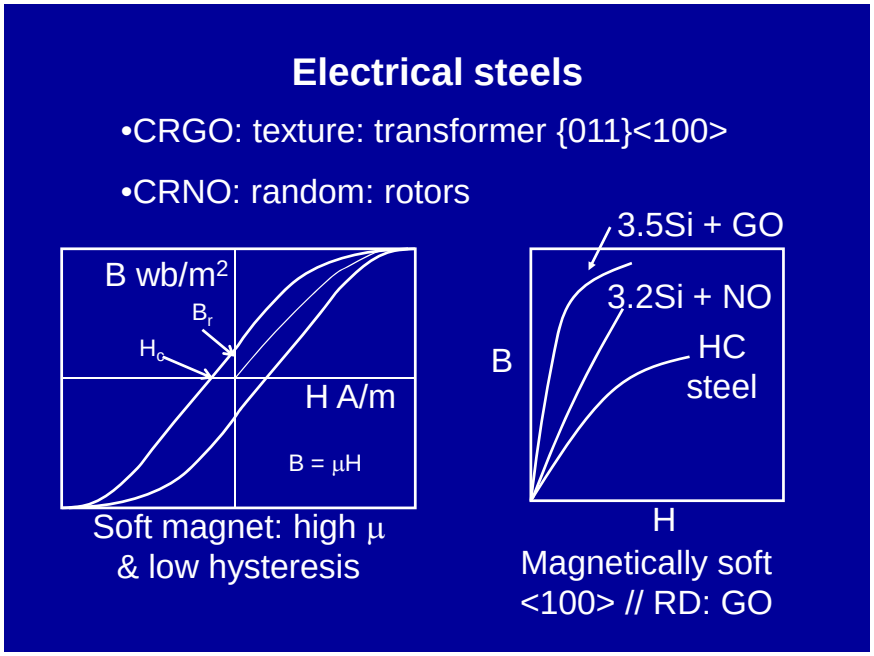
capability several strategies were adopted. The factors that can significantly improve the creep resistance of the alloy are as follows:

- Solid solution (matrix) strengthener: Cr, Co, Mo, W
- γ' former (precipitate): Al, Ti, Nb, Ta
- GB strengthener: B, Zr, C, Hf
- Carbide formers: Cr, Ti, Mo, W, Nb, Hf, Ta
- Oxide scale former: Cr, Al

To improve the temperature capability of wrought alloys a very large number of alloy additions were necessary. Cast single crystal alloy does not have any high angle grain boundary. It only has coherent γ' precipitates in a matrix of γ. The volume fraction of γ' can be as high as 70%. These are extremely stable at high temperature. This is primarily responsible for its good creep resistance. The absence of grain boundaries in super-alloy makes addition of grain boundary strengthener or carbide formers redundant. Single crystal super-alloys are therefore much leaner in composition.

Electrical steel: Grain oriented silicon steel is used as transformer core to minimize the core loss. Slide 12 gives a typical BH loop of a ferromagnetic material. The slope of the linear part of the plot is known as permeability. The area within the loop is a measure of core loss. This is low for soft magnetic material having high permeability, low coercivity (Hc) and low remanence (Br). The second diagram in slide 12 gives the initial part of the BH curve for three different types of steel. High carbon steel has the lowest permeability. It is not a soft magnetic material. In comparison 3.2%Si NO (non-oriented) steel has higher permeability. It is a better soft magnetic material. If you can develop (110) [001] texture in this steel its permeability can be significantly improved. This type of texture is commonly known as cube on edge or Goss texture. This was first discovered by Norman P Goss.

