X-Ray Crystallography
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Lecture - 26
Texture Determination by XRD

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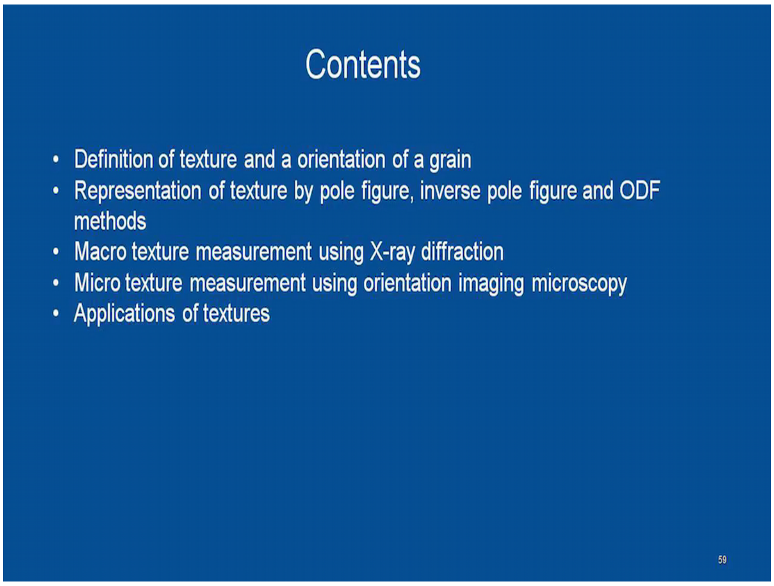

Materials scientists' journalism to believe that the property of a material is a function of it is microstructure. What you mean by microstructure? For a polycrystalline material we know that it is made up of a large number of grains.

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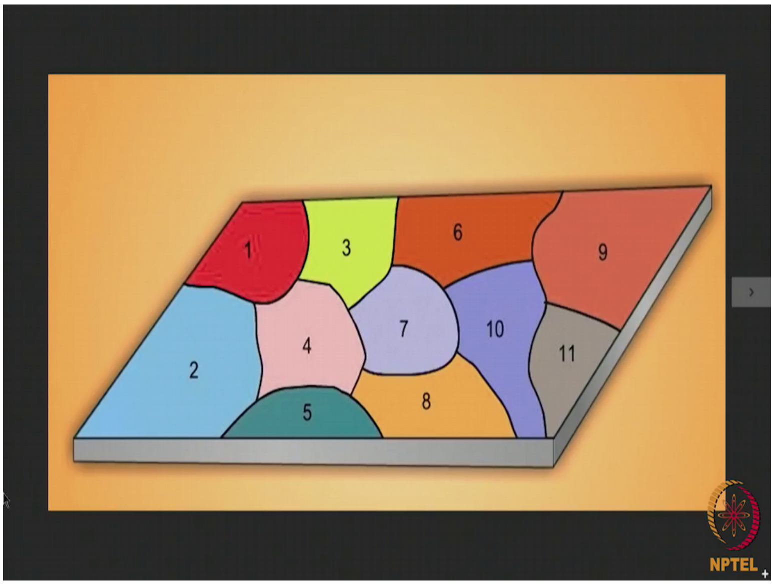

Each grain In fact, is nothing but is single crystal. So, when it comes to microstructure it conveys the idea of how the grains are arranged in the material, how big or how small they are, what is the average grain size? What is there inside the grains? And what is there at the grain boundaries? One aspect which is seem to overlook is the orientation of the individual grains, as I have already said. Each grain is nothing but a single crystal. And therefore, how the single crystal is arranged in space is quite important. Say for example, the normal idea is that every material isotropic; that means, same property in all possible directions.

Now, in this particular figure we denote the orientation by a particular colour. A particular orientation is denoted by a particular colour. So, there are about 11 grains over here and each colour has got each grain has got a different colour indicating that the orientations of no 2 grains are the same. In other words the orientations of the grains are completely random; that means, if say in grain number 1 they 1 0 0 direction points in this direction, in grain number 3 it maybe point in this direction, in grain number 4 it may be pointing in this direction, in grain number 5 in a different direction in vain number 7 in yet a different direction etcetera, etcetera.

In such a case when the grains are arranged in a completely random fashion we say that the material is a random material and hence it is behavior will be isotropic; that means, saying property in all directions; that means, if we take a tensile sample you know parallel to this edge and if we take a tensile sample parallel to this edge or if we take a tensile sample making 45 degree to this edge and this edge. In all cases the tensile property should be the same, but in practice this is never so.

In fact, it has been found that under the sun it is impossible to find a material which is completely random. In fact, some orientations are preferred by many of the grains. Now this phenomenon is known as textures. Say for example, this is the microstructure of a regular material that we come across in this world.

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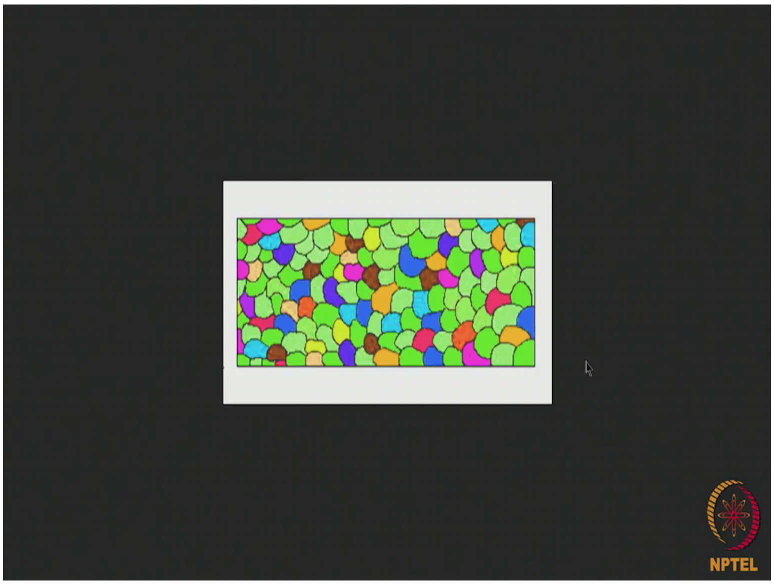

You see that here again a particular grain orientation is denoted by a particular colour. Say for example, this blue denotes a particular orientation of the grains and you can see that not one, but many of the grains have got this blue orientation; that means, many of the grains have got this particular orientation. Again the heavy green colour this green colour is denotes a particular orientation and you can see that many of the grains have got this particular orientation.

Again if you look at the red colour quite a few of them have got this kind of a orientation. So, this microstructure show that out of all the grains present in the material quite a few have is you know similar orientation, again some have another similar orientation, a third group of mains up another similar group of orientations; that means, some orientations are preferred by the grains. So, this material is a textured material. And this is the normal case most or almost all the materials, in this world are texture some are likely texture some are heavily texture.

Now, when you talk about orientation of grains it is necessary to define what is meant by orientation. For this lecture I will concentrate only on sheet materials. So, whenever I talk of orientations etcetera, I talk of orientations of grains in a sheet. Say for example, we have a rolled sheet as shown here.

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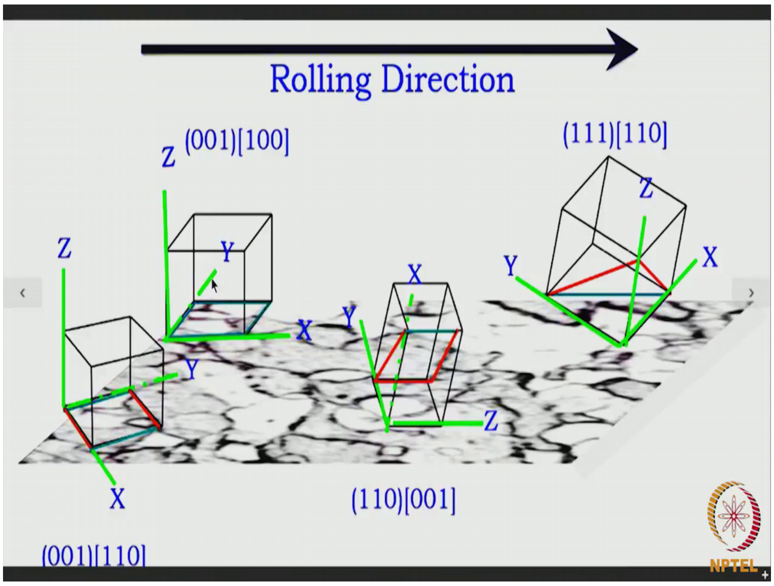

And this is the rolling direction. Now say we consider the grain over here. Now we have drawn the unit cell for the grain in an enlarged manner. So, this is a unit cell of the grain and what is fine that this top plane of the unit cell which is nothing but the 0 0 1 plane is parallel to the rolling plane, is parallel to the rolling plane. Not only that this particular direction of the unit cell which is nothing but the 1 0 0 direction is parallel to the rolling direction.

So, this is a grain in which the 0 0 1 plane is parallel to the rolling plane and 1 0 0 direction is parallel to the rolling direction. We say that this particular grain here has the orientation given by 0 0 1 within first bracket 1 0 0 within third bracket. So, this is the way we describe the orientation of a grain. Similarly over here we find this is a particular grain for which the 0 0 1 plane is parallel to the rolling plain and 1 1 0 direction is parallel to the rolling direction. So, the orientation of the grain is 0 0 1, 1 1 0.

Similarly, this grain has the orientation 1 1 0, 0 0 1 this grain has the orientation 1 1 1, 1 1 0 etcetera. So, this is the normal way we denote orientation of a grain, we collect the h k l, u v w notation; that means, h k l plane is parallel to the rolling plane and the u v w direction is parallel to the rolling direction. It is quite essential as we will find later on to have some idea of what is known as a stereographic projection, in order to understand the way texture data is represented.

Now the topic of stereographic projection has been discussed in depth earlier, I will just give some few important aspects of stereographic projection for the purpose of this lecture.

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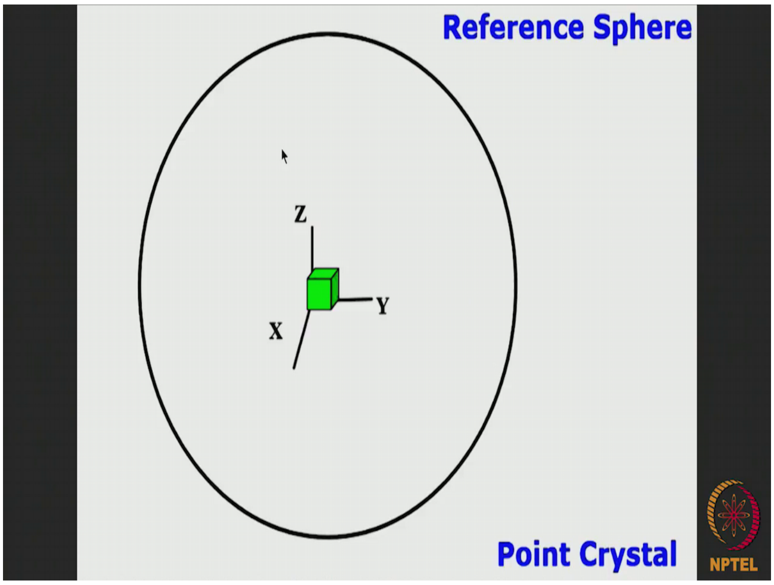

Say for example we are dealing with a cubic material the simplest material and this is the small very small cubic crystal. It is so very small but you can consider it as a single point.

So, we call it a point crystal or we can also call it a point unit cell of the cubic material. Now keeping this point unit cell or point crystal at the centre, we construct a very big sphere we call it the reference sphere. Now the next step is we draw perpendiculars to the 6 faces of the point unit cell on the point crystal.

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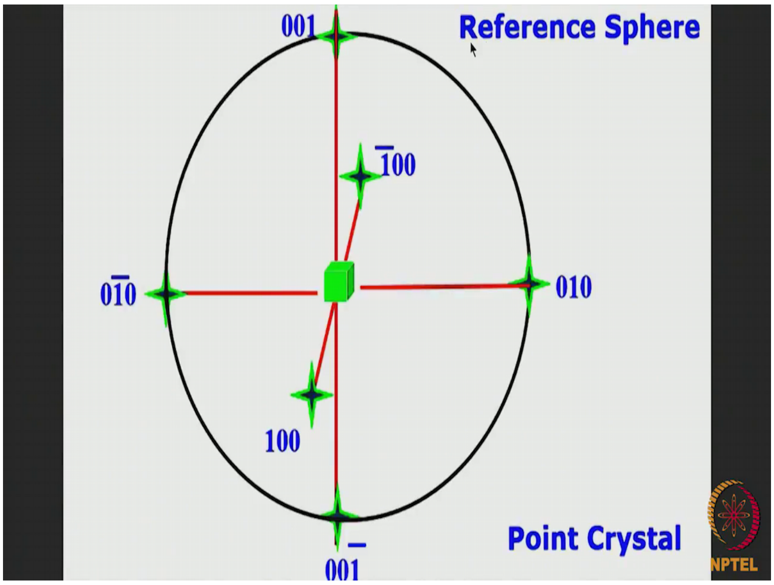

And as you can see over here half of the reference sphere will be on top of this plane and the other half will be at the back. Now if we draw perpendiculars to the 6 phases the perpendicular to the 1 0 0 will be cutting the reference sphere over here again bar 1 0 0, will cut the reference sphere at the back, then this will far the perpendicular to 0 1 0, will cut the reference sphere this is where the perpendicular to 0 bar 1 0 will cut the reference sphere, this is square the perpendicular to 0 0 1 plane will cut the reference sphere and this is square the perpendicular to the 0 0 bar 1 plane will cut the reference sphere.

