Principles of Physical Metallurgy

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Lecture No. # 41

Preferred Orientation: Application

Good morning, last few classes we have been talking about some of the application principles of physical metallurgy that we have learnt. And we did talk about, that most of the metals, that we used, they are made up of several crystals and these crystals, in most cases are randomly oriented, but in certain cases it is quite possible, that this crystals are oriented in a preferred manner. In that case we get certain very specific properties or characteristics and it is possible to exploit this characteristic in several applications, and we will see some of these.

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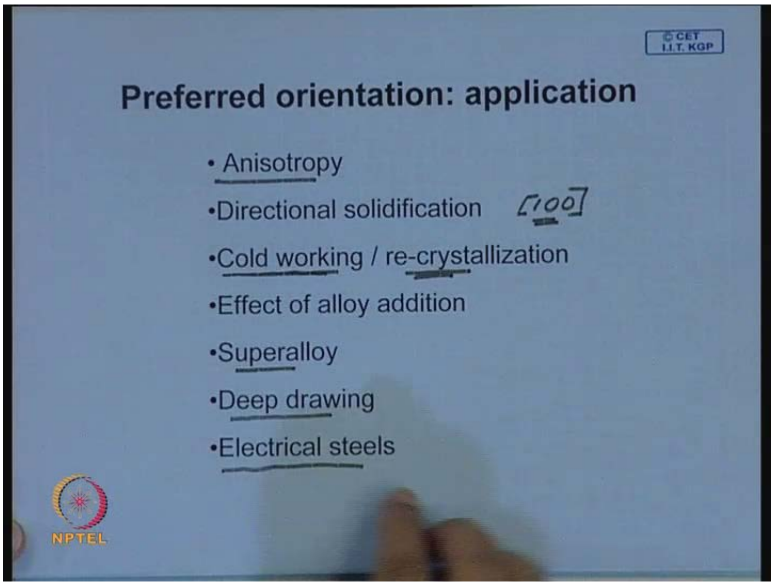

Preferred orientation: application

- Anisotropy
- Directional solidification [100]
- Cold working / re-crystallization
- Effect of alloy addition
- Superalloy
- Deep drawing
- Electrical steels

And under this, under this topic, preferred orientation and application, what we will look at, if crystals are not randomly oriented, then it is likely, that the properties will not be the same along all direction of the product. We will also look at how do you get this kind of preferred orientation. One way is the process of directional solidification. When you solidify or solidification process, the crystals grow preferentially along particular direction, for example, in cubic crystals, particularly bulk of the alloy that we use is a face center cubic. And in many of the cases it is the cube direction along which the growth rate is maximum. So, therefore, it is quite easy to produce crystal having this kind of texture or this kind of preferred orientation.

We can also produce preferred orientation by cold working. We have seen that when you deform a material, the process of deformation is primarily through slip and slip is the process of simple shear. So, there is some amount of rotation associated with it and during the deformation crystal’s orientation change. And finally, the cold work material, when you re crystallize you may get another type of preferred structure. We will look at whether alloy additions or, or the factors, which, that control this kind of preferred orientation, that you get here.

We will talk about few applications, one related to super alloy. We will also talk about some application where making (( )) product, which are cheap products are made by deep drawing, how to get a good formability, so that they can be easily deep drawn and with minimum amount of rejection. And we will also talk about some applications in the electrical steel, where when do we need a preferred orientation and when we do not need preferred orientation and how we can, production root can be modified to achieve this objective.

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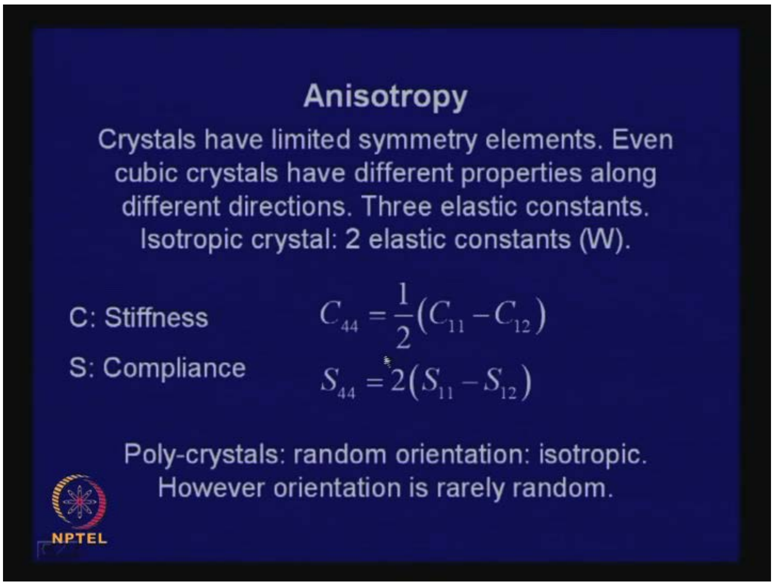

Anisotropy

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.

Now, if you look at the origin of Anisotropy, so in general, the crystals have some symmetry elements. In fact, the cubic crystals, they have maximum symmetry elements, cubic crystal have some finite number of symmetry elements, even cubic crystal, which has maximum number of symmetry element, have different properties along different directions. So, this is, I think we did talk about in detail. And we have seen if you look at bulk of the cases and we look at mechanical properties and which were elastic constant and this is determined mechanical properties, determined by elastic constants. And we have seen that in case of cubic crystal you need through elastic constants, whereas for isotropic material, that is good enough to have to and usually, there is elastic constant for, constant for isotropic material is, one is a Young's modulus. Another we can take either one of the two is a very, often we use quotient ratio as the other elastic constant and if these two are known, the CM modulus can easily be found out.

And in fact, for isotropic material, so we have, we did introduce this concept of stiffness and compliance. They are actually tensored, we looked at its nature and what does this signify? If we look at here that C signifies, it, it, it defines a relationship between stress and strain. So, if, if we say, that if we want to find out stress along a particular direction and then we see this is C ij epsilon j, where sigma 1, 2, 3, 4, it is up to 6, these are, this defines a stress state. Epsilon 1, 2, that is, epsilon 1, epsilon 2 up to 6, that i or j, they vary from 1 to 6, this is the range, and repeaters of x means summation. So, you can imagine you have a large number of these constants and, and there are certain symmetry rules are which you can apply, like stress is a symmetric tenser. So, similarly, strain also we can assume, that this also is a symmetric tenser.

So, you do not have, I mean, you have certain limited number of elastic constants and crystal having least symmetry element, where we have 21 elastic constants. So, this is just recapitulation of what has been done. Similarly, instead of, you can define strain also in the same way, this is S ij. Now, it is possible to show, if you look at this slide over here, it is possible for you to look at how these constant are related in case of anisotropic material. In cubic, this relation will not be valid; this C 44 will not be given by this, these two. Therefore, what we need in case of cubic crystal, three elastic constants, C 44, C 11, C 12 or s 44, S 11, S 12. However, if you look at this elastic constant of tungsten, this is an ideal isotropic, even single crystal tungsten will satisfy this type of relationship.

So, therefore, one point, that you can aim for, that poly crystals, which is made up of several or large number of crystals, so in a fine grain you will have a very large number of crystals per unit volume. So, it is more likely, that finer the grain, that is more likely the property will be isotropic. However, orientation is really random and what do we, what will happen if the orientation is not random. Obvious thing is, say, you may need, I mean, the properties will be anisotropic.