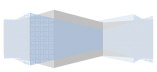


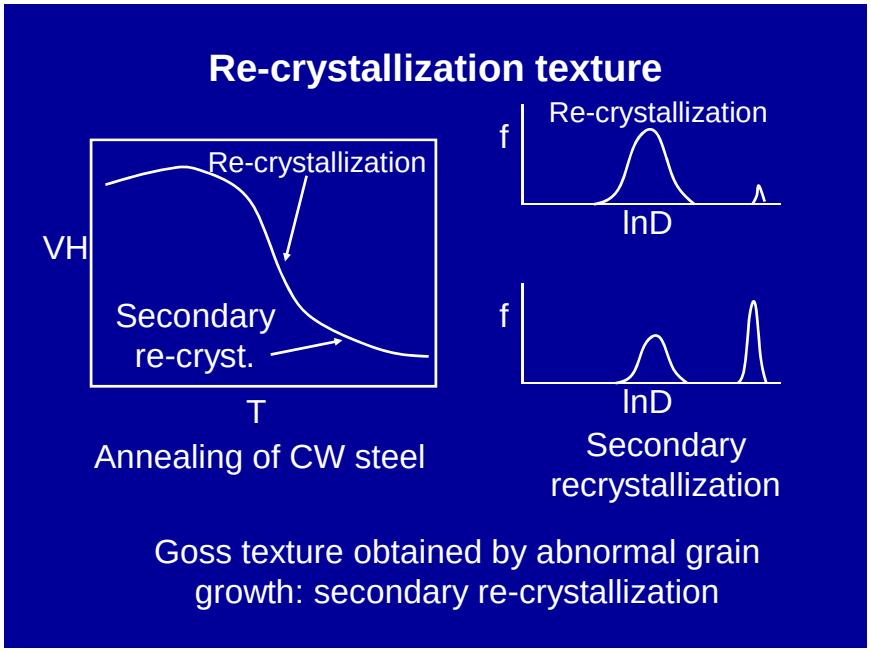


Slide 12

Two types of textures can be developed in Si steel. One known as normal texture has (100) or the cube planes aligned parallel to the rolled face. This is represented as (100) [001]. The second texture commonly called Goss or cube on edge texture has the cube planes parallel to the edge of the sheet. This is represented as (110) [001]. The presence of Goss texture can improve magnetic flux density (B) or the magnetic permeability significantly.

The origin of texture in steel depends on cold work and annealing. Slide 13 shows how Vickers hardness (VH) changes with annealing temperature. The annealing time is held constant. The cold worked grains are replaced by strain free grains of ferrite soon after re-crystallization. At this stage the predominant texture is (100) [001] whereas the Goss texture is relatively weak. However during the secondary re-crystallization stage the grains having Goss texture grow as large grains at the expense of the other.



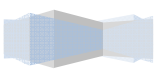


Slide 13

The figure on the top right in slide 13 gives grain size distribution just after re-crystallization. Most of the finer grains have normal structure. Very few grains have the Goss texture. However after secondary re-crystallization the coarse grains grow significantly at the expense of the finer ones. As a consequence there is a significant increase in its magnetic permeability.

Summary:

In this module we looked at the origin of anisotropy in engineering materials that are mostly made of a large number of crystals. This is due to preferred orientation of individual grains or the shape, size and the distribution of its micro constituents. Apart from measurement of properties along different directions the presence of texture can be detected from the intensity of X-ray diffraction lines. Randomly oriented grains give continuous diffraction ring whereas in the presence of preferred orientation the pattern consists of isolated spots aligned along imaginary rings. The information obtained from X-ray diffraction is reported in the form of a pole figure. This is a graphical representation of the distribution of the poles of a particular crystallographic plane on a stereographic projection. The crystallographic texture that develops in a material depends on several processing parameters. These can be controlled to develop favorable texture for a variety of applications. The occurrence of uneven edges during deep drawing of thin steel sheet into cups or tumbler is due to the lack of planar isotropy. This type problem is commonly known as earring. We looked at how such problem can be overcome. The role texture in the development of soft magnetic material and creep resistant super-alloy has also been discussed.