Now, these points are known as the poles of the respective planes.

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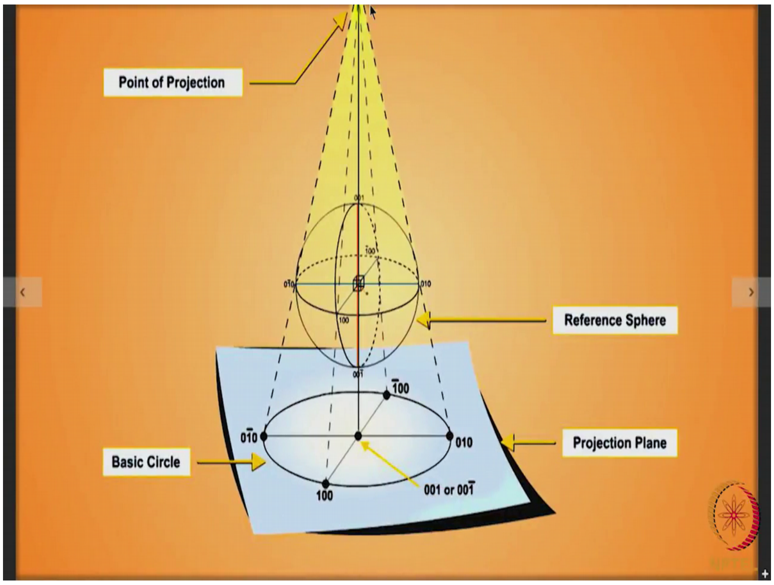

The next step is we take a point of projection and put a source of light over there and we put a piece of paper parallel to the 0 0 1 plane of the point crystal or point unit cell. We allow the source of light the rays of light to pass through all the poles on the reference sphere and these are allowed to fall on this piece of paper. Now as you can see here if we do that we will get the 1 0 0 pole to be projected here, the bar 1 0 0 pole to be projected here, the 0 1 0 pole to be projected here, and the 0 bar 1 0 pole to be projected here, and here (Refer Time: 12:16) the 0 0 1 or 0 0 bar 1.

So, this plane is a plane of projection parallel to the 0 0 1 plane in the point unit cell or the point crystal. And this circle is known as the basic circle it is a projection of the upper half of this sphere of the reference sphere as shown. So, what is happened? Here is we now have a drawing shown over here and we can see that in this drawing or in this projection all the planes you know they are present in the form of projections of the poles. For example, this is the projection of the pole of 1 0 0 this is the projection of the pole of 0 1 0 now in the actual crystal. If you see the angle between the 1 0 0 plane and the 0 1 0 plane it is 90 degrees. And in effect in the projection also this angle is 90 degrees.

So, we see that all the angular relationships between the atomic planes in the point crystal or point unit cell can be found out from the locations of the projected poles. So, this kind of a projection is known as stereographic projections. The names stereographic means angle through projection. So, this is an angle through projection as we can we have already found out. Now this kind of a stereographic projection is very important to know because we will see readily that texture data is very often represented in the form of some special type of stereographic projection call the pole figures. In the previous diagram I showed the poles of only 1 0 0 type planes.

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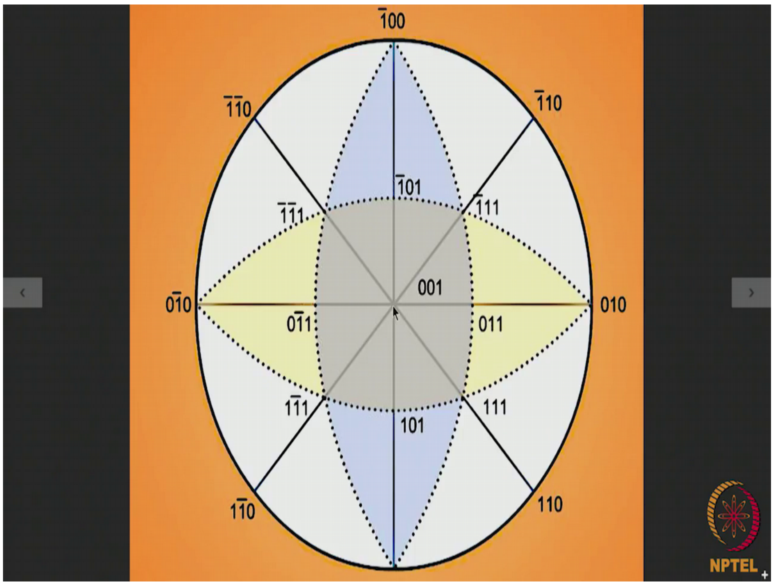

For example, this pole is 0 0 1, this pole is 0 1 0, this is 0 bar 1 0, this is bar 1 0 0 and this is 1 0 0.

Now, in the same diagram in the same stereographic projection we can also plot the poles of other planes. Say for example, 1 1 0 type planes and you know in this projection the 1 1 0 type poles have been plotted. So, this is the 1 1 0, this is bar 1 1 0, this is bar 1 bar 1 0, this is 1 bar 1 0, 1 0 1, 0 1 1, bar 1 0, 1 0 bar 1 1 etcetera and in the same projection you have also plotted the poles of the 1 1 1 type of planes, like this is bar 1 bar 1 1, bar 1 1 1, 1 1 1, 1 bar 1 1. How to draw all these poles have been has been explained in detail in the chapter on stereographic projection.

Now, this particular projection as you already know is called a standard stereographic projection and what kind of a standard stereographic projection? It is a 0 0 1 standard stereographic projection. Why 0 0 1 because you have to remember that the projection plane is parallel to the 0 0 1 plane of the unit cell of the unit crystal. So, this is nothing but a 0 0 1 standard stereographic projection of a cubic unit cell or cubic single crystal.

Now we will discuss how to represent texture data. In fact, I will talk about the measurement of texture later first I would like to talk about the different methods of representing texture of a material.

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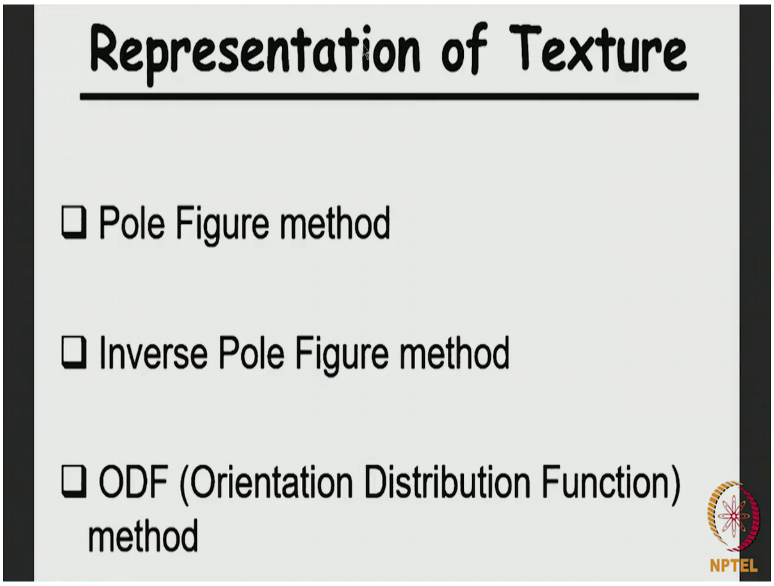

Now, there are 3 different methods the pole figure method the inverse pole figure method and the ODF or orientation distribution function method. The most common method of representing texture is the pole figure method.

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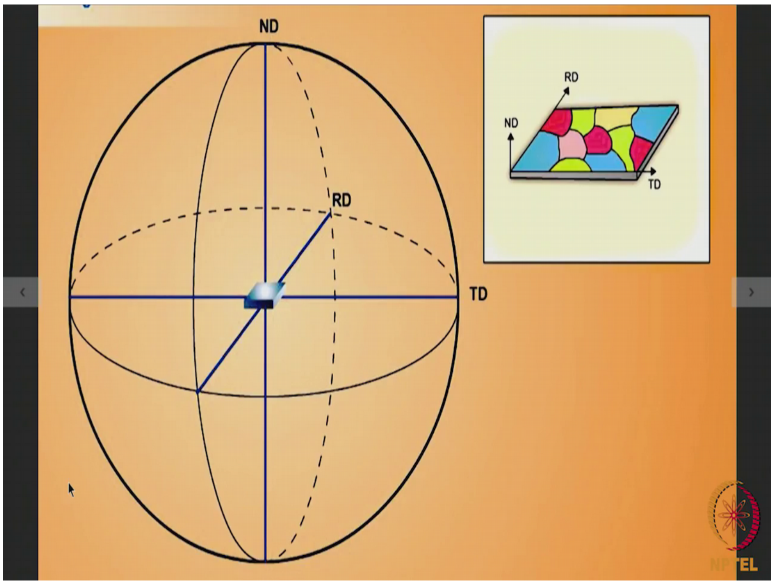

So, what is done in the pole figure method? Say we have this sheet material we want to find out the texture of these sheet materials. Now any sheet material has got 3 mutually perpendicular parameters, for example, the rolling direction the transverse direction and the normal direction. As in case of the construction of a stereographic projection, we take a small part of the sheet and put it over here such that the RD points in this direction TD in this direction and ND the normal direction along this.

Let us consider just one of the grains in this sheet material, just one and say, we want to find out where the 1 0 0 type poles of that grain line. So, what we do? We draw the 1 0 0 direction the 0 1 0 direction and 0 0 1 direction in that particular grain over here. You know that in a cubic material 1 0 0 direction is perpendicular to the 1 0 0 plane 0 1 0 direction is perpendicular to the 0 1 0 plane and 0 0 1 direction is perpendicular to the 0 0 1 plane. So, we allow those directions to emanate from the centre again this sheet is considered a point sheet. So, to say and we allow those directions to be extended So that they can intersect with the surface of this big reference sphere.

Once we do that we find out the projections of those 3 poles. So, first what we do? We consider a very small sheet material from which the texture has to be determined, and considered to be very, very small indeed take one grain and within that grain we choose the 1 0 0, 0 1 0 and 0 0 1 directions. Say and allow those directions to be extended and intersect with the reference big reference sphere over here. Then in a manner similar to drawing of a stereographic projection, we find out the projection of the poles lying on the reference sphere.

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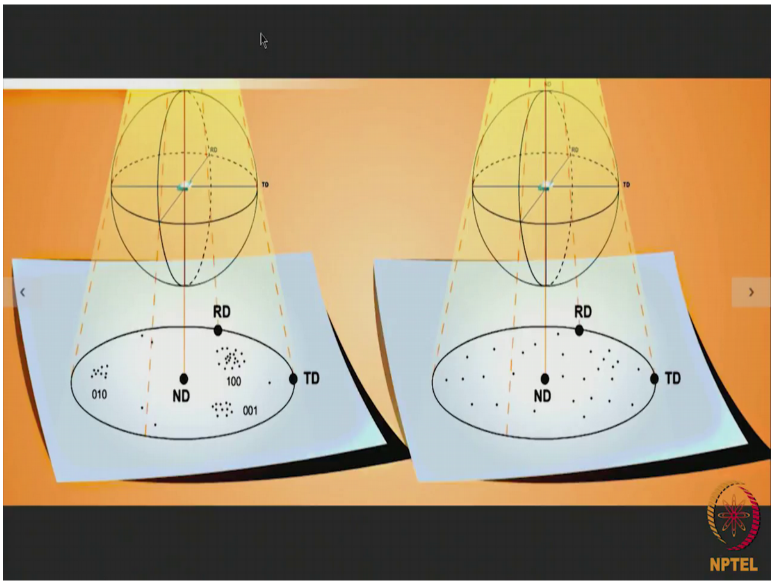

Now, once we do that say for that particular grain, this particular point is the projection of the 0 0 1 pole, this particular point is a projection of the 1 0 0 pole, this particular point is the projection of the 0 1 0 pole in that particular grain. Now suppose if So happens that by plotting the 1 0 0, 0 1 0 and 0 0 1 poles from all the other grains we find that all the 1 0 0 poles on the different grains are clustered together as shown here, all the 1 0 0 poles are clustered together over here, and all the 0 1 0 poles are cluster together over there, then we realize that the orientation of the grains cannot be perfectly random there is some preferred orientation or texture present.