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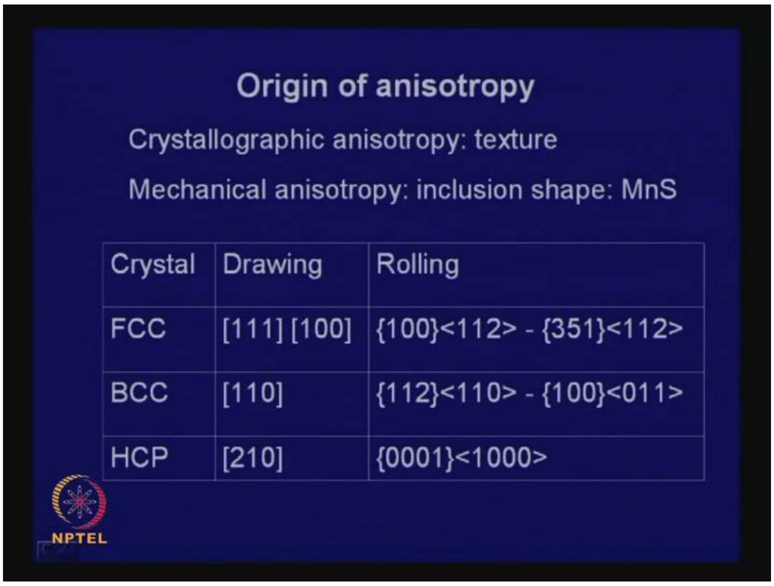

Origin of anisotropy

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>

Now, let us see the origin of anisotropy. Why do we get anisotropy in a material? There are two kinds of anisotropy, one is crystallographic anisotropy, metals are made up of, have crystalline structure. Even in poly crystalline material there may be, crystals are oriented in a preferred manner and poly crystalline material will also show, that crystallographic type of anisotropy and sometime we call this crystal, this crystallographic text arrangement as a texture. This has a certain preferred orientation of texture and then it will have different properties and different reduction.

Another reason for anisotropic behavior of the material in poly crystalline material is many cases we have seen, that the metals are not, I mean, they are often not made up of single phase. There are certain amount of unintentional phases, which are present, like inclusions and sometimes some of these inclusions, like manganese sulphide in steel. They change their shape; they get elongated during the plastic deformation or thermo mechanical processing stage. So, in the material you will have this elongated manganese sulphide along the rolling directions. Therefore, you have that arrangement, the macroscopic arrangement, microscopic arrangement, different phases. Therefore, have certain pattern and which will make the property anisotropic.

Now, let us see why does this type, anisotropic crystallographic, anisotropic develop in a material and what are the factors, which will determine? Obviously, deformation is determined by, primarily by slip and training. They were the two modes deformation, but bulk of the deformation in metals, they are through slip. Now, if you have a different crystal structure, it will affect the texture, that you get. It will also determine by the process of deformation that you are giving, if this is being drawn, in that case you have one kind of effect. If it is being rolled, then you have another kind of effect.

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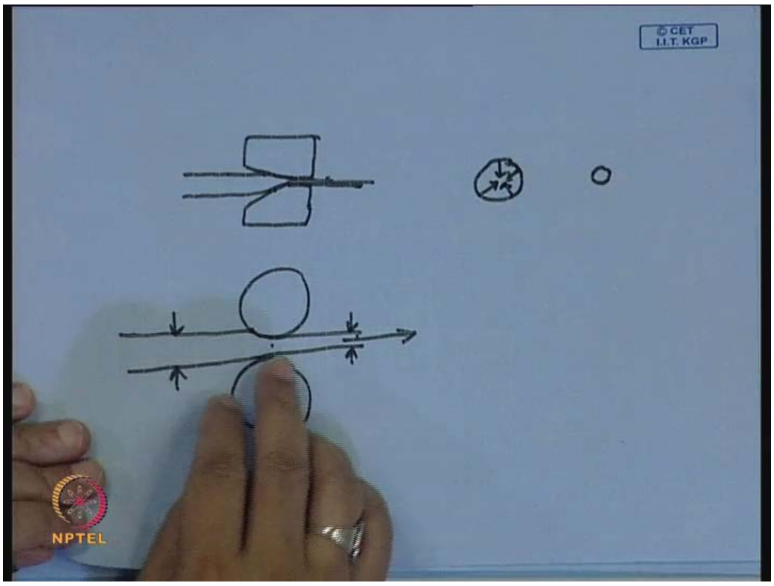

And if you recollect the drawing, so drawing is, you have a dye, you have a dye and dye like this and your product, you know, this is your sample and you try to pull it through the dye, so you have reduction. So, this is your initial cross-section. After drawing, this reduces to this, so that means there is deformation in this direction. And every in this direction there is a diameter reduces and the length increases. So, you, you can see, that drawing is a process where you have two directions, you have reductions and another direction you have elongation. And we also assume that volume does not change during deformation, so this is one difference.

Whereas in case of a rolling, if you recollect, you have a slab passing through and you have a reduction in thickness; the thickness reduces. This is the initial thickness before rolling and after rolling this is the thickness, so there is a reduction in one direction and elongation in this direction and the other direction perpendicular here, there is a negligible deformation. So, you can say this is plain strain deformation, whereas in this particular case you can see, this is, you have strain in three directions. So, that is the basic difference.

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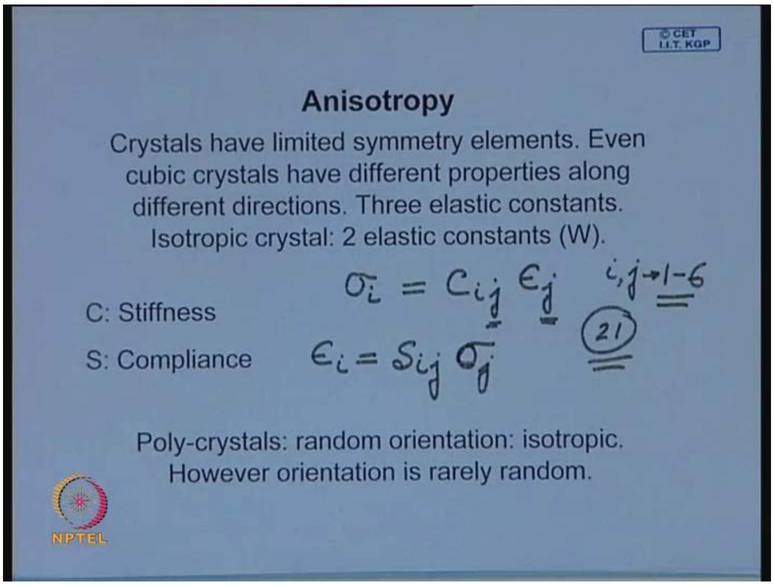

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Anisotropy

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

S: Compliance

$$\sigma_i = C_{i\underline{j}}\,\underline{\epsilon_j} \qquad \underline{i, j \rightarrow 1-6}$$

$$\epsilon_i = S_{ij}\,\sigma_j \qquad \underline{\textcircled{21}}$$

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

And because the, excuse me, because the state of stresses are different, you get different types of texture and which is listed over here in case of a drawing and it changes depending on the crystal structure. Rolling, you can get one type of preferred orientation, whereas in case of drawing you get another.

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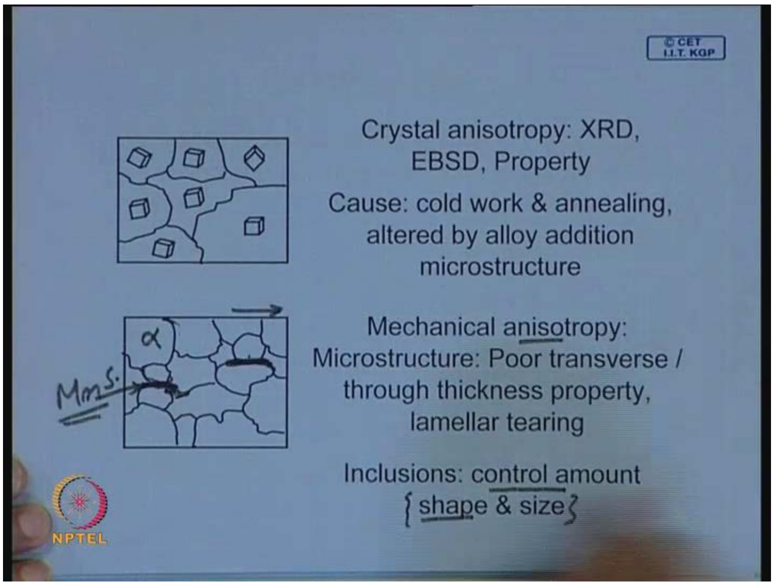

Crystal anisotropy: XRD, EBSD, Property

Cause: cold work & annealing, altered by alloy addition microstructure

Mechanical anisotropy: Microstructure: Poor transverse / through thickness property, lamellar tearing

Inclusions: control amount {shape & size}

Now, this is a typical example, which is shown. A metal, which is made up of several crystals, so these are, each grain means one crystal and although, in two-dimension figure, that we see under micro structure, but these grains are actually a three-D object and it has a particular, prefer, particular orientation and we are try to represent this orientation by this small cube. And you see, in each of these cases the crystals are differently oriented and this can be determined. There are different techniques, X-ray diffraction technique, electron beam, electron back scatter diffraction pattern, that is a, this is a special attachment, which is attached to electron microscope by this. Also, you can explore the extent of an, extent of the crystal orientation or textures, which is present in the material.