Exercise:

1. Is it possible to infer whether a hot rolled steel plate would exhibit poor through thickness ductility by looking at its optical microstructure?
2. Why should polycrystalline alloys have different properties in different directions?
3. Why are nickel base single crystal super alloys the most preferred material for gas turbine blades?
4. Which crystallographic direction of Nickel base superalloy should have the highest strength?
5. Which properties will you look for while selecting steel for deep drawing application? Give reasons.

Answer:

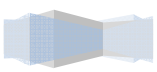
1. The presence of inclusion (mostly MnS) elongated along the direction of rolling is responsible for poor through thickness ductility of steel plate. Microstructure of a longitudinal section would show elongated inclusions. The ratio of its length to thickness depends on the total deformation the plate has undergone.

2. The main reasons for polycrystalline alloys exhibiting different properties along different directions are (a) preferred orientation due to either cold work or re-crystallization texture (b) presence of elongated inclusions.

3. Gas turbine blades have to withstand high stresses at elevated temperature (850˚C). Therefore the main mechanism of failure is creep. This occurs through nucleation & growth of cavities. Grain boundaries are the most preferred sites for cavitation. Absence of such sites in single crystal gives it the best creep resistance. Apart from this the crystal axis having maximum creep strength is oriented along the maximum principal stress to exploit its anisotropic behavior.

4. Nickel base superalloy has face centered cubic structure. Its preferred slip system is$\{111\}\langle 1\bar{1}0\rangle$. The axis having maximum strength should have minimum Schmid's factor. <111> has minimum Schmid's factor.

5. Deep drawing is a sheet forming process. The material should have high through thickness strength so that during forming there is minimum loss of thickness. Whereas along planar direction it should have identical formability. Plastic strain ratio R gives a measure of formability. Deep drawing grade of steel must have high $\bar{R}$ and minimum



ΔR. The former ensures minimum thickness strain whereas the latter indicates planar isotropy (this is needed to avoid earring problem).

Appendix

Representation of preferred orientation in sheet metal

The origin and the importance of preferred orientation have been explained in detail in this module. A little more details on the representation preferred orientation in sheet metal is given in this section.

In the case of a wire representation of preferred orientation is rather simple. It might be sufficient to know which crystallographic direction in each grain is aligned along the wire axis. However knowledge of preferred orientation in sheet metal is also of considerable interest. It affects closely related to its formability. Here it is necessary to describe the orientation of grains along three directions: rolling direction (RD), transverse direction and normal direction (ND). These are perpendicular to each other. Figure A1 (a) shows pole figure of sheet metal. It displays the location of a particular pole (for example 111) in a stereographic projection with respect to the three axes ND, RD & TD. Figure A1 (b) represents the corresponding inverse pole figure of ND. It suggests that the top face of most of the grains in the sheet is a cube plane. To describe the preferred orientation of a sheet you need 3 inverse pole figures one each for ND, RD and TD.

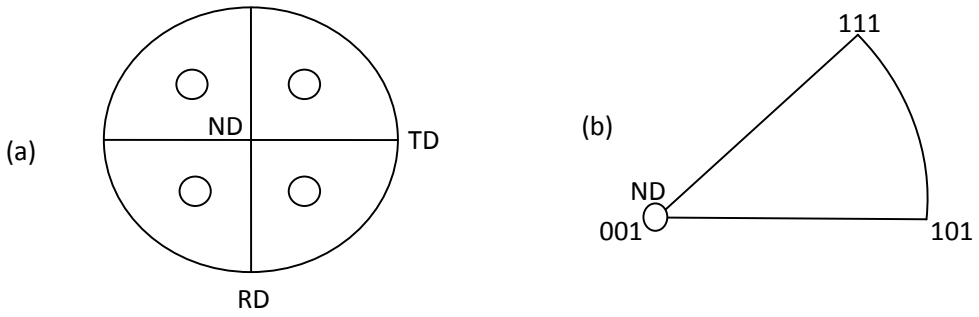


Fig A1: Illustrates the difference between a pole figure (a) and an inverse pole figure (b). The former shows the location of a given plane normal with respect to the sample axes. In this case it shows the location of 111 poles. Usually for FCC metal three common pole figures are those of 100, 110 and 111. Inverse pole figure gives the location of a sample axis with respect to the crystal axes. The location of ND is displayed in (b) with respect to the orientation of the crystal axes. It is an inverse of (a). In order to describe the texture or preferred orientation in a sheet product, 3 inverse pole figures are required; one each for ND, RD and TD.