If it were a completely random material, in that case what we would have seen all these poles 1 0 0, 0 1 0, 0 0 1 all this poles would have been uniformly distributed over this projection plane. Now so, this is a stereographic projection of the 1 0 0 type of poles from the grains in a sheet material. Not only that in this stereographic projection the specimen parameters are also present. So, this kind of a stereographic projection on which the specimen parameters are also superimposed is known as a pole figure. So, a pole figure shows the distribution of the poles of a particular type of planes on which this specimen parameters are also superimposed.

Now, as I said already this is the pole figure obtained from say a random material, where all the poles are arranged in a random fashion. Now how do we describe the density of the poles here, the way we do it is in this manner. Say for example we find out a small area we mark a small area in the pole figure of a random material. And exactly at the same location of the pole figure from the experimental material we mark the same area. Find out the number of poles within that area; find out the number of poles in this area. Then divide the number of poles within this area in the experimental material by the number of poles in the corresponding area for the random material.

In this case there are 10 poles within this region and exactly in a similar region for the random materials is 1. So, we write 10 on this contour line indicating that this is a contour line whose intensity is 10 times of the random material. Similarly we can have a contour here containing other poles and the corresponding contour here and again in the similar method we can find out that this contour is 5 times random, then this particular contour is 2 times random. So, we do not mention the random over here we simply write 10 5 and 2 indicating that these are 10 times 5 times and 2 times random. Similarly we can show the density of poles by contour lines over here and over here.

So, we have now represented the poles of a particular type of planes in a number of grains of the sheet material in the form of a pole figure. Not only that we are also determined the density of the poles with respect to the density of poles in a random material. So, as I said this is our pole figure. You see having a pole figure is not enough. Now we will have to read this pole figure in order to find out what kind of texture the material has. So, this part I am coming to later on.

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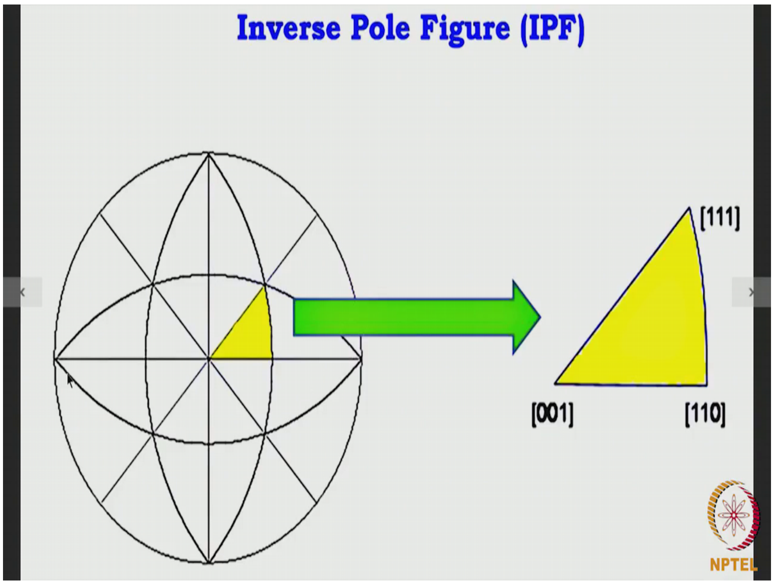

Now let us talk about this second type of the second method of representation of texture. It is called the inverse pole figure method, it is called the inverse pole figure method; if we go back a little bit if you remember the standard 0 0 1 stereographic projection.

You see all these lines as shown here have divided the entire circle into 24 equal triangles; so to say for example, here 1, 2, 3, 4, 5, 6, 7, 8, 9, 10; so 11, 12. So, there are above this line there are 12 triangles below this line another 12s so, there are 24 triangles. Now these 24 triangles have got something in common for example, say you take this particular triangle one of the corners is 0 0 1, another corner is bar 1 0 1, another corner is bar 1 1 1; that means, all these 24 triangles are uniform in the sense that one of the corners gives you a 1 0 0 type of pole second corner gives you a 1 1 0 type pole a third corner gives you 1 1 1 type of pole.

So, they are equivalent so to say all of them about the same characteristic. Take this particular triangle you know here you will find this is a 1 0 0 type pole, this is a 1 1 1 type pole, this is a 1 1 0 type pole. So, any texture data we can represent in one of the unit triangles. So, to say so, that is the idea behind the inverse pole figure method. So, in the inverse pole figure method we choose a particular triangle here this is as we have seen this is a 0 0 1, this is 1 1 0 and this is the 1 1 1. So, this is the unit triangle. Now what we do here in the inverse pole figure method? We plot the frequency of a particular direction of the sample within this space.

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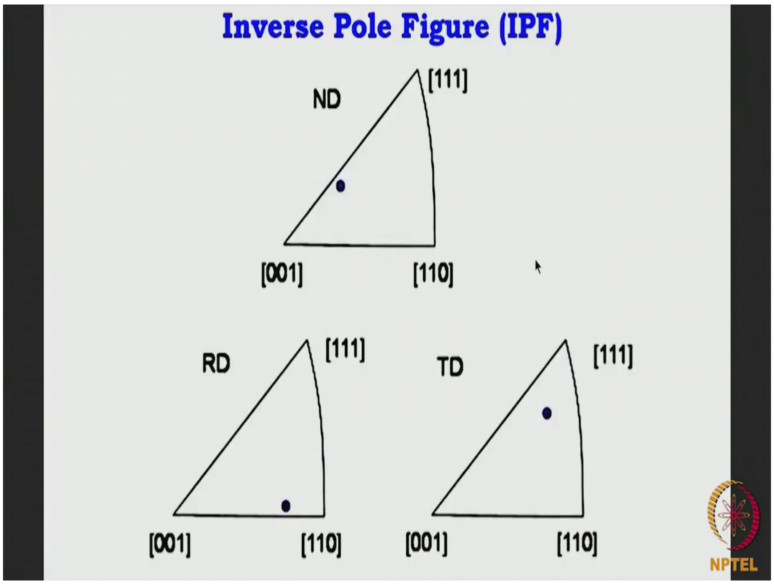

Say for example, we talk about a sheet material we talk about one grain and say the normal direction. What is the normal direction? We plot the location of the normal direction by a point over here.

Similarly, in a sheet material you have got the rolling direction say the rolling direction is plotted is a point over here in another unit triangle. And then comes the transverse direction. Then the transverse direction is plotted as a point over here. So, for that particular type for the particular grain you know we can have an idea of it is orientation by plotting the normal direction rolling direction and the transverse directions in 3 unit triangles in this manner. Now when we have a large when you consider large number of grains in the sheet material, and if we find all the normal directions are cluster together over here, all the rolling directions are cluster together over here, all the transverse direction plots are clustered together over here we can see that the material is a texture material.

If on the other hand when you consider a large number of grains in the sheet material and if we find that the normal directions distributor all over, the rolling direction is distributed all over, the transverse direction distributor all over that shows that is a random material.

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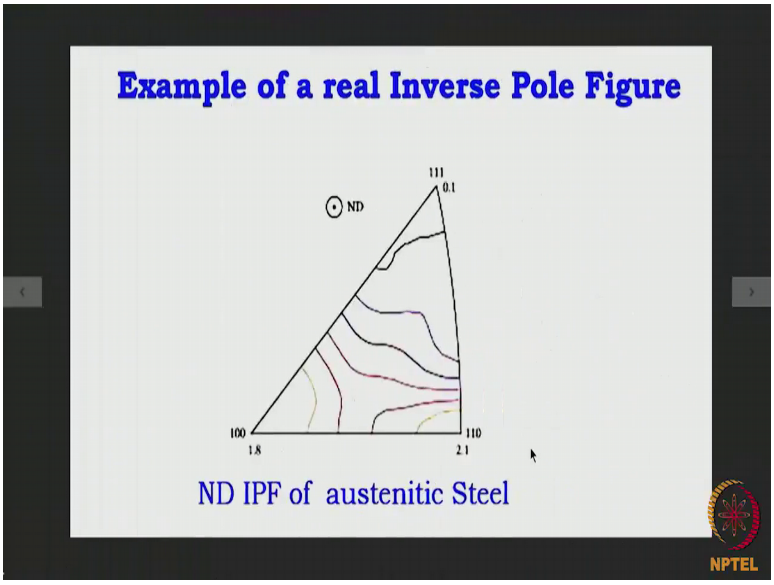

Now example of a real inverse pole figure is giving here. So, this is the normal direction inverse pole figure of austenitic steel. So, here this is the normal direction as important and these are all the contour lines with respect to the random material. So, if we can see that how the normal directions of the different grains are arranged you can see that here the intensities 2 point one times random; that means, for most of the grains the normal directions have orientations close to 1 1 0. And quite substantial number of grains are such that the normal directions are close to the 1 0 0, because you see here you know it is 1.8 times random.

But what about the 1 1 1 very little; that means, practically in this material the normal direction for none of the grains. So, to say is close to 1 1 1. So, in this way we find out we represent texture by using what is known as an inverse pole figure. Now I come to the third method of representing a pole figure.

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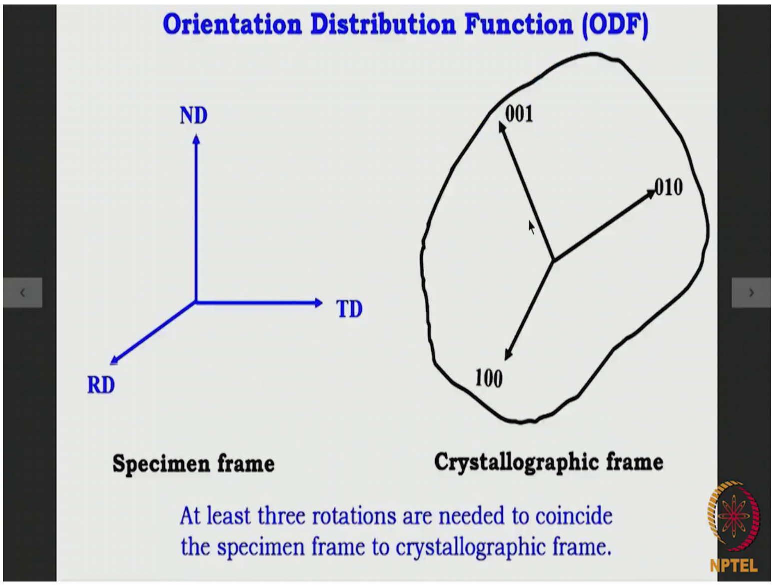

It is called the orientation distribution function or ODF method. Now in this method the way we represent texture or we way we represent an orientation is completely different from what we have known up till now. Say for example, if we take a sheet material specimen then the sheet material specimen has 3 sample parameters. One is the rolling direction, the other is the transverse direction and the third one is the normal direction. And all this 3 directions are mutually perpendicular to one another.

Now, this 3 constitute what is known as a specimen frame. So, these 3 constitute what is known as the specimen frame, and this is the same for all the grains within the specimen. Now let us take just one of the grains of our sheet specimen. Now if we look at the 3 directions 1 0 0, 0 1 0 and 0 0 1 in one of the grains, we know that they are mutually perpendicular to one another. So, this set is known as the crystallographic frame, for grain number 1 for another grain it may be a different set for a third grain it maybe still different set.

So, we have for each grain a crystallographic frame consisting of the 3 mutually perpendicular directions 1 0 0, 0 1 0, 0 0 1 we have well we have assume cubic material here. And for all the grains within the sheet material this specimen frame is the same consisting of the RD TD and ND directions. Here we define orientation by finding out what should be the angular rotation given to this crystallographic frame of a grain, in such a manner that 1 0 0 becomes the same as RD 0 1 0 becomes the same as TD and 0 0 1 becomes the same as ND. In fact, mathematical it can be shown that at least 3 rotations are needed to coincide the specimen frame with the crystallographic frame.

Now so, how you define the orientation of a grain in this particular case? So, this is say grain number 1 in our specimen, this is the specimen frame which is fixed for all the grains within this specimen, and within the grain number 1 this is the crystallographic frame. So, what we do now? We try to coincide this particular crystallographic frame with the specimen frame in such a manner that 1 0 0 becomes the same as RD 0 1 0 becomes the same as TD and 0 0 1 becomes the same as ND. Now as I have already said at least 3 rotations will be needed to coincide this frame with the other one.

Now, several systems of rotation have been suggested, but we mostly use the one which has been given by professor Bunge. Now let us see what we do by the Bunge method.