And we can also measure different property along different directions and you will find the properties, elastic modulus you can find in different directions and, and you find they are different. So, these are the evidence of crystallographic anisotropic and the reason for this anisotropy is cold work. And if you yield a cold work material depending on the magnitude of cold work, to get a typical annealing texture and these are also altered by alloy addition and also, the micro-structure also affects. Say, different phases, if it is a two phase or a micro-structure, if there are some alloy additions, then also they affect that texture, that you get in the material during processing and this is an example of mechanical anisotropy. So, here what we have, what has been shown, that you have an inclusion something here, so this is a material, which has undergone large deformation.

If you look up here this is manganese sulphur, they get elongated and maybe, there, they will, then they will get elongated most of the time. And after, during deformation you know if it is hot working, these grains get re-crystallized. These are the main grains, they get re-crystallized. Let us say this is (( )), this is manganese sulphide. So, these are non-metallic inclusion. They have totally different characteristics; bonding in this direction is not very good. So, if you measure these mechanical properties along this direction, you will find, since these are aligned, so you may, should find, that better strength in this directions. But in this direction, these boundaries, they are weak and it fracture and sometime, so these are, and it also causes some problem during welding. It results in lamellar tearing, so mechanical anisotropy origin lies in a microstructure and particular one of these factors is the inclusion.

And how do you control this mechanical anisotropy or you want to avoid this anisotropy you can control that amount, so have as little inclusion in the material as possible and also you try to control its shape and size. By controlling shape and size you can try and make the material as isotropic as possible.

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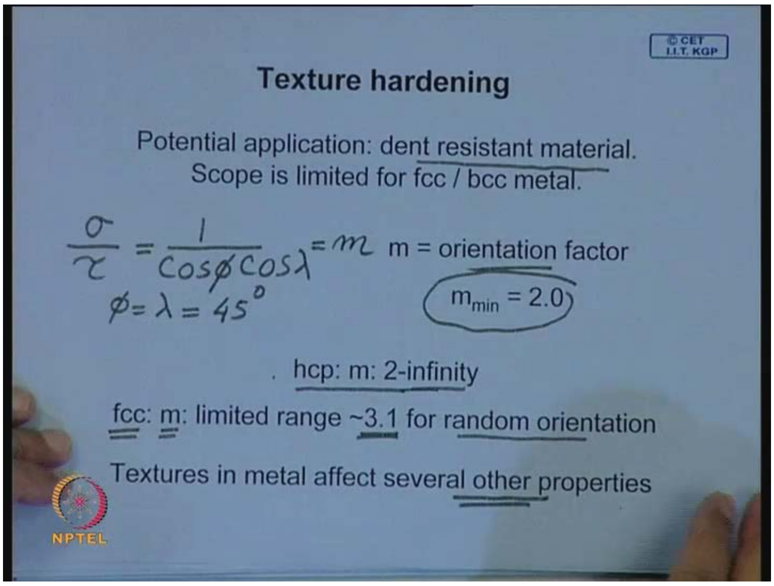

Texture hardening

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

$$\frac{\sigma}{\tau} = \frac{1}{\cos\phi\cos\lambda} = m \quad m = \text{orientation factor}$$

$$\phi = \lambda = 45^{\circ} \qquad \boxed{m_{min} = 2.0}$$

hcp: m: 2-infinity

fcc: m: limited range ~3.1 for random orientation

Textures in metal affect several other properties

Now, since the material have different properties along different direction, is texture hardening? Is this a possibility? Now, bulk of the metal, that you use, they are highly symmetric, they are bcc or fcc. So, aluminum is face center cubic; steel, it is primarily (9)), it is body center cubic. So, in this case, because of that high symmetry element the scope is very limited and if you recollect this relationship, that shear stress, this is the resolve shear stress and because the deformation takes place through shear on particular slip link, so that means if you resolve the shear stress on the specific slip plain, you know, that is a load, that is applied. This is over cross-section area, so this is the tensile load that you applied to test specimen.

This is the shear stress on the specific slip plain and this is the orientation factor, cos phi cos lambda is the orientation factor. So, in a way you can say, that ratio of, ratio of tensile stress over shear stress, this is equal to this, 1 over cos phi cos lambda. So, this is the orientation factor we call this as m, that is, the orientation factor. Now, what will be the minimum value of this? This is minimum when cos phi cos lambda is maximum and we know, that this is maximum when phi is equal to this equal to 45 degree. Therefore, minimum m is this. Now, in case of face centered cubic you have a limited scope for increasing or, or changing this m and if, if it is perfectly random orientation, m is around 3.1, whereas hcp metal, that is a wider scope.

So, if at all, so if at all, you know, the texture hardening is to be exploited you have to look for hexagonal close pack structure and possibly, ideal hexagonal close pack structure, so there only it is possible. So, if you want to have a dent resistant material you develop a texture. So, that is dent resistant that will be possible on, if you, if the material has hexagonal close pack structure. So, textures in metal, nevertheless, affect several other properties and which are worth exploiting and we will see that how this is done.

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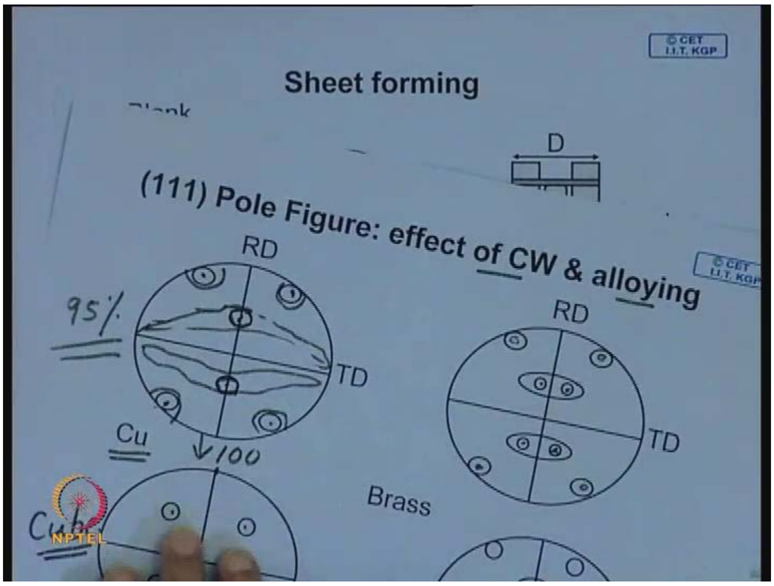

Sheet forming

(111) Pole Figure: effect of CW & alloying

A quick look at the factors that control texture and the material. Obviously, the texture origin of the crystallography structure, we have seen, lies in that cold work, the deformations. Now, in alloy, say, particularly also, alloy addition does effect the texture. So, if you cold work copper, you get one kind of texture; brass, you get another kind of texture. Origin, in fact, does lie in, in the slip and the slip we know takes place through movement of dislocations. Now, if a material, when you alloy, usually refine, the stacking fault energy decreases, so you have the perfect dislocations. They split up in to partials and stacking fault energy means low stacking fault energy, means large distance between the partial dislocations. So, if the dislocations are spilt they have little difficulty in slipping, in cross slipping, they cannot cross slip, they can move only in one plane. So, you can reason out, one reason for why this alloy addition controls the texture is because the movement of dislocations, they depend significantly on the stacking fault energy.

Another reason for this texture, that develops a re-crystallization process, now this, when re-crystallization takes place, re-crystallization after re-crystallization, the new grains, that they form, that they are not necessarily randomly oriented, they depend on several factors. One could be the amount of cold work that you have put so already. If it is a high texture material, that is, lightly re-crystallize material also will have a texture. Again, if there are certain inclusion present, some carbon nitrides in steels, like if aluminum nitrides, they, they actually develop a certain kind of preferred orientation. The inclusions or precipitates, if they are present in the material, they also will control the type of texture that will develop during re-crystallization, temp, during process.