Although normal and inverse pole figures adequately describe orientations of individual grains in a sheet with respect to its 3 reference axes (ND, RD & TD) there is another more popular way to represent it. This is based on Euler angles representing specific rotations (ϕ_1, ϕ, ϕ_2) required to align the cube axes of individual grains to coincide with the reference axes. Each grain is likely to have a specific set of Euler angles. The number of grains having Euler angles within ϕ_1, ϕ, ϕ_2 and $\phi_1+d\phi_1$, $\phi+d\phi$, $\phi_2+d\phi_2$ in a unit volume denotes an orientation distribution function (ODF).

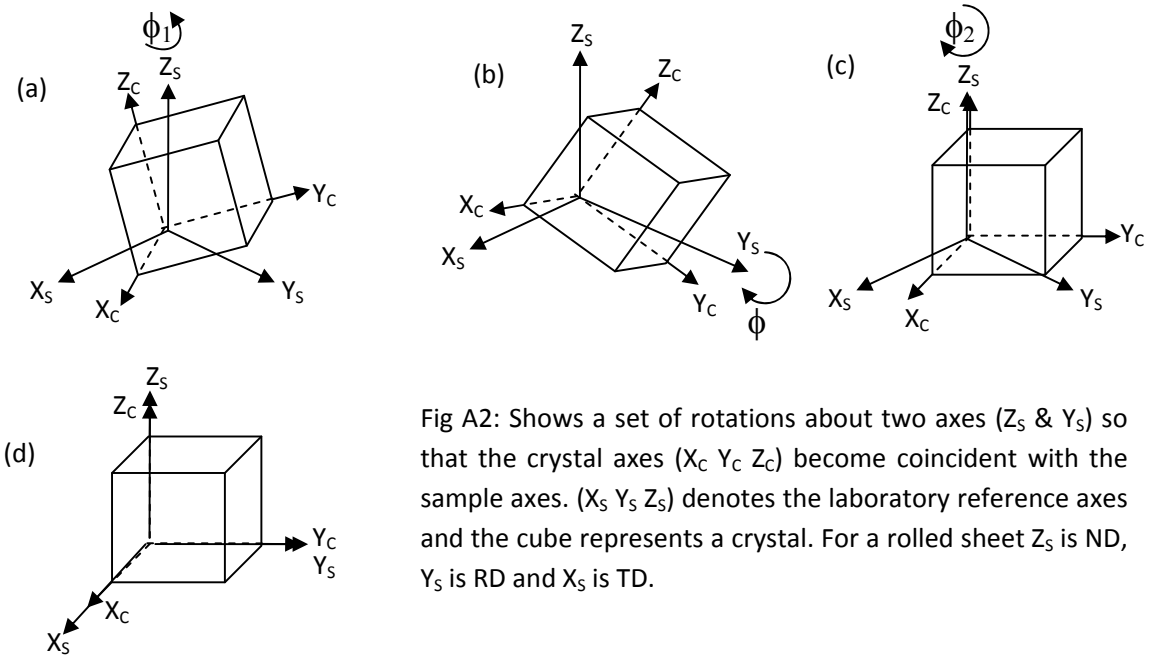


Fig A2: Shows a set of rotations about two axes (Z_S & Y_S) so that the crystal axes (X_C Y_C Z_C) become coincident with the sample axes. (X_S Y_S Z_S) denotes the laboratory reference axes and the cube represents a crystal. For a rolled sheet Z_S is ND, Y_S is RD and X_S is TD.