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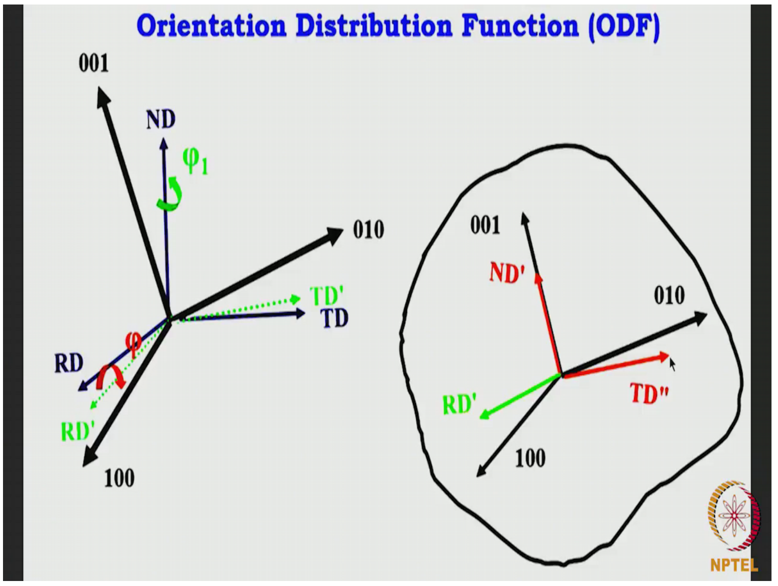

So, what we have done here this is our specimen frame RD, TD, ND this is our crystallographic frame 1 0 0, 0 1 0, 0 0 1. So, we have taken the crystallographic frame here and without doing any rotation, put it on top of the specimen frame by coinciding the centre. So, without any rotational movement we take the specimen frame takes the specimen of the crystallographic frame from here, and put it on top of the specimen frame over there. Now Bunge suggested 3 consecutive rotations of the crystallographic frame, in such a manner that ND and 0 0 1 coincide RD and 1 0 0 coincide TD and 0 1 0 coincide.

Now, let us see what kind of method you have suggested. Well, Bunge suggested 3 consecutive rotations around the specimen frame; around the specimen frame to make it coincident with the crystallographic frame. So, the first rotation he suggested is by an angle phi 1 around ND. So, the first rotation here suggested is by an angle phi 1 around ND. So, how much is phi 1? You see the moment we give a rotation around ND RD no longer stays in it is original position RD shifts to the position RD prime TD shifts to the position TD prime.

So, Bunge suggested the amount of the rotation phi 1 should be such that the new position of RD which is RD prime becomes perpendicular to the plane contained by 0 0 1 and ND. So, he suggested that the first rotation we give around ND by an angle phi 1 such that the new position of RD which is RD prime becomes perpendicular to the plane contained by 0 0 1 and ND. So, once this is done. So, this is what happens here. So, this is RD prime this is TD prime this is the position of RD prime here TD prime. Now the second rotation here suggested is around RD prime by an amount phi. So, he has suggested a second rotation by an angle phi around RD prime.

So, how much is phi? Phi is such that ND and 0 0 1 they become coincident. You see by the first rotation already we have seen then RD prime becomes perpendicular to the plane contained by ND and 0 0 1. So, he gives a second rotation around RD prime such that ND and 0 0 1 they become coincident, and this will be apparent in the next diagram.

So, you see that after the second rotation, you know 0 0 1 and ND I become coincident this is RD prime TD has travel to a different position call TD double prime. Now Bunge suggested a hard rotation and how much is that? He has suggested a rotation by an angle phi 2 around the common ND and 0 0 1 direction; that means, now the rotation is about the common ND and 0 0 1 direction by an amount phi 2.

How much is phi 2? Well, it is such that RD prime becomes coincident with 1 0 0 TD double prime become coincident with 0 1 0. So, this is a scheme of rotation which was suggested by Bunge there have been other people also who suggested other types of rotations, but most of the crystallographers around the world they follow Bunges method. So, if we now talk about the orientation of grain number 1, as I told you before this is the crystallographic frame of grain number 1, is this is our grain number 1 this is the crystallographic frame up grain number 1. So, you wanted to make this crystallographic frame coincident with this specimen frame and according to Bunge we find that we have to have a series of 3 rotations phi 1 phi 2. So, the values of phi 1 phi 2 they denote the orientation of this grain number 1.

Similarly, for a second grain within the specimen it has got a different crystallographic frame. And again you find out; what are the corresponding phi 1 phi 2 values in order to make the 2 frames coincident.

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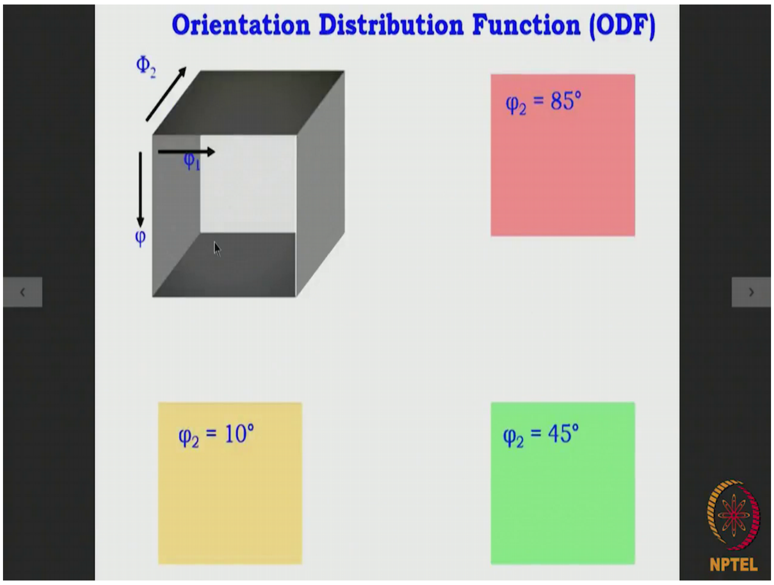

So, we see that instead of describing orientation of a grain by h k l, u v w we define the orientation grain by specifying the 3 angular rotations to be given to the specimen frame in order that the crystallographic frame of a grain can coincide within. So, if we now consider an imaginary space we call it the orientation space say this is the 3 dimensional orientation space, and say this is the origin this is phi 1 this is phi and this is phi 2. So, phi 1 phi 2 they denote a 3 dimensional orientation space, in this space if say the phi 1 any point within this orientation space will denote the orientation of a grain.

Because any point here will have the coordinate's phi 1 phi 2 any point here another point will be a different set of phi 1 phi 2. So, any point within these 3 dimensional space will denote orientation of a particular grain now if we find by plotting the orientations of a large number of grains in the sample, that all the points are clustered together within the space we can say that the material must be texture material. On the other hand if all the phi 1 phi 2 values for the different grains are distributed uniformly inside then you can say that the materials the random material.

Now, what is the size of this orientation space you see for cubic materials the orientation space is such that phi 1 varies from 0 to 90 degree, phi varies from 0 to 90, degree phi 2 varies from 0 to 90 degree, actually the size of the orientation space depends on the symmetry elements possessed by the sample and also the material. For cubic material only you know we have got a an orientation space which is cubic in nature and where phi 1 phi 2 independently vary from 0 to 90 degree.

Now, any information within a 3 dimensional object you know can be resolved by taking lot of sections of the 3 dimensional space. So, people you know prefer looking at the orientation distribution of grains within this 3 dimensional space by taking sections the sections can be taken parallel to this side, sections can be taking parallel to this side or parallel to this side.

So, for example, this particular the front section this is phi 2 is equal to 0 degree section, the back section here is phi 2 is equal to 90 degree section. Similarly we can have phi 2 phi degree section 10 degree section as we want. So, this is say the phi 2 85 degree phi 2 10 degree phi 2 45 degree sections.

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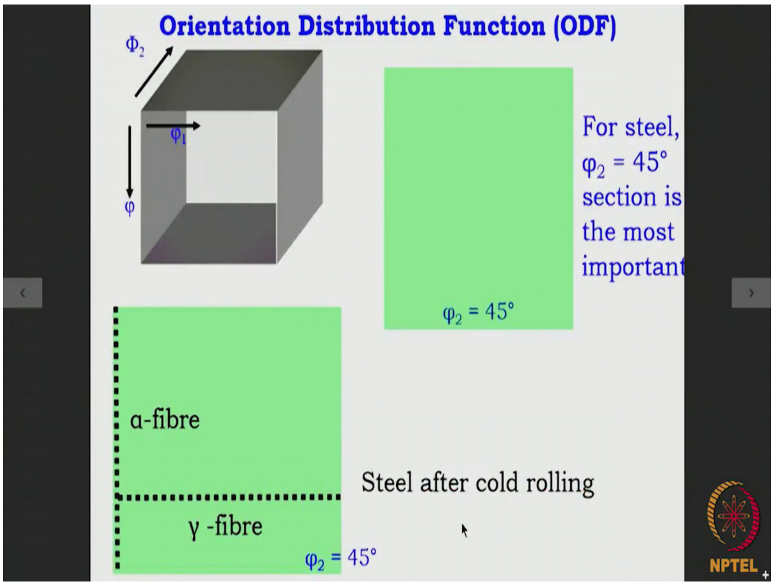

For still engineers the most important section of the orientation space is it phi 2 45 degrees section.

Why it is so important? Because if we take a steel and cold roll it very heavily, whatever the kind of steel, we have we will see that in general most of the dense repole density will lie along this line in this section and also along this line in this section. And all orientations lying along this line is known to constitute what is known as the gamma fibre and all orientations lying along this line are known to constitute what is known as the alpha fibre.

So, phi 2 45 degree section is very important for the steel engineers, but you know depending on the material depending on the type of work we are doing we can take phi 1 sections phi sections whatever we want.

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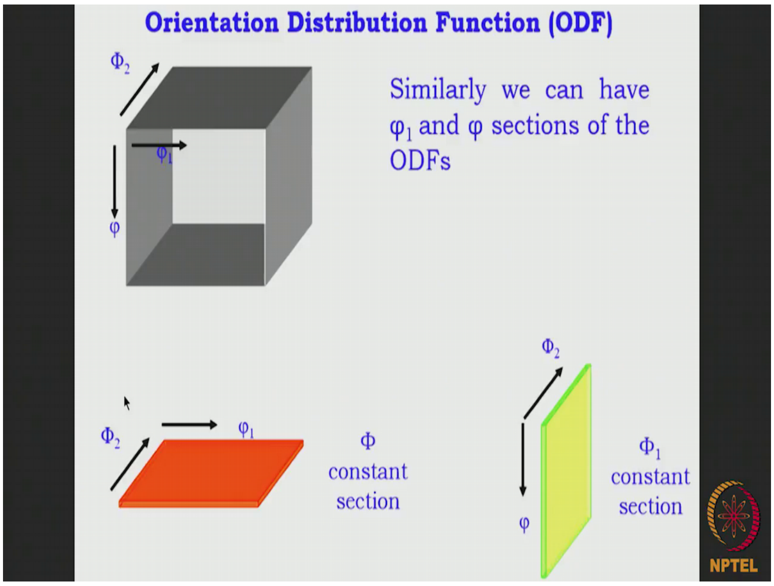

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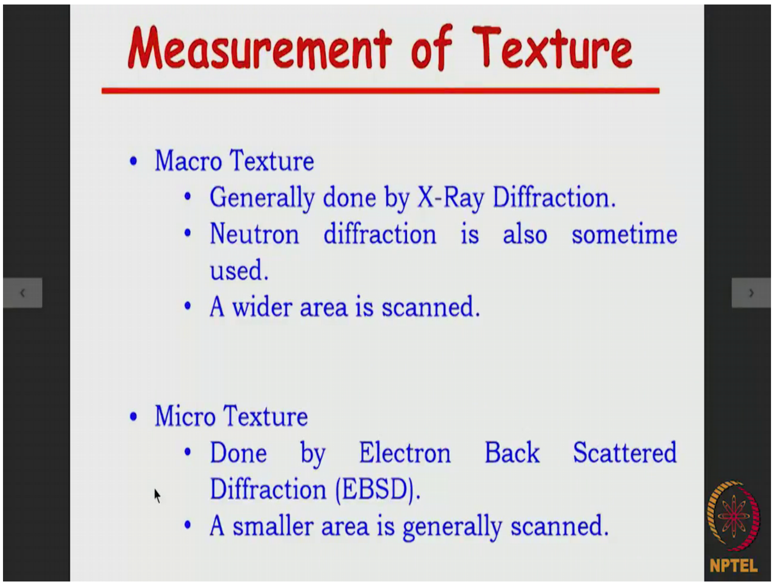

Now, we come to the measurement of texture. When you talk about the measurement of texture we distinguish between what is known as the macro texture or macroscopic texture, and the micro texture or microscopic texture. Now what is macro texture? In this particular method we generally used X-ray diffraction to measure the texture and sometimes when the grain size is rather large neutron diffraction is also used. Now in this method we scan a very wide quite a wide area of the sample, So that the texture data is representative of the whole sheet material.