Similarly, secondary re-crystallization, this is the last stage of the re-crystallization process. When few of the grains, they start to grow abnormally and this happens when this precipitate most of the time. This precipitate, when they dissolve, they are not able to pin the boundary and if such a thing happens you have a, you may have a different kind of a texture. In certain cases this is exploited, particularly in electrical stains.

Now, the question is what happen, how do you represent this preferred orientation? And we did talk about it, pole figure is used to represent the preferred orientations. Now, here what we do actually, in a, represent it in a kind of stereographic projection. Say, suppose this is the base circle, so this is the rolling direction, this is the transfer directions and if we, if it is a perfect, let us say it is a single crystal you have and we are trying to plot this 111pole figure, this will be located. There will be four different 1, 1, 1 plane and there will be, this will be represented by four pole. And in fact, if you have large number of such crystals in the material, it is very likely, that if there are random orientations, they will be uniformly distributed all over this. So, if it is uniform, that means distribution, then it is a random orientation. But what happens when you cold work or something? They try to arrange along a particular direction. In that case, these are this intensity contour (( )) at the density of poles. How many numbers of poles are there? So, instead of them being located all around, they are located at certain isolated places and this is called pole figure. And schematically, I have tried to show this pole figure effect of cold work and rolling. So, this is, if you have 90 percent, 95 percent cold work, they have large amount of cold work, better is the texture that you develop. What happens, but is not, I have just tried to show some of the places you have, you will have four regions actually where this 1, 1, 1 poles will be located. So, if there is a pole here, there is a diametrically. So, here also you made, yet, some amount of reflections. So, they may be located in certain areas like this, like this or maybe, it is not as perfect, maybe, they are located some of these regions at quite possible. So, this is the type of textures that you get in the pole figure, you get in a cold work copper.

If it is brass, then you find, that nature is little different. So, here the brass, so possibly it cannot cross slip, because of that low stacking fault energy, you may find the type of texture that they develop is little different. And when you anneal, possibly in this case you get, you are likely to get a particular type of, this is the texture and if you see, that this is have something similar to cube texture, a cube texture. So, that means, this rolling direction is a 100, a cube direction. Similarly, if you anneal this cold work structure you will get a different type. I have just systematic, you, you should look up that exact text book, you will see how, what a pole figure looks like.

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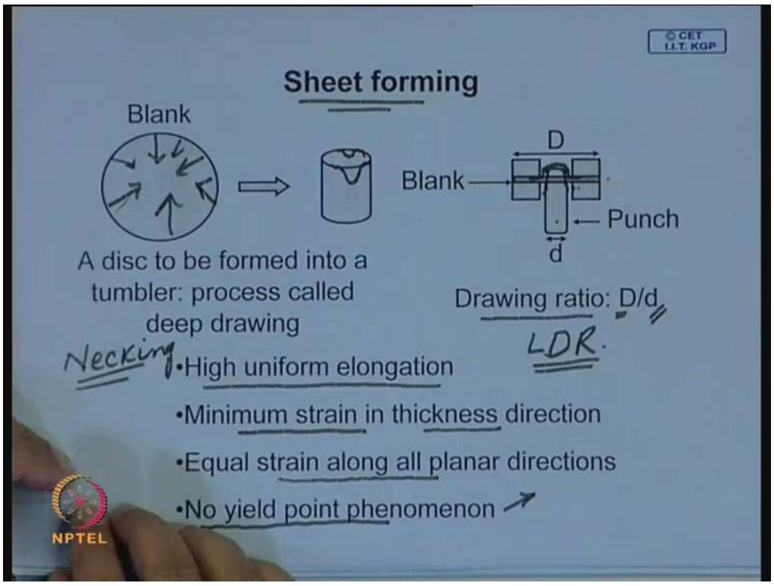

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Sheet forming

A disc to be formed into a tumbler: process called deep drawing

Drawing ratio: D/d

LDR.

Necking

- High uniform elongation
- Minimum strain in thickness direction
- Equal strain along all planar directions
- No yield point phenomenon

NPTEL

Now, let us see some of the applications. In certain cases we know that and to some extent anisotropy is desirable, whereas in certain other cases, is undesirable. Now, look at the case of a sheet forming. How do you do sheet forming? You have a plank and from that you are trying to deep drop and make a tumbler like this. This is cylindrical object and this is a sheet, a disc as been cut and from this disc you want to give it this shape. So, the process is this plank is kept between a die and you push it through a punch and there will be a particular, say this demonism and there maybe some clearances required and you may need a little lubrication, and when you push it what happens? This flows and then the material flow like this, like this, goes out, pushes this material flows like this and finally, you get this type of a structure.

And what is done? It is possible to find out the drawing ratio, this is the diameter of the plank, is capital D, diameter of the punch is small d and this ratio is called drawing ratio. And you can try to find out limiting drawing ratio, LDR. So, how much you can draw? So, that means, initially you will see, that this, how large this ratio can be? If it is larger, that means, it has a good deep drawability. Now, in that case what do we need? So, you need high uniform elongations, there should not be any local deformation.

We know, in the stress-strength diagram, the, the, there is a, after a certain critical strain local deformation takes place, there is necking. So, there should not be any necking, necking to be avoided. So, the material must have high elongation, there should be minimum strain in the thickness, directions, material should flow in this direction only. The deformation should be the planer deformation through thickness, there should be minimum strain in the thickness direction and there should be equal strain along all planar directions. So, different direction, planar direction, the strain should be as close as possible. If it is not close in certain directions, it flows more or certain direction it flows less, say, suppose in this direction you get this kind of a structure, which is called erring. And another important thing is there should not be yield point, yield point also gives local deformation (( )) form and which leaves unpleasant marks on the deep drawn product and which customer will not like.

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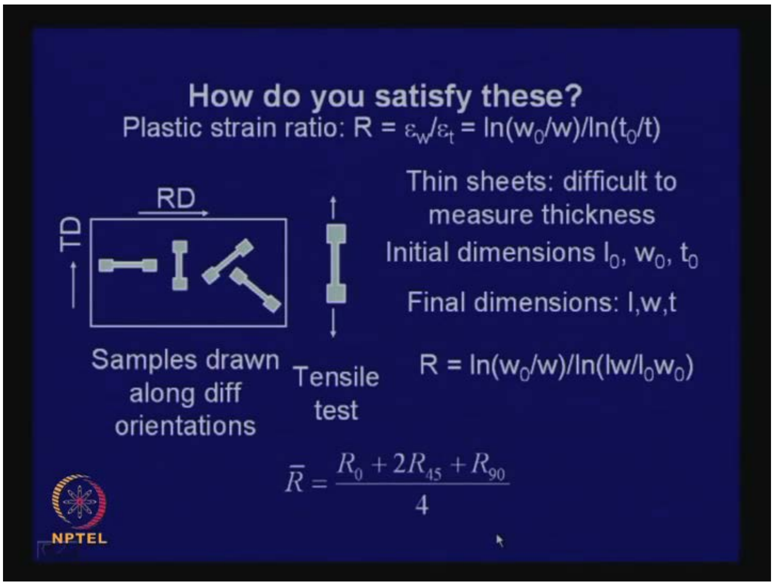

How do you satisfy these?

Plastic strain ratio: $R = \varepsilon_w/\varepsilon_t = \ln(w_0/w)/\ln(t_0/t)$

Thin sheets: difficult to measure thickness

Initial dimensions l_0, w_0, t_0

Final dimensions: l,w,t

Samples drawn along diff orientations

Tensile test

$R = \ln(w_0/w)/\ln(lw/l_0w_0)$

$$\bar{R} = \frac{R_0 + 2R_{45} + R_{90}}{4}$$

So, therefore, and the question then comes how do you satisfy this? So, in that case you need to have high plastic strain ratio. We shared, that is, what is this plastic strain ratio? Strain in the width direction, strain in the thickness direction and this should be as low as possible and this should be high, and this is how you determine this. This is the width before deformation; this is the width after deformation.

So, what you do? You have a sheet and from this sheet what you do? You try and find out, you make specimens along different orientation. This is aligned along rolling direction, this is along transfer direction, this is at 45 degree angle to rolling directions and this is also at 45, but differently oriented. This is oriented like this; this is oriented like this and what you do? You do a tensile stress and w is the width and t is the thickness. And when you measure the strain, try to find out true strain, which is define, defined as log to the base e, natural logarithm of w naught over w. Similarly, this is strain along thickness directions and often it is little difficult to find out.