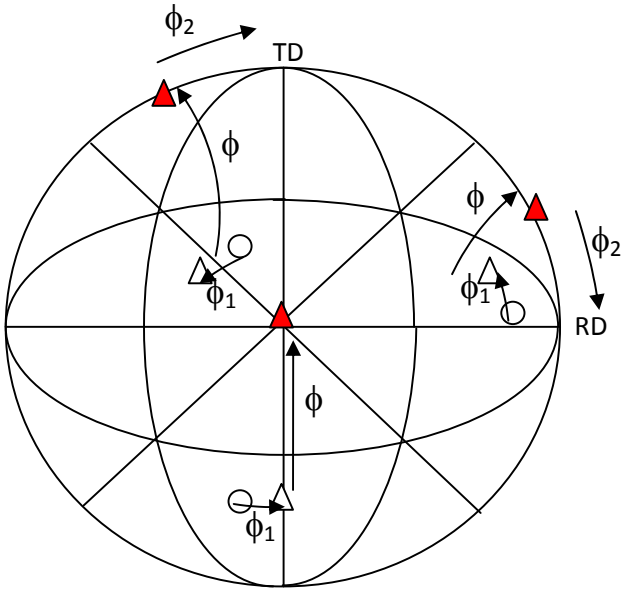


Fig A3: Explains with the help of a stereographic projection how the crystal axes may have to be rotated to get aligned along the three laboratory reference axes (ND: plane normal, RD: rolling direction and TD: transverse direction). The points denoted by unfilled circle are the initial locations of the cube poles; the unfilled triangles are the location after a rotation of ϕ_1 about ND, the filled triangles are the location after a rotation of ϕ about RD and ϕ_2 is the final rotation about ND. These three angles are known as the Euler angles. The projection plane is ND.

Figure A2 represents the orientation of a specific crystal (X_c, Y_c, Z_c) with respect to a set of 3 laboratory reference axes (X_s, Y_s, Z_s). The first rotation ϕ_1 is about Z_s so that crystal axis Z_c lies along the plane X_s Z_s. The second rotation ϕ is about Y_s so that Z_c gets aligned along Z_s. The final rotation ϕ_2 is about Z_s. As a result of these three rotations the crystal gets aligned with the laboratory reference axes. Figure A3 shows a set of 3 rotations that are needed so that the crystal gets aligned with the laboratory reference axes. A stereographic projection may help you appreciate the concept of Euler angles used to denote the orientation of a specific grain or a crystal.

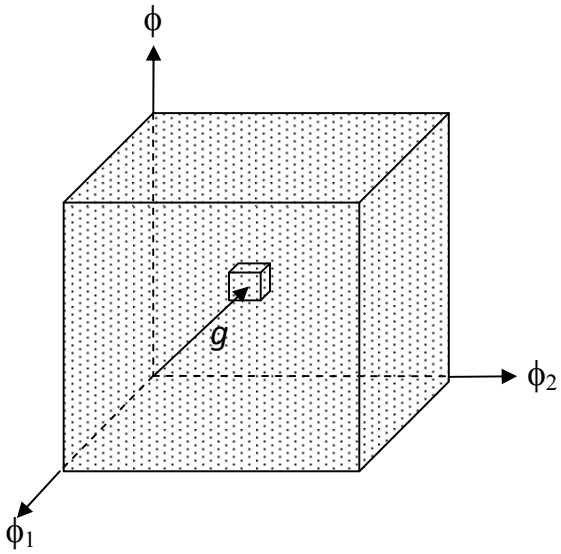
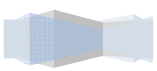


Fig A4: Shows the locations of differently oriented crystals present in the sample in Euler space. In this case the points are uniformly distributed. It suggests that the grains are randomly oriented. A function $f(g)$ denotes the volume fraction or the number of grains located within a small volume at the tip of the vector g. The integral $\int f(g)dg$ over a region gives the number of crystals present in this part of the Euler space. It is commonly known as ODF: Orientation Distribution Function. If the grains are randomly oriented ODF is a constant. It is independent of location. However in the presence of preferred orientation it is a function of Euler angles. The points denoting crystal orientation will no longer be uniformly distributed. These are usually found concentrated in certain regions.