So, it is on a macroscopic scale a large number of the orientation is found out from a large number of grains and the texture is representative of the sheet material. Now there is one thing which we must realize when it measure the macro texture, from the macro texture it is impossible to find out what kind of orientation the grains the individual grains are having?

On the other hand micro texture is carried out by electron back scattered diffraction or EBSD as we will see and here a smaller area is generally scanned; that means, you can have a small micro structure in the material and it is possible to find out the texture from that small micro structural region. So, you can get texture from a much narrower region not only that it is also possible by this method to pin point, what orientation the grains within that microscopic region has. So, this is a big advantage compared to the other one. Because here you can look at the micro structure and you can also find out the orientations are individual grains, which you cannot do in case of macro texture.

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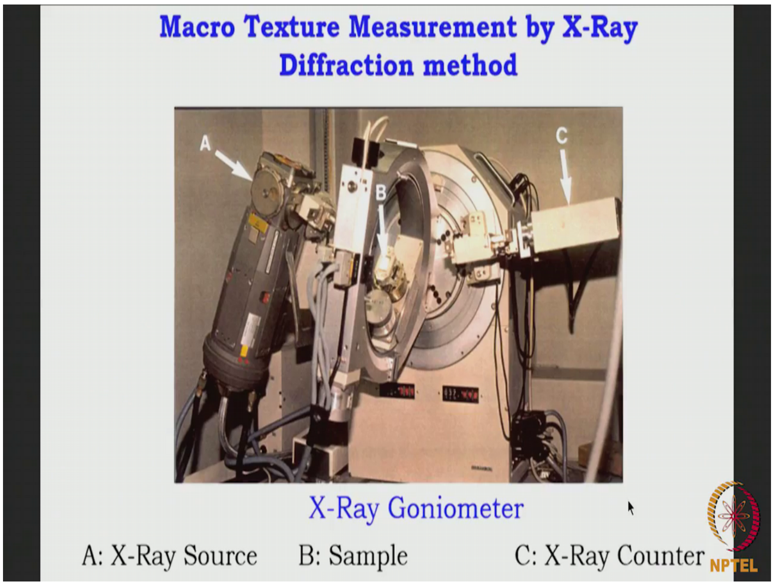

As I said macro texture measurement is normally carried out by X-ray diffraction. Now this is an X-ray diffraction unit with what is known as X-ray texture goniometer. So, here this is the X-ray source and you have got your specimen over here, and you have got the X-ray counter to measure the diffracted radiation in this direction.

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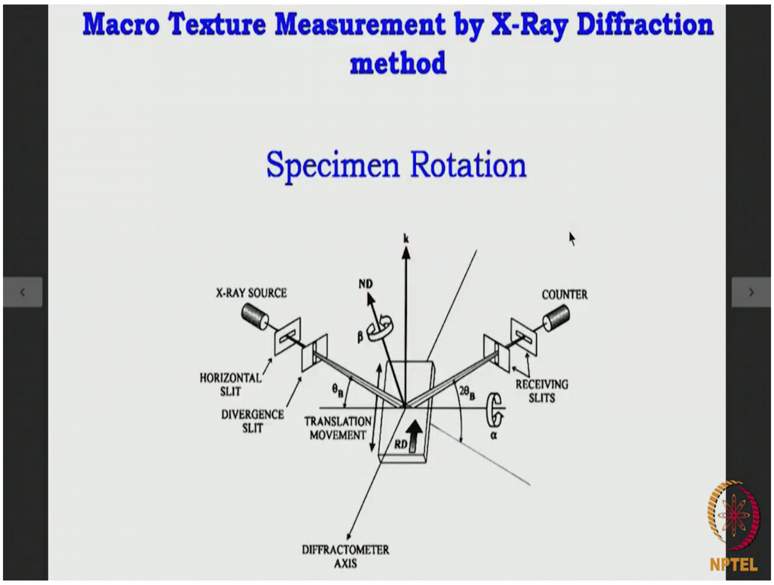

Now the specimen which is put in the texture goniometer is not stationary. In fact, when you have the X-ray beam falling on the specimen as is done you know for normal X-ray diffraction work. The X-rays are incident over a very small area of the sample, you see the small area need not cover many of the grains in the sample.

But when you talk about texture, we need orientational aspects to be known from as many grains as possible within the material, but the X-ray beam that is incident the beam dimension is very, very narrow so that may not cover many grains So that is the reason why while measuring texture by X-ray diffraction the specimen, we take is given some movement. For example, the specimen is allowed to translate. So, if you have the specimen you allow The specimen to translate.

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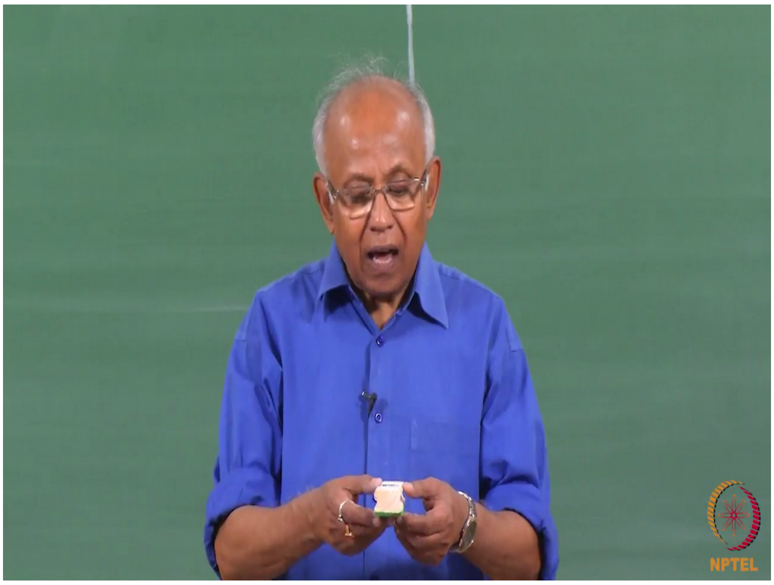

So, this is the direction incident radiation this is the direction of the diffracted radiation. So, the material is allowed to translate in it is own plane. So, what happens once it translates? The area covered by the X-ray beam extents over a larger region to cover a larger number of grains. The specimen is given a second rotation also for example, it is allowed to rotate in it is own plane. So, you say that there are 2 rotations given to the specimen.

So, this is your specimen X-ray beam is incident in this manner diffracted beam is going out in this manner the specimen is giving a translationary movement, and at the same time the specimen is allowed to rotate in it is own plane; that means, why it is doing the translationary movement it also rotates around then axis perpendicular to the sheet. So, it is doing like this. So, it is making a translationary movement and at the same time it is also rotating in it is own plane. So, you see that this specimen is given 2 kinds of movement a translation movement, and also a rotation movement like this. Now once the entire you see for texture measurement as I have already discussed.

When you want to find out the orientational information from the grains, we just choose one particular type of planes. We are not we do not consider a larger number of diffraction for the larger number of planes at the same time. So, we concentrate on the diffraction taking place from only one type of plane this is very important. Say for example, a particular h k l plane is taken into consideration. So, depending on the walk to be carried out say we want to find out the orientational aspects from 1 1 1 planes of as many grains as possible or depending on what kind of information, you need we may try to have information from the 2 0 0 planes from as many grains as possible etcetera etcetera.

So, what I mean to say is, when you do the texture measurement, you know it is just like a measurement a normal measurement in X-ray diffraction, but we want information from only one type of planes. Say for example, we are interested to find out the texture by considering the orientational aspects of only the 1 1 type of planes from many grains. So, what you do? We put the specimen in the diffractometer in such a manner if you know the specimen what kind of specimen it is you know we know what is the d value for the 1 1 1 planes and once you know the d value for 1 1 1 type of planes and if we know the wavelength of the monochromatic x radiation. So, lambda is known d is known we can find out the value of theta from Bragg equation lambda is 2 d sin theta.

So, for that particular type of diffraction only the specimen is fixed in the diffractometer making the correct Bragg angle and this is the counter. So, this angle is 2 theta b angle between the incident direction and the diffraction direction. Now once the direction of incident radiation and the direction of the diffracted radiation are fixed, no more changes allowed.

So, we do not change anything else, the only thing is we give certain movement to the specimen the idea is to make as many grains as possible to be irradiated by X-ray So that we get information from as many grains of the specimen as possible. So, say we start the material in a horizontal position like this, and you know X-ray beam is incident over here and it gets diffracted in this manner the specimen starts giving the translational, we give the specimen the translational motion and at the same time it rotates in it is own plane.

Say it moves in this manner and completes the 360 degree rotation around it is perpendicular. Once this is done you know whenever this operation is going on the intensity which may be diffracted you know is all the time recorded by the counter. So, once it moves in it is own plane by 360 degree then the specimen you know is rotated by say 5 degree around this axis. This is the axis I am talking about, this is the axis. So, the specimen rotated by say 5 degrees in this manner, why we do this kind of a movement?

You see it may So happen that in it is present position none of the grains have their 1 1 1 planes in a diffracting position.

But you know those 1 1 1 planes maybe slightly away from the diffracting position. So, if we give a movement like this those 1 1 1 planes may come in a diffracting position so that is the reason why you know we move the specimen around this axis as shown over here when alpha degree which is 5 degrees initially. So, it is moved by 5 degree and again it is given in that condition it is given to and fro motion and a rotational motion like this and we allow it to continue for 360 degree motion. Once this is done then it is again moved by 5 degree around this axis and the same type of movement is given to the specimen. All the while the intensity diffracted you know along this direction is recorded by the counter.

So, if we start the specimen from a horizontal position you know by this movement we come upto the vertical position, or if we start from the vertical position we ultimately come to the horizontal position in intervals of 5 degrees So to say. And all the while the intensity that is diffracted by the specimen will be recorded by the counter. Now the question is how we try to correlate the intensity that is obtained by the counter at different times with the grains which give rise to those diffracted radiations. So, how we do that? You see normally the diffracted radiation is plotted in the form of a diagram like this.

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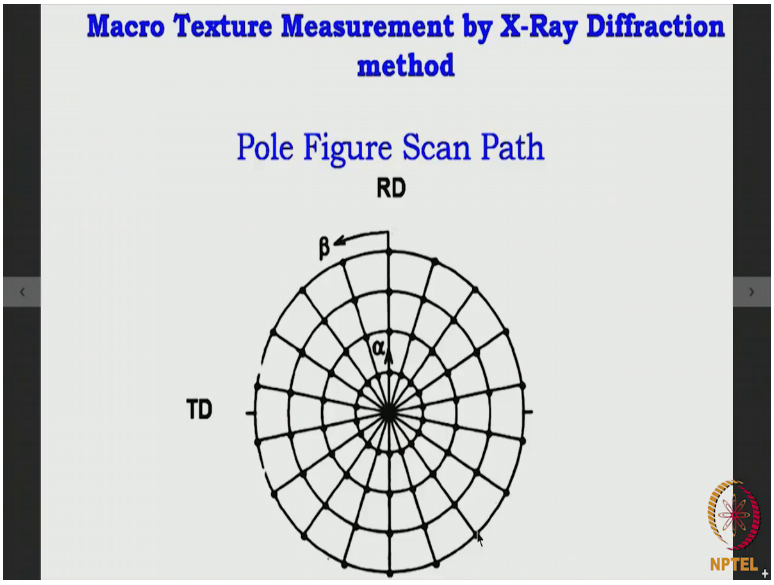

You know we have got a diagram like this. So, this is centre and these circles are at say 5 degrees away. So, this is the 5 degrees circle 5 degrees away, this is 10 degrees away, this is 15 degrees away, this is 20 degrees away upto about say 90 degrees.

Now, this kind of a diagram used to record the diffracted radiation. Now how it is done? I will explain to you in the next diagram.

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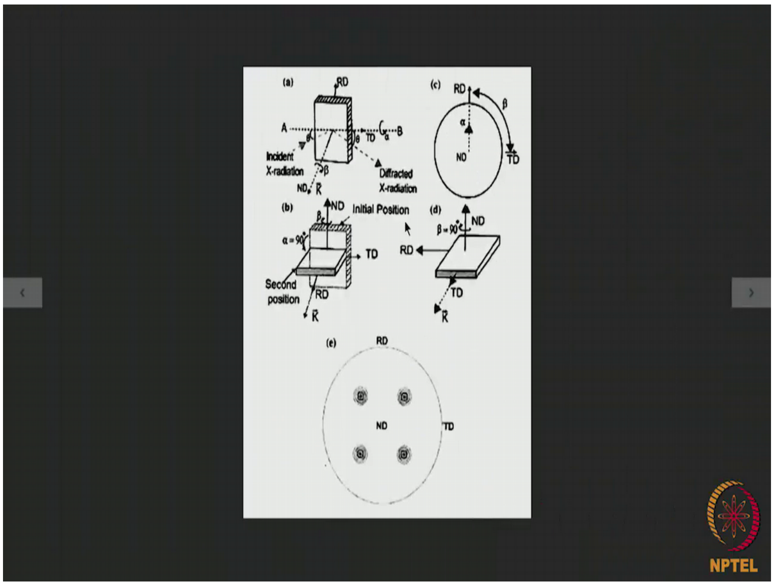

Say for example, we start our experiment in this manner, we take the specimen in a vertical position say this is our specimen, and we take it in the vertical position. And we fix the direction of the incident x radiation, we also fix the direction of the diffracted radiation. So, in this position this is the RD the rolling direction this is the TD and this is the ND or normal direction. Now here is what we have the k vector you know k with a bar on top this is the k vector, what is the k vector? K vector divides the angle between the incident direction and the diffracted direction. So, it divides it bisects the angle between the incident x radiation direction and the diffracted directions. So, this is the k vector.