You may find that often it is difficult to measure thickness. So, what you do in this particular case? What you do is you try to find out the length and the width because thickness is it is a normally very thin sheet. If it is a thin sheet its accuracy is less in thickness measurement. And what you do by volume constancy? You can convert, you can move the, calculate the thickness and this is what has been done, I leave this to you. So, these are the fine initial dimension. This is the final dimension and this is the expression for plastic strain ratio and what you do? When you do the tensile test on differently oriented samples, you get different values. So, this is the value, r naught is the value of plastic strain ratio along rolling direction; this is R 90 is along transverse direction and this is that 45 direction. And you have two samples, so you find out average R bar.

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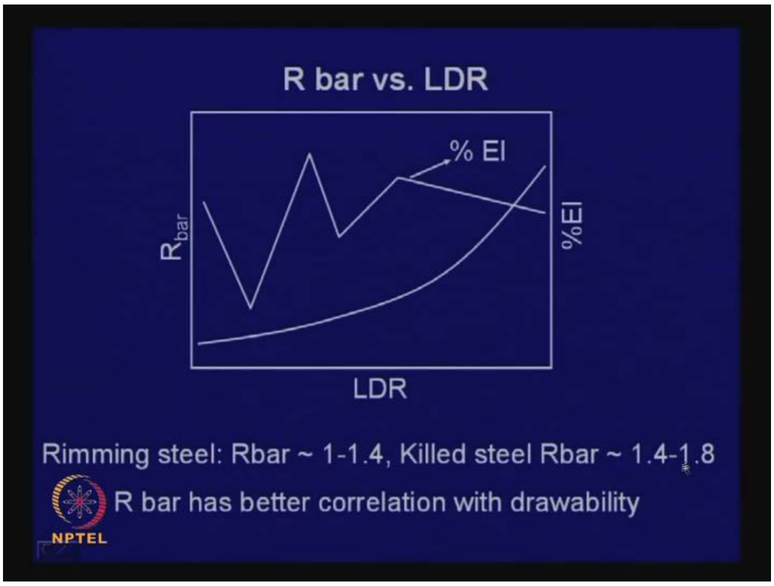

R bar vs. LDR

Rimming steel: Rbar ~ 1-1.4, Killed steel Rbar ~ 1.4-1.8

R bar has better correlation with drawability

And what has been found out is this R bar value; this average R bar has a direct correlation with limiting drawing ratio. That means, this explains at this code gives a better correlation or is a better indicator of the ability of the material to be deep drawn. So, R bar is a method, R bar is a property, which gives, which is measure of deep drawability of the material. The most other deformation processes, we go by percentage elongation and you will find, that even if you do, it is erratic, it does not have a direct correlation with LDR.

And rimming steels, they have, repair, relatively poor R bar, whereas in killed steel, because of aluminum, presence of aluminum, aluminum nitrite, a material during deformation processing develops a preferred structure and this has a high R bar value. So, R bar, R bar has better correlation with drawability and usually, and there are certain extra deep drawing grade steels, where even this is close to 2.

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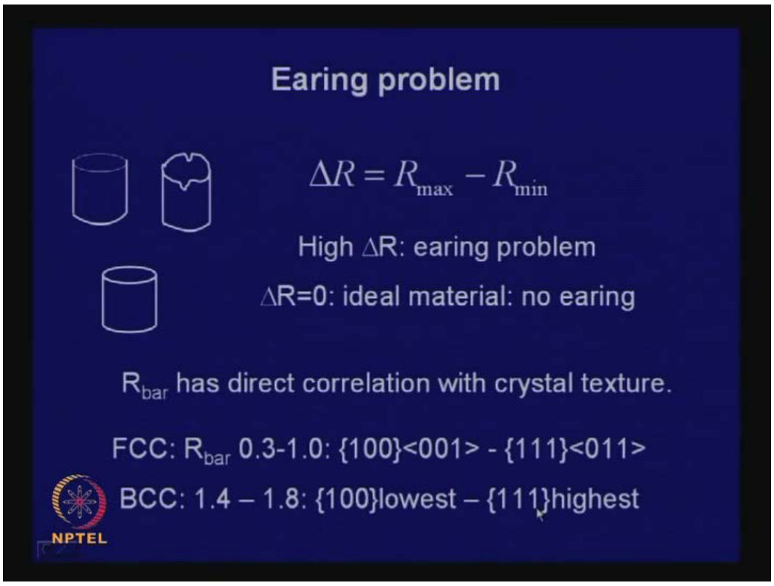

Earing problem

$$\Delta R = R_{max} - R_{min}$$

High ΔR: earing problem

ΔR=0: ideal material: no earing

R_{bar} has direct correlation with crystal texture.

FCC: R_{bar} 0.3-1.0: {100}<001> - {111}<011>

BCC: 1.4 – 1.8: {100}lowest – {111}highest

There is another problem we just mentioned, that, that is a problem of earing if this deformation is not uniform in all direction. So, that means, what you need here is the material should be anisotropic as far as the thickness, direction, strength is concerned, but the material should be isotropic as far as this planer deformation is concerned. So, if it is, that means it should not form that earring if, if in certain direction this is the earring problem.

So, if you, if you have tumbler you are making, obviously you have to cut it also. That means, there is a rejection, this is a waste. So, to cut down the waste it is necessary the material should have, should not suffer from this type of earring problem and this is possible when you find out R along different direction. To find out what is the maximum value of R and what is the minimum and this range is called delta R. So, low delta R means this is the ideal. If this is 0, that is, low delta R, this is the ideal material for deep drawing, there is no earing problem. Whereas, if delta R is high, then it is likely to have a earing problem and R bar has a direct correlation with crystal texture and which is given here for face center cubic.

Of course, you cannot get a very high because of that, whereas in bcc it has many more slip system and here, it is much, it has a better drawability. You can get even R bar as high as 1.8 in aluminum kill still or even, certain extra deep drawing quality steel even higher. And usually here, if you have this kind of a texture, if the roll surface is close to 100 plane, it has a lowest value, whereas if this is parallel to that 111 plane, then it has the highest deep, highest R bar.

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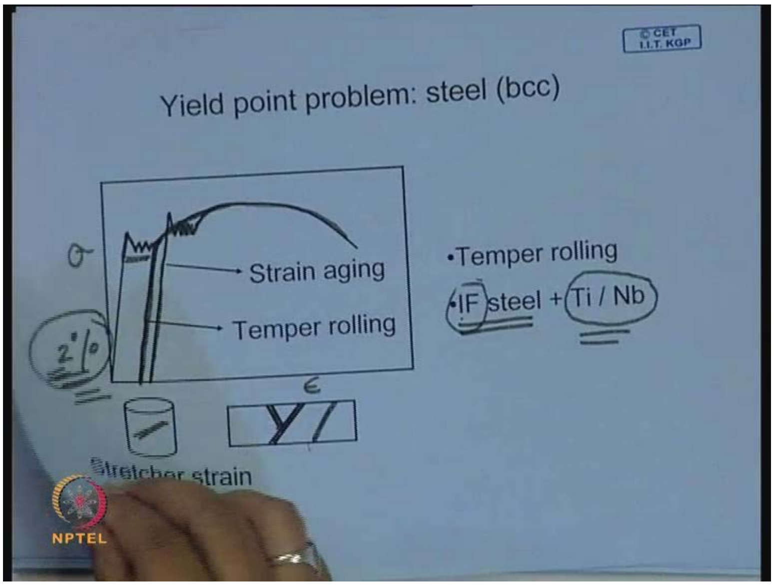

Yield point problem: steel (bcc)

•Temper rolling

•IF steel + Ti / Nb

Now, the problem of yield point is illustrated here and we know that low carbon steels, which are actually the bulk of the steels are low carbon steel and low carbon steel, the stress-strain diagram if you look at, there is an yield point phenomenon. So, this is stress, this is strain and this is the upper yield point.

When it exceeds this and there is (( )) yielding here and then it grows like this. so, you have uncontrolled deformation over here and when this happens, there are udder bands formed on the surface and this udder bands, they leave uneven marks on the, these, these are highly deformed areas. So, these marks are quite visible and in fact this treasure marks if you get on this, you know, a product own (( )). So, one way of avoiding is many of these steels, you know, you give a temper rolling, may be two percent cold drawn. So, after this you unload and then, you know, then the stress strain diagram, it does not show it is a smooth transition. It does not have, it does not show yield point phenomenon, but the problem is you know, they are also susceptible to strain aging, left room temperature long time it can reappear and if it reappears, then again, because of the strain aging, again this will have a difficulty to withdraw.