Figure A4 represents location of individual grains in Euler space. It also introduces the concept ODF as an integral function. The individual points within the cube denote location of gains. In the absence of any texture or preferred orientation these are uniformly distributed in the entire Euler space. Figure A5 (a) shows a situation where these points are clustered within certain regions of this space. There is also a marked difference in the concentration of such points within these clusters. This is an indication of the presence of preferred orientation or texture. Figure A5 (b) gives a sectional view of fig A5 (a) at a specific value of ϕ. It suggests that the magnitude ODF is high in certain areas. The distribution of points within these clusters is converted into contours. At set of such maps at regular intervals of angle (ϕ) gives a complete description of texture. It can be used to predict properties like elastic modulus from ODF.



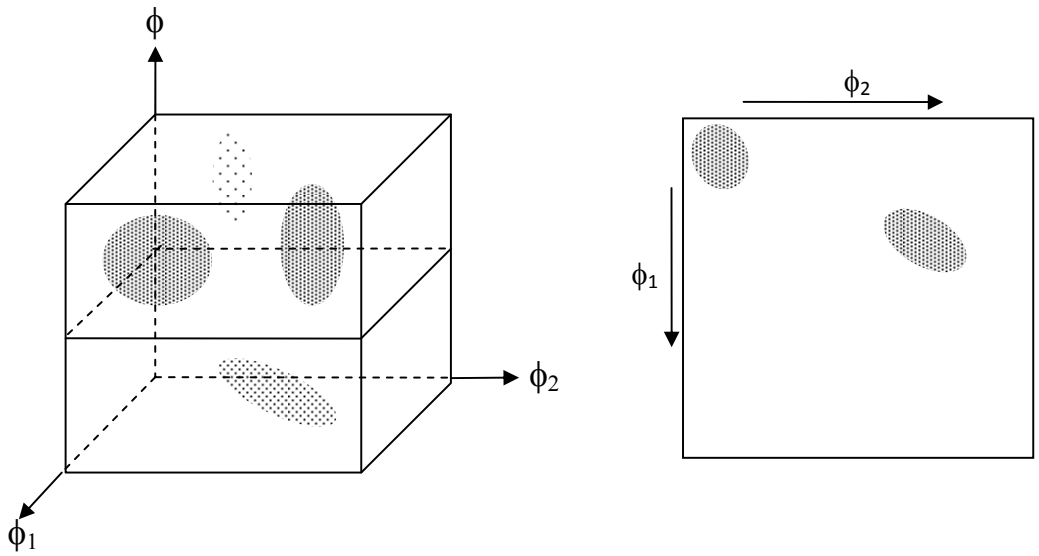


Fig A5: (a) Shows the way crystals are oriented in a rolled sheet in Euler space. (b) Gives a sectional view of the 3D Euler space in (a) at a given ϕ. Often a set of such plots at regular intervals of ϕ is used to describe preferred orientation in sheet products. The distribution shown can also be represented in the form of contour plots. A set of several such sectional plots are needed to describe a complete orientation map.

Additional tests for sheet metal formability

Formability of steel by and large is inversely proportional to its strength. Interstitial free steel having little C or N has low strength (YS < 270MPa) but excellent ductility. Conventional high strength steels (HSS) have additional solute elements. Their strength mainly comes from grain refinement, solid solution and precipitation hardening. This includes C-Mn, BH (Bake Hardening) and HSLA steel. However, their ductility is inferior to that of IF or mild steel.