So, when the sample is in it is vertical position you know the beginning of the experiment the k vector and ND they are in the same direction. Now suppose the specimen you know is given it is translationary motion and it is rotational motion in it is own plane and it is done after every 5 degree. So, this is the first position then it comes to these 5 degrees 10 degrees and comes to this position.

So, the second position is this, from here say it from the vertical position the specimen comes to the horizontal position. Now when it happens, what happens here now when it comes to the horizontal position we find now RD which was in this direction RD comes in this direction. So, RD becomes the same as the k direction. So, you say that the k vector RD become the same.

So, this is the second position now suppose this specimen is rotated in it is own plane. So, if it is rotated in it is own place so your RD is now pointing this way. So, if it is rotated 90 degree then RD goes in this direction and TD and k vector they become the same. So, this is a position like this. So now, when it is rotated you know the in the horizontal position if it is give in a rotation of 90 degree in this direction then RD comes over here, and TD which was in this direction by 90 rotation it is come over here and k vector it. Now assumes the same direction of the k vector you see the k vector never changes because the direction of incidents and the diffracted radiation they never change.

So, the k vector does not change. So, you see that when you come from the vertical to the horizontal position k vector which was along ND in the vertical position, now it comes to the RD position; that means, it start with you know if we take this figure as a circle and if suppose this particular position you know if you have the vertical specimen the vertical position and we take a projection plane parallel to that. So, this is the projection plane parallel to the vertical position. So, in this condition the ND or k vector they are over here. So, k vector position is over here. Now when the specimen changes from the vertical position to the horizontal position, what happens? K vector becomes the same as RD.

So, the k vector effectively travels from ND to RD because you know this is RD this is ND this is TD. So, in the vertical position k vector is here in the horizontal position k vector is there. So, you say that when you know we change alpha, you know as alpha changes the k vector changes from here to here. And when in the horizontal position it changes by 90 degree; that means, k vector it is synonymous to RD here. So, when it moves 90 degrees the horizontal position k vector becomes synonymous to TD. So, from RD to TD k vector starts from here and goes over there.

So, you see that whenever a specimen is moving in it is own plane, and making to an flow direction then actually the k vector travels from here to here. And when the specimen is giving different degrees you know change by say angle alpha like this around this axis, then k vector changes from here to here. So, knowing this you can easily figure out where you can plot the diffraction data, if this type of a diagram. And this diagram is nothing but you know a kind of stereographic projection of the 1 1 1 poles emanating from the specimen. So, when you are right and this position and you find the diffracted in intensity has got certain value. So, you plot the diffracted intensity over here. Then you go to change this to 5 degrees from here it changes by 5 degrees and do the same kind of rotation and then you are in this kind of a circle 5 degrees away from the ND. And you measure whatever the diffracted radiation along this line.

In a similar manner when it is changed to 10 degrees then you go to the 10 degrees circle and whatever diffracted radiation is obtained in the counter you measure over you plot over there. So nowadays the movement of the specimen is synchronized with the plotting of the intensity is in this kind of a figure. And once this is done we get what is known as a pole figure over here.

So, you say that this is a pole figure because here you have got the 1 1 type pole densities and we have also got the specimen parameters marked on it ND RD and TD. So, you say that by X-ray diffraction, what we do is we find out the density of the 1 1 1 type of poles from the specimen under different conditions of movement and rotation. And this is plotted in terms of a pole figure here this is 1 1 1 pole densities and here the specimen frame represented by RD ND and TD.

So, this is essentially what is known as a pole figure which has been drawn by x RD experiments. Now getting a pole figure is the first part of the job, now we have to interpret the pole figure, that from the pole figure what knowledge we have about the texture of the material? Say for example, I show here a 1 1 1 pole figure or nickel; that means, it is you know this nickel was heavily cold rolled a 95 percent and then it was anneals So that the whole thing recrystallized.

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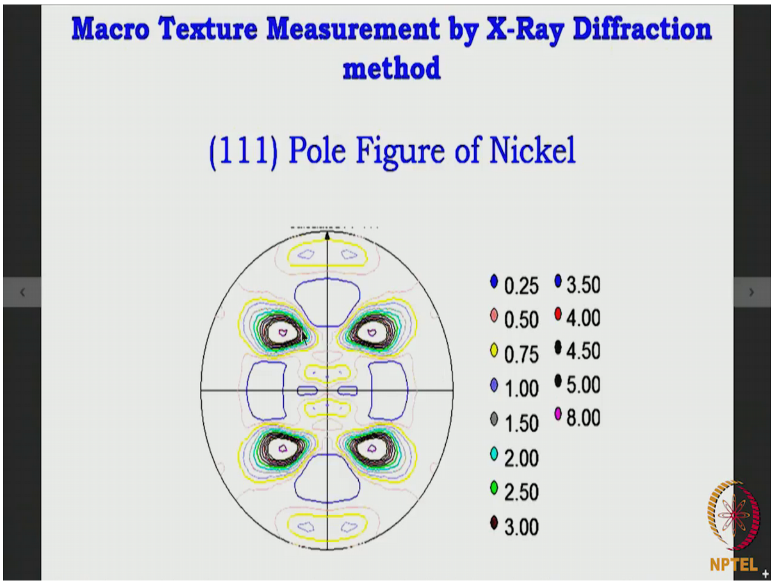

So, this is the pole figure of recrystallized nickel, this is the rolling direction, this is the transverse direction and this is the normal direction. So, all these different colours talk about the densities of the poles over here in terms of random.

Now, this is the kind of experimental pole figure we obtained by measuring the 1 1 1 poles of nickel. Now what kind of texture the material must possess, how do we know that? Now please remember that this pole figure was drawn by taking the projection plane parallel to the original specimen position. So, if the original specimen position is like this the projection plane is parallel to this. So, this pole figure has been taken on a projection plane which is parallel to the specimen surface, and what type of poles have been plotted? This is these are the 1 1 1 type of poles which have been plotted. Now how do we read this particular pole figure?

Now, in order to read a pole figure we have to have a large number of standard stereographic projections with us. Now if you remember we talked about a 0 0 1 standard stereographic projection. So, what we do? We take the 0 0 1 standard stereographic projection and superimpose on this pole figure.

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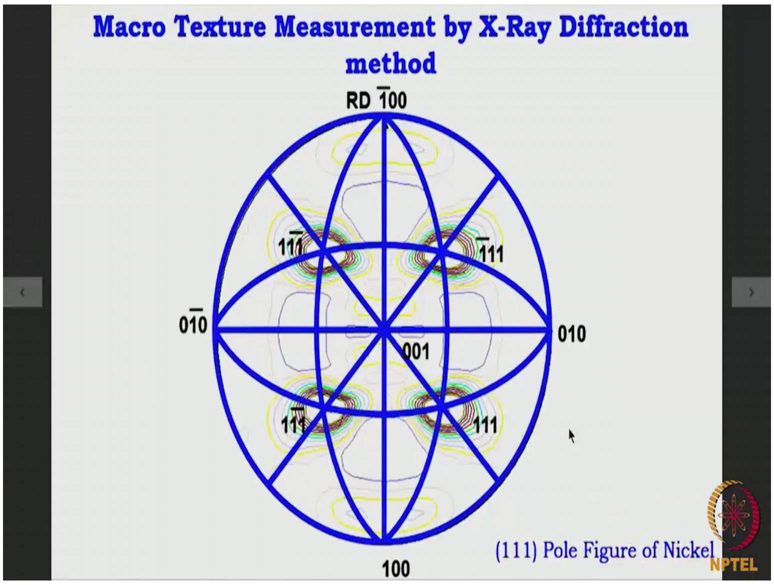

Once we do that you see this is what the situation looks like. So, the blue coloured diagram is the 0 0 1 standard stereographic projection. And below this we have got the pole figure where the 1 1 1 poles have been plotted.

Now, the interestingly we find that all these high pole densities in the actual pole figure they coincide with 1 1 1 pole positions in the standard stereographic projection. But how is it possible? You see we have drawn we have got 1 1 1 pole densities we have measured 1 1 1 pole densities and plotted them in the pole figure, and their locations this. And when I superimpose the 0 0 1 standards stereographic projection, I find that all the 1 1 1 poles of the standard projection they coincide with those 1 1 1 density pole densities.

So, what does that mean? You see when you when you talk about the stereographic projection on the pole figure here the which is below the standard stereographic projection, the pole figure was drawn again I must mention to you the pole figure was parallel to the specimen surface. And the standard 0 0 1 stereographic projection was taken by taking a the projection plane parallel to the 0 0 1 plane. So, it automatically suggests that if the 1 1 1 pole densities of the pole figure coincide with 1 1 1 locations in the standard stereographic projection it automatically suggest that it is possible only when the projection plane of the stereographic standard stereographic projection is the same as the plane of the surface of the sample.

That means it is possible this kind of a you know match is possible only when the specimen surface is parallel to 0 0 1. So now, you know that we have got a specimen you know from this pole densities pole figure we have got a specimen to surface must be parallel to 0 0 1, otherwise you know the 1 1 1 pole densities in the pole figure would not have matched with the 1 1 1 type of poles in the 0 0 1 standard stereographic projection. So, the standard stereographic projection here is one where the projection plane was parallel to the 0 0 1, plane and the pole figure here is one in which the plot has been made on a plane parallel to the surface of the sheet material.

So, the surface of the sheet material must be 0 0 1. So, the first part of the problem we found out figure out which plane of most of the grains is parallel to the sheet plane. So, it is 0 0 1 and which direction is parallel to the rolling direction as you can see here after superimposition, this is the RD of the pole figure and this is a bar 1 0 0 of the standards stereographic projection. So, we can immediately say that this kind of pole distribution when you get in a pole figure that corresponds to a texture given by 0 0 1 bar 1 0 0.

That means h k l is 0 0 1 u v w is bar 1 0 0. So, in order to read a pole figure it is necessary to have quite a large number of standard stereographic projections that will help.

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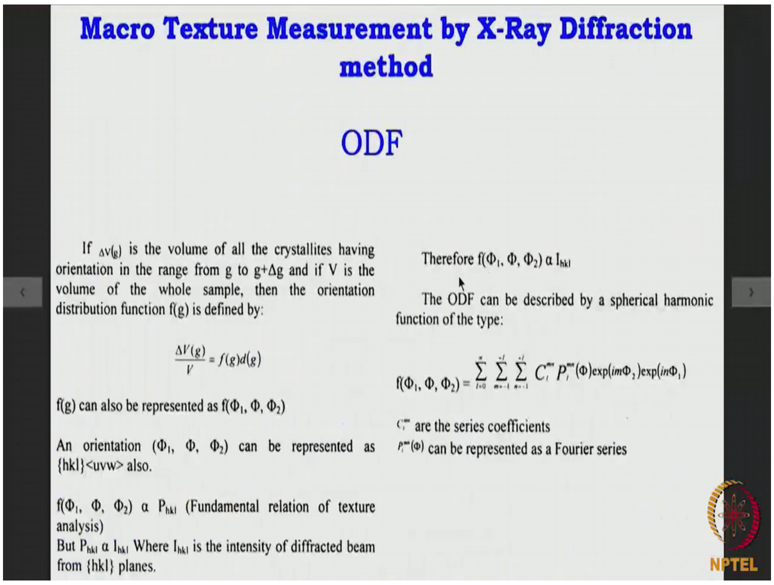

Now we come to macro texture measurement by ODF, you see what is done in case of ODF in the orientation distribution function. Here what we do is we describe the pole density within the 3 dimensional orientation space by a function of this time this is called a spherical harmonic function. You see this is very similar to you know what we used to do in our first year physics, you know if we wanted to find out the distribution of free electrons in an atom by what is known as a Schrodinger function is very similar to that. Now here you know there are 3 terms one is a function of phi and there is a function of phi 2 a third one a function of phi 1.