So, if temper rolling is done you have to see, that it must be deep drawn within a specified period of time and if that time is exceeded again, that kind of temper rolling may be necessary. Another way of avoiding this altogether is not to have any interstitial in the material. Interstitial free steels do not suffer from this yield point problem and also, you may ensure that there is no yield point problem. You have some strong carbide problem in the material. So, these are the ways by which you can avoid that yield point phenomenon.

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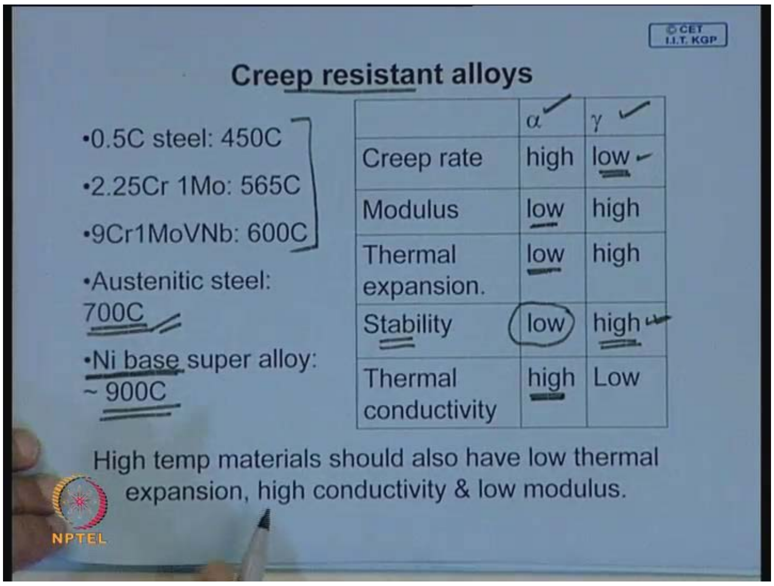

Creep resistant alloys

- 0.5C steel: 450C
- 2.25Cr 1Mo: 565C
- 9Cr1MoVNb: 600C
- Austenitic steel: 700C
- Ni base super alloy: ~ 900C

	α ✓	γ ✓
Creep rate	high	low
Modulus	low	high
Thermal expansion.	low	high
Stability	low	high
Thermal conductivity	high	Low

High temp materials should also have low thermal expansion, high conductivity & low modulus.

Now, we quick look about the last class. We did talk about the creep resistant material and bulk of these are poly crystal (( )), these are the materials, which are used and we have a potential is austenitic steel is also used for as a quick resistant material. And as far as steels are concerned, this table gives you the comparison of the creep high temp or creek resistance of alloys depending on the crystal structure. This is (( )) steel, austenitic steel.

Of course you need, one criteria is you must have low creep rate. So, as far as this lows pack structure gives lower creep rate, so here austenitic steel is preferred. But the other, you know, you also want to have low modulus, low thermal coefficient expansion and high thermal conductivity. In that case the thermal stresses, there will be minimum because many of this high temperature materials, they, they often subjected to repeated shutdown. Then, startup and shutdown and that is the time you have high thermal stresses; to avoid that you need to have low modulus, low thermal coefficient of expansion, high conductivity.

So, here, (( )) steel codes over austenitic, that austenitic steel, they have a low creep rate and also they have better structural stability because here, if you heat it beyond a particular temperature, it again gets converted in austenitic. So, that is one limitation of this and there are, attempts are on to improve this temperature, it stability of genetic steel because it has certain other attractive properties. And if you go to even higher temperature, then obviously, you have to use even better material. And nickel based super alloys is one of the common high temperature, creep resistant materials.

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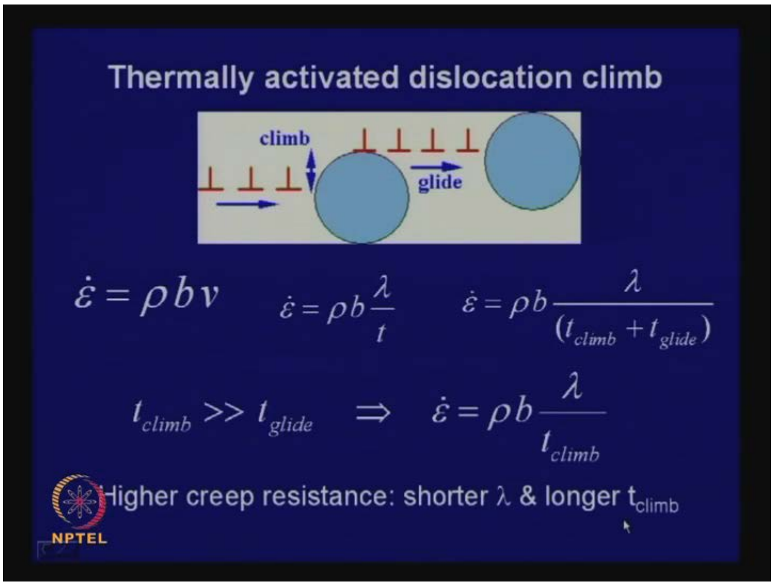

Thermally activated dislocation climb

$$\dot{\varepsilon} = \rho b v \qquad \dot{\varepsilon} = \rho b \frac{\lambda}{t} \qquad \dot{\varepsilon} = \rho b \frac{\lambda}{(t_{climb} + t_{glide})}$$

$$t_{climb} >> t_{glide} \quad \Rightarrow \quad \dot{\varepsilon} = \rho b \frac{\lambda}{t_{climb}}$$

Higher creep resistance: shorter λ & longer t_{climb}

Now, we did look at the process of the criteria for the selection of materials for creep resistance and one of the mechanism of creep is movement of glide, dislocation of glide, but this glide is also controlled by claim process because most of these, particularly nickel based material, you have high volume fraction of this precipitate and this precipitates are quite large. So, if you have a dislocation, if you have this dislocation, to move it has to overcome this precipitate and this can do by, either by shearing or by avoiding this by through climb.

And if you assume, that this climbs over it, in that case we have seen in last class, this is the expression. If you recollect, then we can make this process of climb difficult by making this larger. That means, if this is larger it will live longer time to climb. So, this high teak climb means lower creep rate.

Similarly, you need to have large volume fraction of precipitate, in that case you will also large, and large volume fraction means, this smaller distance lambda is the inter particle distance. Large volume fraction will be smaller inter particle spacing, so you need to have shorter inter particle spacing and longer precipitate, larger precipitate.

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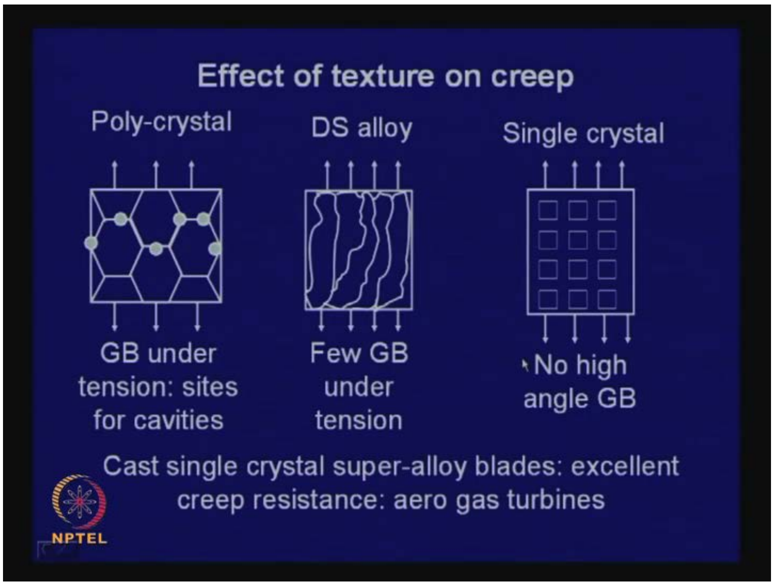

Effect of texture on creep

GB under tension: sites for cavities

Few GB under tension

No high angle GB

Cast single crystal super-alloy blades: excellent creep resistance: aero gas turbines

So, in fact it is quite interesting. Let us look at the effect of texture on creep and so, by this, in fact nickel base super alloy are very effective high temperature material and in fact, the initial super alloy, they were poly crystalline, poly crystalline. The failure takes place through cavitations and these are the grain boundary at the site where cavitations takes place and particularly, the grain boundary where the load is tensile. This is the tensile load, so these are the grain boundary where cavitations take place. And because of that the effective strength decreases and they have poor creep property.