High r-bar, low delta-r and high stain hardening index (n) gives a good idea about the formability of steel having primarily fine ferrite grains. However these may not be enough to describe sheet formability of AHSS having multiple constituents like martensite, bainite and austenite apart from ferrite (DP, TRIP steel). Although AHSS has higher strength than conventional HSS their ductility is inferior to that of even HSS. A few additional tests have been developed to evaluate its formability so that it gives a better idea whether it can be formed into the final shape without any defect. These are given below.

Stretchability: It is a measure of sheet formability. A disc having a specific diameter held at its ends is pushed with a punch. The maximum dome height attainable without rupture gives a measure of its formability. The same test can also be performed on a hydraulic rig. Since there

is no solid punch the result is not affected by friction. If the height of the dome is H and d is the diameter of the disc, the ratio H/d is defined as stretchability. In a way it is similar to LDR (Limiting draw ratio).

Bendability: It measures the ability of a sheet to withstand bending. When a sheet is bent the outer fiber is subjected to maximum tensile stress. If it exceeds a critical value fracture appears at its outer face. This depends of bending radius (r), bend angle, sheet thickness (t) and flow stress of material. The ratio r/t where t is the sheet thickness is called bendability. Smaller ratio means better bendability.

Flangeability: It is evaluated by hole expansion test. A disc having a hole of diameter d_0 is held at its outer edge in a fixture while a conical punch is used to expand the hole. The sheet would bend and the hole would expand. The edge of the hole is subjected to maximum deformation. If d_f is the diameter of the hole at which a crack develops, the ratio d_f/d_0 gives a measure of the flangebility of steel.

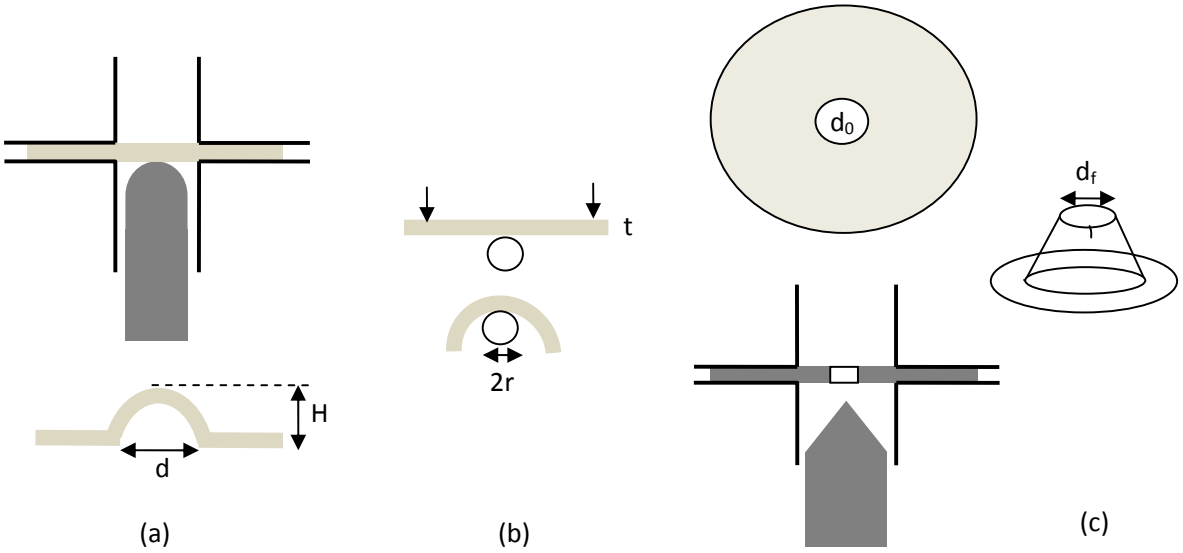


Fig A6: A set of sketches illustrating how the following tests are performed on sheet metal:
(a) Stretch-ability = H/d (b) Bend-ability = r/t (c) Flange-ability = d_f/d_0