So, these are all mathematical functions and these can easily be found out for different values of phi and phi 1 and phi 2 and tabulated. Now in this part this are the coefficients c l m n this coefficients. In fact, are related to the pole densities in a pole figure. So, in a way whatever data we get in order to draw the pole figure that data is transferred in this particular type of spherical harmonic functions. And we describe the pole density by a function of this type f phi 1 phi phi 2. So, if delta V g is the volume of all the crystallized having orientation in the range from g to g plus delta g and if V is the volume of the whole sample then the orientation distribution function is defined by this. So, this is the orientation distribution function delta V g by V we write it as f g d g ok.

Now, this f g gs orientation can be represented as f phi 1 phi 2. Now it is quite possible to find out what is the h k l, u v w value for a particular value of f phi 1 phi 2 you know, this can be found out because these are mathematically related. Now this function is proportional to you know the pole density of the h k l planes in the pole figures you know, this is a fundamental relation of texture analysis. But you see the pole density is proportional to intensity of diffracted beam from the h k l planes.

Therefore, you know this function is related to the intensity obtained by diffraction from the h k l planes so that is what I told you already that this function can be found out from the pole density data by treating the data in the form of a mathematical function. And then we can plot this function in the orientation space 3 dimensional orientation space and we get the ODF or the orientation distribution function.

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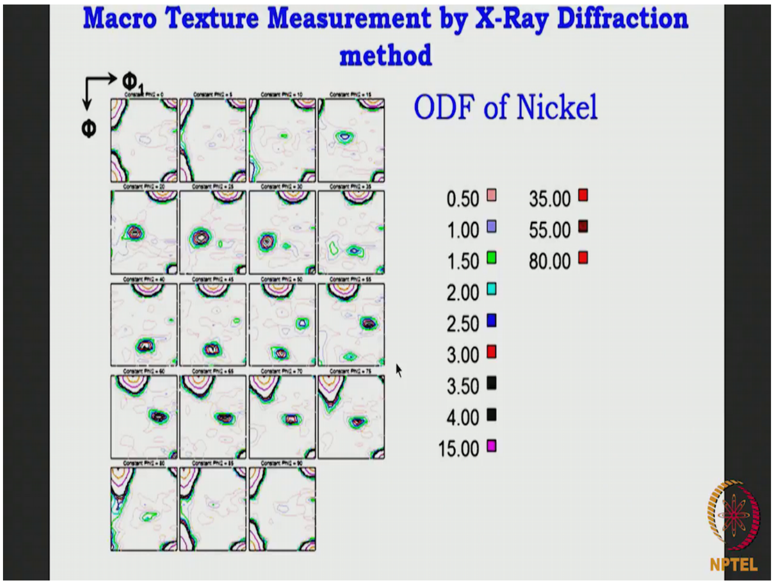

Now, this shows you know they it is again the ODF of recrystallized nickel for which you have shown the pole figure previously. So, this is the ODF of the same sample of nickel and here we have taken a you know a various sections of the ODF of the 3 dimensional orientation space, as you can see for each section this is the phi 1 direction this is the phi direction. So, this is phi 2 0 degree this is phi 2 phi degree section this is phi 2 10 degree section this is phi 2 15 degree section etcetera etcetera this is phi 2 90 degree section.

So, the entire pole density distribution within the 3 dimensional orientation space can be represented by finding out the various sections of the 3 dimensional orientation space in this manner. Now why people go for ODFs? You see whatever orientation data we plot in a pole figure. In a pole figure within such a small space you know you have to plot the pole density. Now if suppose the texture is such that there are 4 or 5 different types of components maybe h k l u v w some grains have orientation close to h k l u v w some grains have orientations h 1, k 1, l 1, u 1, v 1 w some grains have orientations close to h 2 k 2 l 2 u v w u V u 2 V 2 w 2 etcetera etcetera.

Then all those texture components they are smeared on a in a circular pole figure. So, within a small space you have got lots and lots of poles and it may be very difficult to figure out you know what are the specific texture orientations, but in case of an ODF you know we have a much bigger space in which to represent orientation. So, it has a much better resolution. And that is the reason why people use the ODFs now a day they prefer using ODFs over pole figures, although most of the routine work is still carried out using pole figures. Now since the data used by pole figures and ODFs are the same we cannot say there one is more accurate than the other no the accuracy is the same in both cases.

The only thing is the ODFs have a better resolution then the corresponding pole figures.

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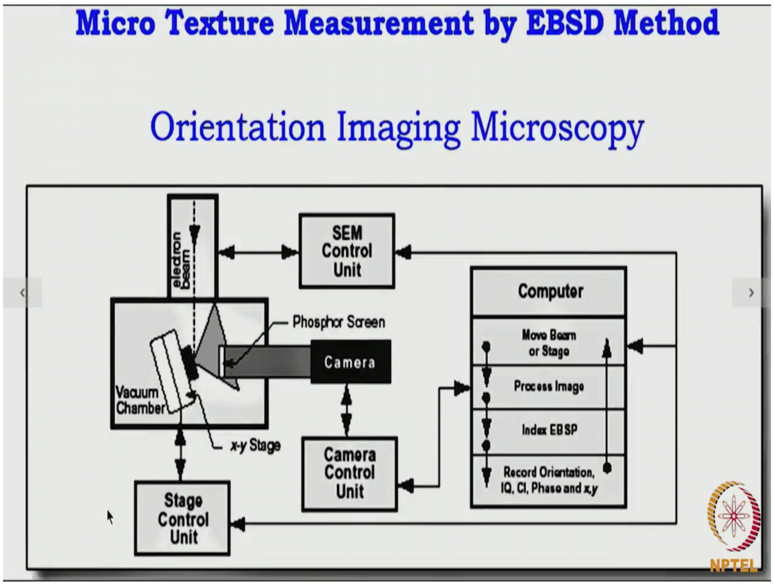

Now we go to micro texture measurement by electron back scattered diffraction method. We use an equipment which is nowadays known as the orientation imaging microscopy. You see it is basically a scanning electron microscope with which a EBSD attachment electron back scattered diffraction attachment is attached. You see what happens here you have the electron beam the scanning electron microscope and it falls on your specimen this is your specimen, and you can have both things one of the other you can have the image and also you can have the EBSD pattern.

So, it is just like what we get from a transmission electron microscope, we can have the image and you have the diffraction pattern. From the image we get the micro structural aspects and from the diffraction pattern we get the orientational aspects. In a similar way you know in an orientation imaging microscopy. We get not only the image, but at the same time, we get the orientational aspects from the electron backscattered diffraction pattern.

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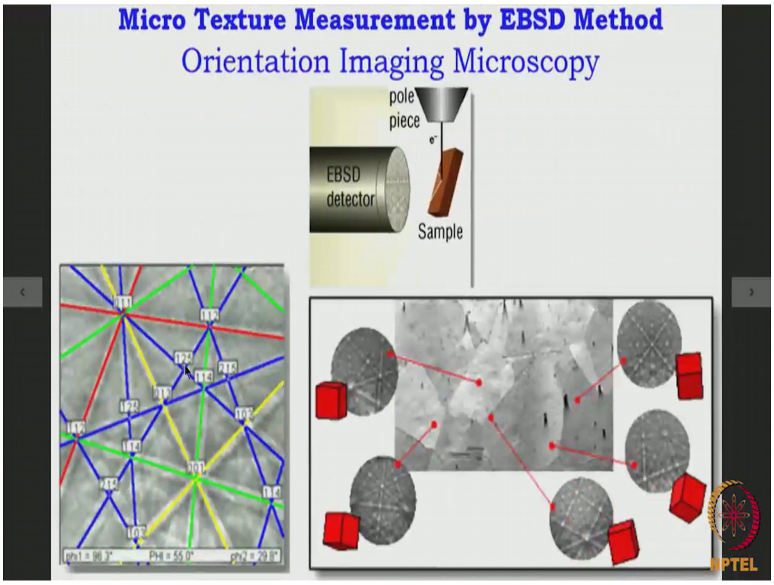

Now if you look at the electron backscattered diffraction pattern, they look very similar to the kikuchi patterns which are obtained from rather thick specimens in a transmission electron microscope. And from the kikuchi pattern it is possible to accurately determine the orientation.

So, in this particular method we see that if this is the microstructure this is the microstructure you can see the grains over here. And you can find out the EBSD patterns from each and every grain. So, you say that this is a method in which you not only get microstructure, but at the same time you also have an idea of the orientation aspects. So, this is in a way one step ahead of the macro texture which is measured by a X-ray diffraction, because there we cannot pin point which grain has got which orientation. The output from orientation image in microscope is given in terms of what is known as An orientation map.

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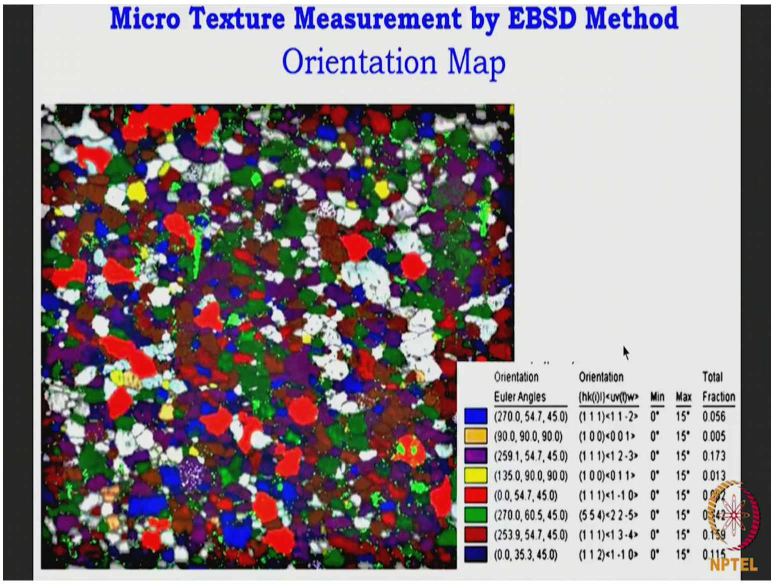

You see these are all the grains, you know you can see the grains very, very clearly what the grains are colored.

You know each colour gives a particular orientation. For example, look at the blue colour grains. So, what are the blue colour grains? These are 1 1 1, 1 1 bar 2 type of grains you know, the phi 1 phi 2 value phi 2 phi 1 phi 2 values are giving over here. And you know not only that the fraction of such grains in the entire microstructure is also given in this column. So, you say that with orientation imaging microscopy when you do the micro texture measurement by EBSD method. So, you say that when we do the micro texture measurement by the EBSD method, we not only get the microstructure, at the same time we also get data regarding the orientational aspects.

Not only that we can pin point which grain has got what kind of orientation. So, this is a big advancement and that is why orientation imaging microscopy is becoming more and more popular these days and nowadays most of the people in different laboratories academy institution and industries. They measure texture with the help of orientation imaging microscopy; that means, which has same EBSD attachment, the only thing we have to be careful about when you measure texture in this orientation imaging microscopy. We should be careful to take a large number of grains you know under purview otherwise whatever texture we determined will not be representative of the sheet sample.

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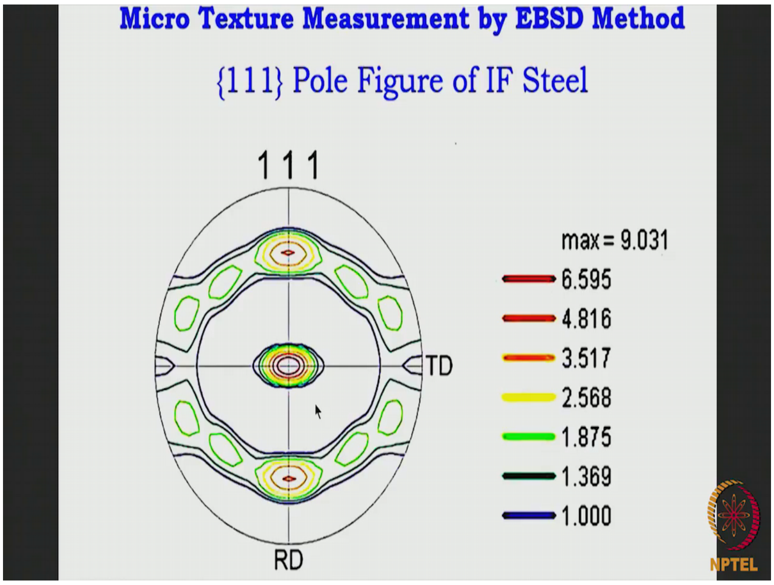

Now, this is the 1 1 1 pole figure of an interstitial free steel which was measured by the EBSD method and this is the ODF of the same steel again measured with the EBSD method.