Now, correspondently, if you try to avoid these types of grain boundaries, say, if you directionally solidify, then grain boundaries are aligned. In that case, you have minimum amount of grain boundary perpendicular to the direction of stress, in that case, found the directionally solidified alloy. You have fewer cavity sites, I mean, fewer sites where cavity can nucleate under tension. So, therefore, they are likely to give better creep resistance and in extreme case you have a single crystal, have, do not have any grain boundary, but again we need to have precipitate.

So, what you have is nickel base super alloy, you have gamma prime and this gamma prime precipitates are coherent precipitate. Coherent precipitates have low surface energy, they are highly stable, they do not grow at, I mean, growth rate is minimum and therefore, they have high structural stability. And you have large volume fraction of precipitate, but overall structure, it is a single crystal, there is no high angle grain boundary. So, they exhibit very good creep resistance. In fact, cast single super alloy blades, they have excellent creep resistance and mini aero gas turbine. Even some new generation of power, this land base turbines are also, I mean, these are the potential materials to be exploited.

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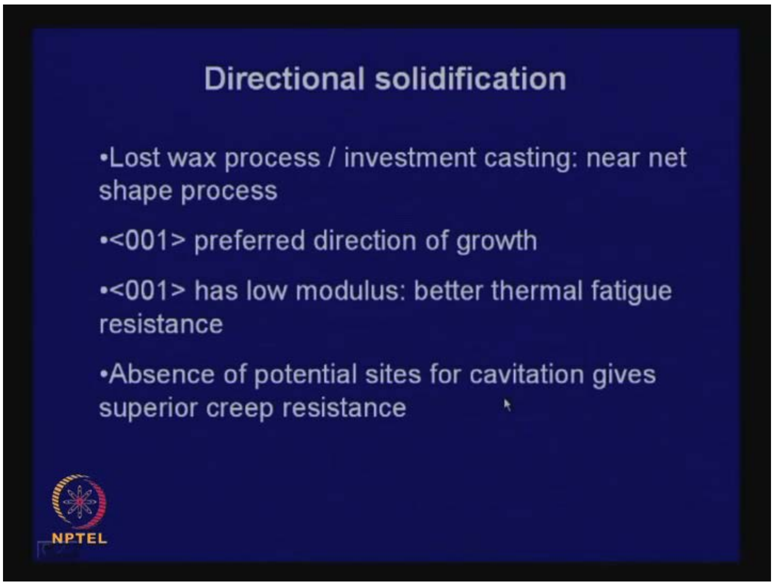

Directional solidification

- Lost wax process / investment casting: near net shape process
- <001> preferred direction of growth
- <001> has low modulus: better thermal fatigue resistance
- Absence of potential sites for cavitation gives superior creep resistance

But, this directional solidification quick look, I mean, this I am just named, so this is the, because they cannot be deformed. So, the material, when you make the product it should be near net shape product and this is done by precision casting and lost wax process and investment casting. These are the techniques, this is the cube, direction is the preferred direction of growth, this is the direction, growth rate is maximum and often, this is also direction, which has low modulus.

And in fact, they have better thermal fatigue resistance. And many super alloys, we also find this is the direction, which has very high creep resistance So, therefore, I mean, nickel base super alloy, this is the preferred direction that we want and the reason for good creep resistance is absence of potential site for cavitations.

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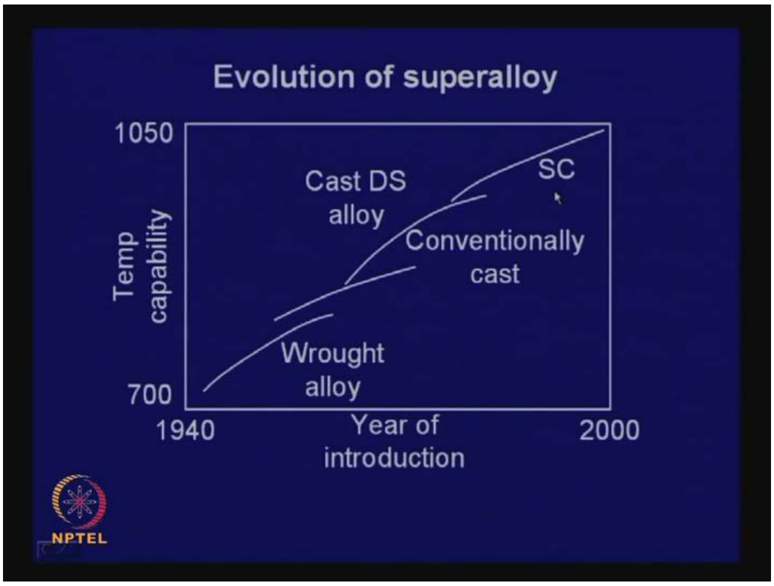
Evolution of superalloy

And this diagram gives you how this super alloy evolved over a span of just 50, 60 years and here, only our understanding of the physical principle of the transformation and physical metallurgy was been primarily responsible in extending the temperature capability, which was around, just around the World War time when the gas turbine was developed and that is the time the initial blade material were made up of wrought alloy, and the temperature was around this.

And today, this turbine blade temperature can go as high as around 1000 degree centigrade and it is the single crystal blade, which can withstand this. So, in fact, this did not happen just as a, I mean, increment, there has been incremental development. Wrought alloy’s temperature capability by alloying addition making creep difficult; it was possible to increase it substantially. Then came conventional casting because if you increase the creep resistance too much, these materials are difficult to deform, so then all their alternative is conventionally cast, the precision casting techniques and then, but these are still poly crystalline material.

Then, the directional solidification developed around 60s and from mid 70s the single crystal leads became available and they are currently was a most attractive material for aero gas turbine.

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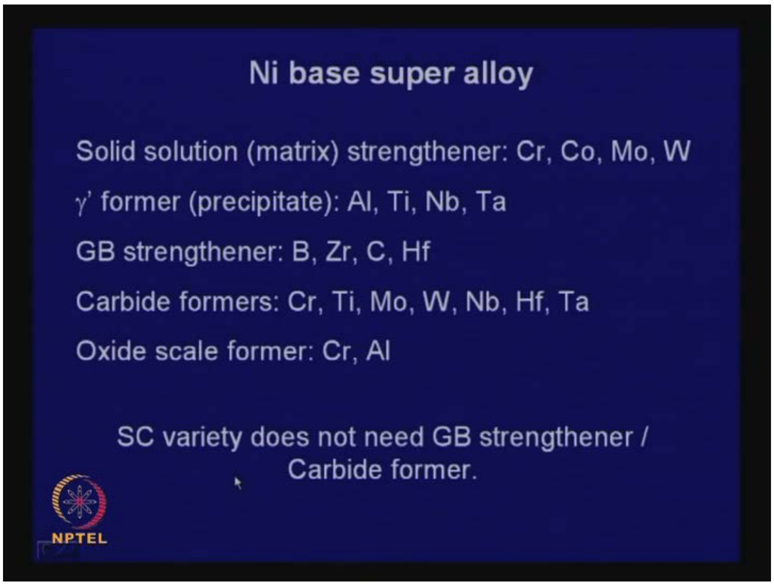

Ni base super alloy

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

SC variety does not need GB strengthener / Carbide former.

And these are actually the alloy elements, have a quick look, which you can consider as a summary. You have certain alloy elements, which are present in solid solution and they are called solute solution or matrix strengthener, and these are the elements: chromium, cobalt, molly, tungsten, whereas you also need to have precipitate. Some of this modern turbine blades, they have 70 percent gamma prime, these are hard face gamma prime former and these gamma prime precipitates are primarily Ni 3 Al or Ni 3 Ti or it can also be niobium and tantalum. Also, is a similar type of precipitate forms and similar type of precipitates forms and they are coherent precipitate.