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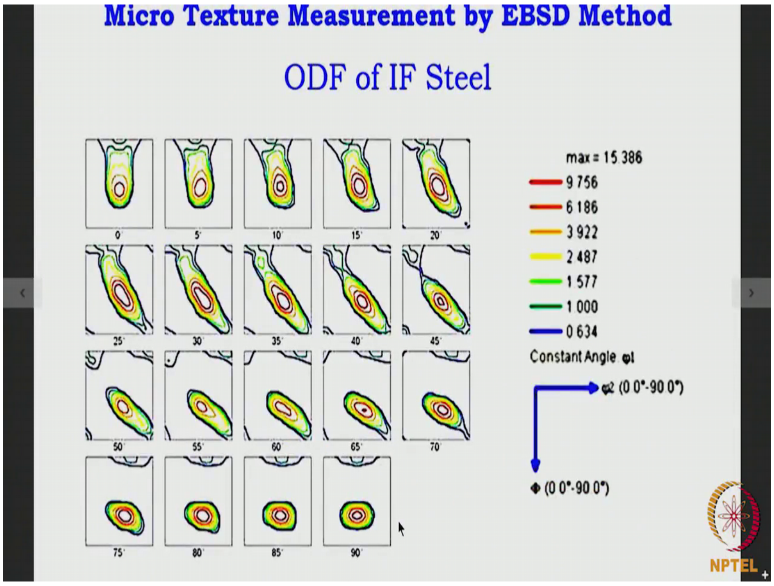

You see the orientation imaging microscopy gives you lot more information to for example; by the EBSD method we can have information about the grain boundary character distribution.

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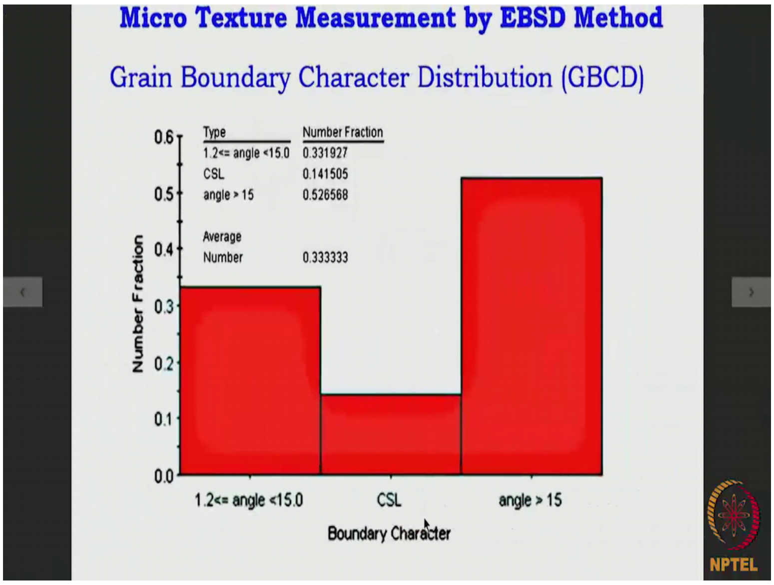

So, what is the fraction of grain boundaries? Which are the low angle boundaries? What are the high angle boundaries? And the c s l boundaries all this information can be obtained from this orientation.

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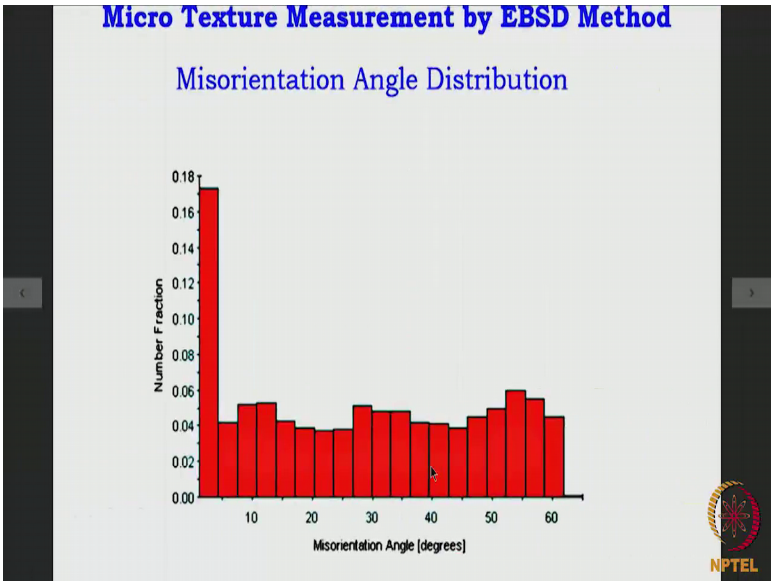

Imaging microscopy it can also a lot of information about how the misorientation angle distribution takes place in a particular area amongst the different grains.

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You can see here, texture has many, many applications. You see when you talk about deep drawing quality steels for automobiles, we find that steels which have the sheets having grains which have their 1 1 1 planes parallel to the sheet plane there will be better for the drawing quality steel.

So, there is a need for production of a short textured in the deep drawing quality steels for auto bodies, then in superconductor substrates also now a days he find that you know the high temperature superconductor y b c o yttrium barium copper oxide. You know that yttrium barium copper oxide cannot be put into the form of a wear you know. So, what we do we deposit yttrium barium copper oxide on a substrate on nickel tungsten alloy. Now it has been found that if the substrate is textured the texture is taken by the oval line y b c o, and if the nickel tungsten alloy has a sharp cube texture cube texture means the most of the grains have the 1 0 0 planes parallel to the rolling plane and 0 0 1 directions parallel to the rolling direction. Then that type of texture is taken up by the y b c o and what is the effect the effect is the critical current density improves by 10 to the power 5 to 10 to the power 6 times.

So, you see how important texture is in coated superconductors substrates again for aluminium beverage cans you have to have the right kind of texture to avoid the earring propensity, then an electrical transformers steels we know that in cold rolled grain oriented steels are very much needed for electrical transformers in order to minimize the hysteresis loss. So, texture is very, very important over there then there are So many other applications on thin films coatings corrosion and many more. Now I would finally, I would like to tell you show you a 3 diagrams which shows how important texture is to the engineer.

Say for example, when you talk about a deep drawing qualities steel, in a deep drawing quality steel we have to when you deep draw a steel deep drawing means we take a sheet of steel and cut out a portion and you know say for example, if we have to make the upper portion, the upper portion of the motor car we have the die take the steel and pressed against the die very hard so that the steel takes the shape of the die. So, in one go you make the whole upper part of a motor car. Now in order to do that the steel must be highly deep drawing driver and what we mean by deep driver? You know if you take a sheet steel and if you want to draw it like that we want that the sheet will spread in it is own plane much more before the thickness gets reduced.

Because then it will fail now in order to do that we must have a situation where the strain in the width direction of the steel divided by strain in the thickness direction should be the value should be as high as possible.

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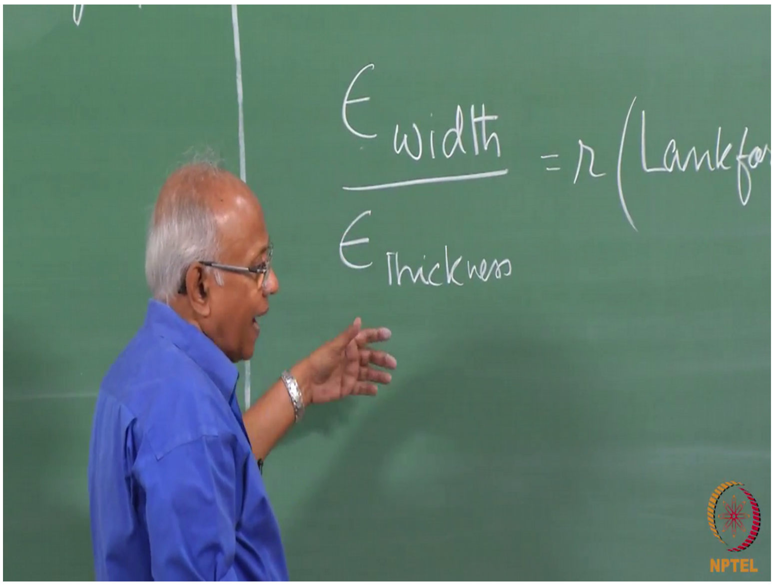

Now this ratio is known as r it is call the Lankford parameter, so Lankford parameter. So, in order that the steel can be deep drawn it is essential that this value is much higher than this value that will ensure. That when we draw the steel you know when it will spread in it is own plane much before the thickness reduces so that (Refer Time: 84:31) you know failure will occur.

So, for any sheet steel which we used for making auto bodies you know for deep drawing is the process, this value should be as high as possible. And as you can see here I have plotted all these value the r values for differently textured material.

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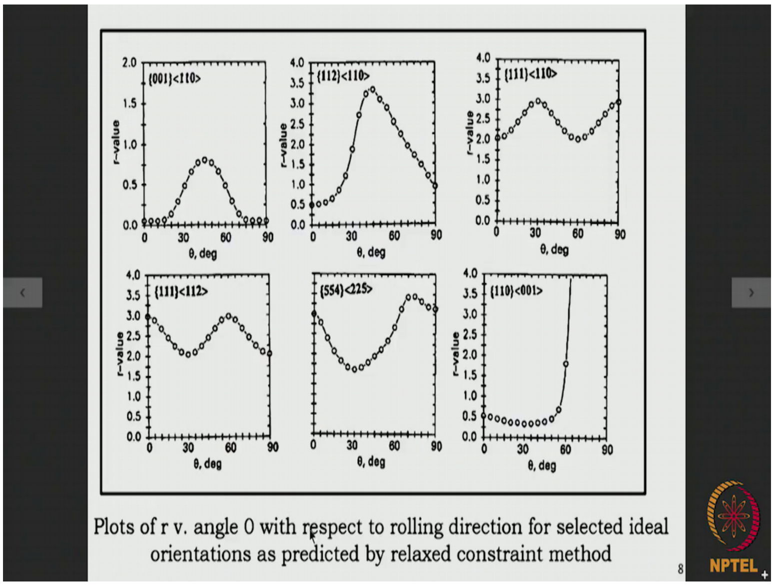

So, this is 0 0 1, 1 1 0 textured material this is for 1 1 2, 1 1 0 textured material, this is for 1 1 1 1 1 0 textured material. This is 1 1 1, 1 1 2 textured material, etcetera, etcetera. And this is the angle to the rolling direction of the sheet. So, you can see the r can vary you know very largely you know in the differently textured material.

So, you can say that how texture effects the r value. So, this is one of the examples I which I wanted to tell you how important texture is in industrial practice. Now this is another diagram, where I have plotted sigma theta by sigma 0. So, what I have done essential is, I have taken a sheet material.

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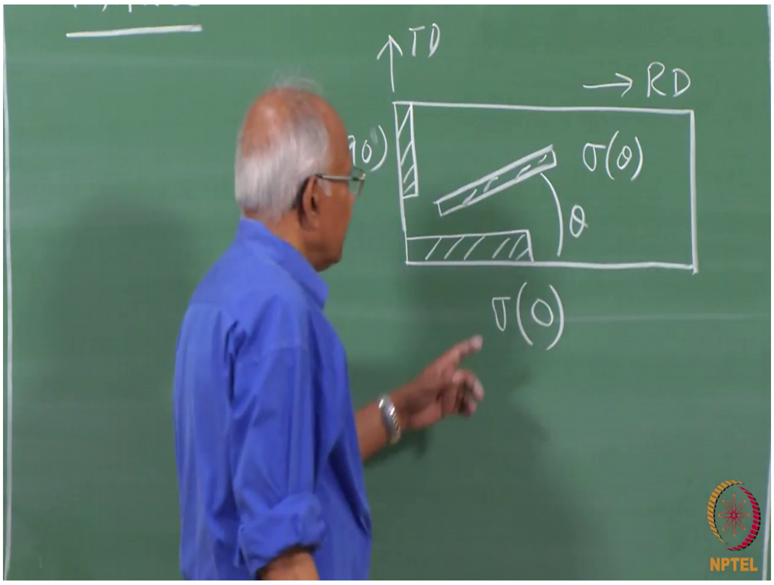

I have taken a sheet material say this is the rolling direction. This is the transverse direction; I will of course, this is the normal direction. Now if we take a tensile sample along the rolling direction you know, we consider that direction that value is written as sigma 0. Now if we take a tensile sample you know, in the transverse direction along the transverse direction, the value obtain of the tensile strength write as sigma 90.

So, if we take if we take any other directions say this direction mix making an angle, we can angle theta with a rolling direction then we call it sigma theta. So, what we have done we have divided sigma theta by sigma 0 and that value has been plotted against theta for differently textured materials as you can see over here. And you can see how they vary you know with theta and with different texture components.

Finally, I will show you a case where you have plotted Young's modulus versus theta for differently textured material. You say Young's modulus is a structure intensity property; that means, by changing the microstructure you cannot change Young's modulus. But Young's modulus is very much a function of the texture of the material. And that is amply shown by these diagrams.

So, finally, I would like to say this much that texture is very much important just like microstructure. And in our under graduate days, when we were young we were told that property of a material is a function of it is microstructure, but this is no longer. So now, we know that property is a function of microstructure as well as texture. And the importance of texture is growing day by day, and therefore this can no longer be ignored.