In case of polycrystalline material you need to have grain boundary strengthener. Normally, the grain boundary strengthener segregates in the grain boundary. In grain boundary if alloy content is higher, they have higher strength. So, segregation actually is the key, is the grain boundary strengthener. So, these are the grain boundary strengthener.

You also have some carbide (( )) and this carbides also will be present near the grain boundary and they will also strengthen the grain boundary. And we also need good oxidation resistance, so these are chromium and aluminum, they help develop a protective oxide scale on the (( )), oxide scale on the blade material and this prolongs its life. And in fact, if you go for single crystal variety, then many of these need not be added, like grain boundary strengthener you do not need, but you need to increase its capability.

You possibly need certain elements, which have very high melting point. They are often added, like uranium, to increase the solvers temperature or melting temperature. So, in short you can say the single crystal variety does not need green boundary. So, they are actually linear alloys.

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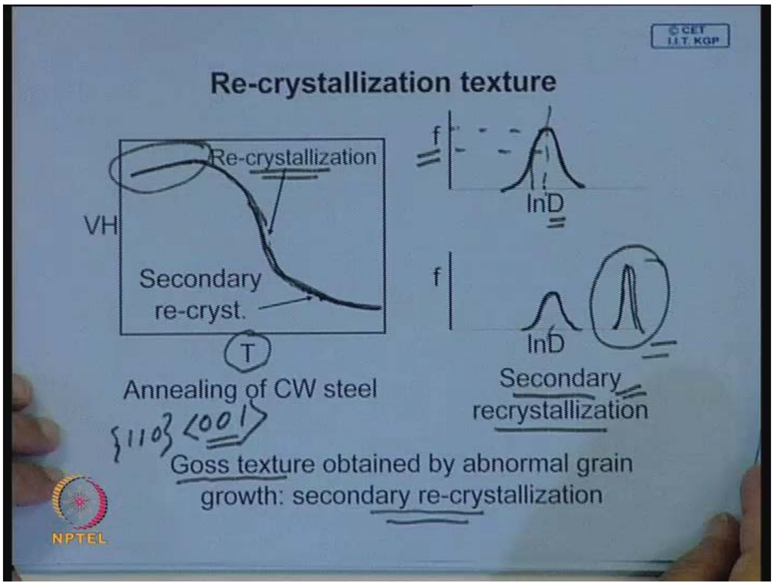

Re-crystallization texture

Goss texture obtained by abnormal grain growth: secondary re-crystallization

And let us now look up another exploitation of this preferred orientation is in case of electrical application. Electrical applications, one type of application are when, wherever you know, like transformer these are stationary parts. So, here you need a texture material because iron, if it develops this kind of a texture, then this, this is the direction in which it magnetizes very easily and this is the preferred texture. And in fact, if this is show, then this type of material will be, have exhibit a good soft magnetic property, which is required in transformer. It should have an, in fact, this is a VH (( )), which is and the area of this VH (( )) is the major of hysteresis and this gives amount of the heat, that is generated during in a transformer. This can give an idea about the heat.

And if you have the soft magnetic material with a minimum, the hysteresis loss, that will be ideal and this is possible by you know, controlling the texture. If you try to develop this type of texture, this will be minimum, and also there is another way of improving, cutting down that, that heat generation is the current, that, which induces the teddy current, and if, which is done by alloying. And usually, this is the VH plot, that initial permeability is important. It must have high permeability; this slope is the permeability, so this is 3.5 percent silicon grain oriented. So, this is the texture material.

So, here texture is preferable in (( )) former because they are static. They are not rotating, whereas other extreme in rotors, you know, it rotates. So, here the steel on which that winding is made, you know, it should not have, preferred orientation is not desirable. So, you try to have non oriented sheet here. So, here, you need an isotropic material, whereas here you need anisotropic material. So, these are the, in this particular case, obviously you will make in the sacrifice, mu is low and if that is high carbon steel or cast iron added, they even have, they are actually preferred as high carbon steels, they are preferred as a permanent magnet, So, soft magnet, so like for transformer application you need high mu low hysteresis and whereas rotor also, you need high mu. So, you add, you do add silicon and you have better mu here, but point is you need random orientation, that non-oriented sheet in this particular case and magnetically soft alloy here.

If it is at this kind of a texture, this is the parallel to the rolling direction and this is updated by controlling the processing. And in fact, if you look at the processing of the re-crystallization of cold work structure, if you recollect for low carbon steel, you may, some of the steel, you, here a little low carbon steel. This is a typical annealing plot in a venue, anneal, the hardness initially may increase a bit, but later on it decreases.

This is the steam aging path, but let us forget this part here and when this re-crystallization takes place, new strain free grains form and after a certain stage, you know, (( )) this present age, you go on increasing the temperature, beyond the certain temperature this precipitates. Whatever on inclusion, whatever is there, they dissolve and that is the time there will be uncontrolled grain growth and this is called secondary re-crystallization. And during that time what happens?

This will be the initial grain size distribution, D is the grain diameter and usually, grain size distribution in anneal structure; you have a log normal kind of a distribution. This is the frequency you have, that certain number of grains this is. So, for this diameter this is the frequency. So, many grains have this diameter, so many grains have this diameter and when the secondary re-crystallization sets in, suddenly you find a bi-model kind of distribution and towards the end what happens? This finally will disappear and you will have a large grain. This is the kind and this secondary re-crystallization texture, this is the gross structure, texture which is 110 and here this is the soft magnetic axis. Therefore, by secondary re-crystallization you can develop steam, which is ideal for transformer applications. So, this is where it is preferred.

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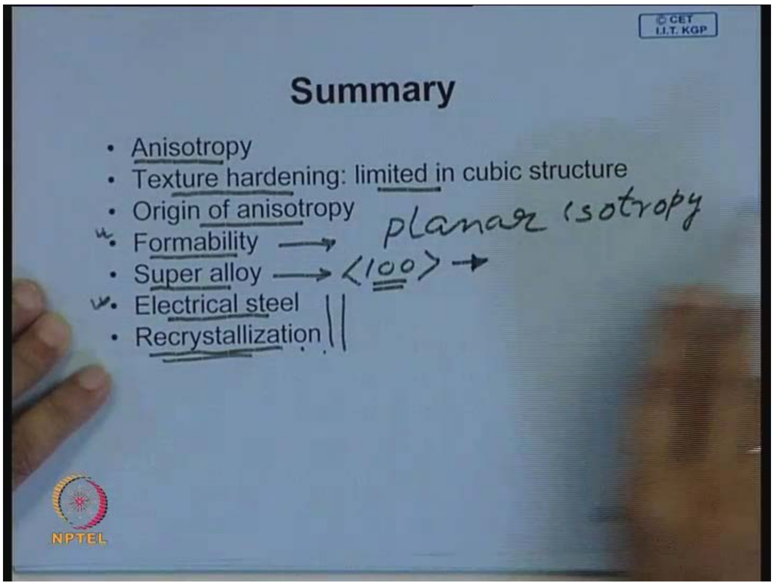

Summary

- Anisotropy
- Texture hardening: limited in cubic structure
- Origin of anisotropy
- Formability → planar isotropy
- Super alloy → <100> →
- Electrical steel
- Recrystallization

Therefore, what we looked at today sum up, we looked up anisotropy. Anisotropy in certain cases, it can be exploited, it is advantageous. We looked at texture hardening and we looked at its limited scope in cubic structure, but in certain hexagonal cubes back structures, it is, possibly it can be exploited. We looked at origin of anisotropy; we looked at certain other applications, like where anisotropy is required. So, in case of formability is an example where you need planar isotropy, but through thickness anisotropy. So, here, you need a texture to be developed as a special material.

We also looked at super alloy, this is the high temperature, texture material have better creep resistance. When you have this nickel base super alloy, if you have 110 direction as the direction, tensile direction, then you have better creep resistance. And this is obtained by, this is primarily obtained by controlling the solidification process to directional solidification.

We also looked at electrical steel and we looked at how the structure can be develop by controlling re-crystallization, by controlling the re-crystallization is the key thing. Whether you have this precipitate or you do not have the precipitate, you get different kinds of texture and this is the key to develop application steels, for either electrical applications or formable verity of steel.

So, with this we cover this chapter on application of preferred orientation or texture material, where, and we just seen certain cases it is advantageous and where it is advantageous and what is the method of developing the desired structure. With this we finish this topic and next class we will take up a new topic.

Thank you very much.