Texture in Materials
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Module - 10
Texture in FCC, BCC and HCP materials
Lecture - 52
Texture in HCP Polycrystals - II

Good afternoon everyone, and today we are continuing with our Module 10 which is Texture in FCC, BCC and HCP Materials. In the last three classes we have completed FCC, BCC and we started HCP materials. This is lecture number 52 and here we will be learning more about Texture in Hexagonal Close Packed Polycrystals, this is part 2.

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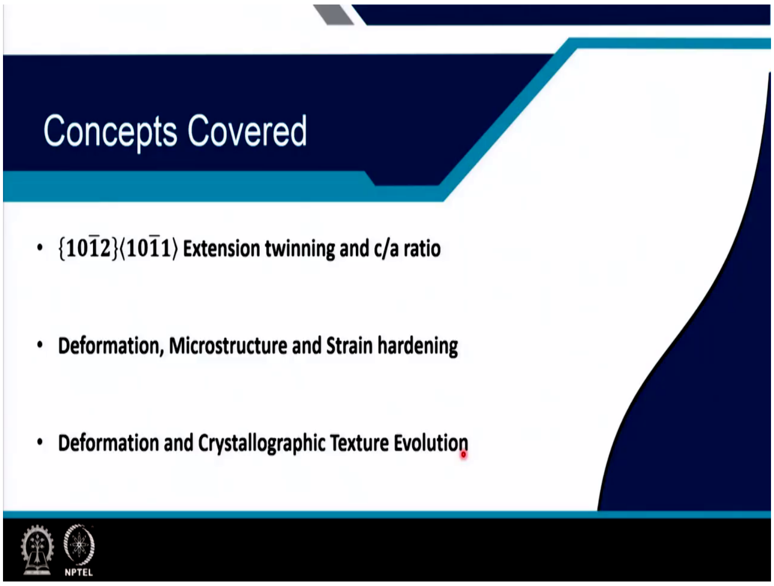

So, the concepts that will be covered in this lecture class will be to understand in a depth about 101 bar 2 101 bar 1 extension twinning and its effect on the c by a ratio. Secondly, we will understand the deformation behavior of hexagonal close packed material in terms of the metal which is titanium.

And you will understand that how microstructure evolves and how the texture and microstructure involves in developing the strain hardening behavior. Thirdly we will go and see the deformation and crystallographic texture evolution in this. So, let us start with today's lecture.

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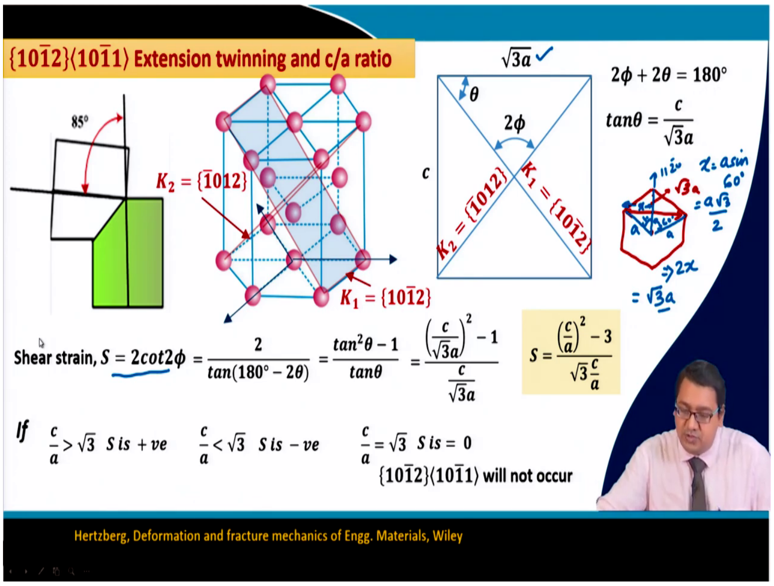

101 bar 2 101 bar 1 type extension twinning now that is what we were learning in the last lecture, we saw that there are few twins two types of twins which is extension twin one of them is the 101 bar 2 101 bar 1 type and there are two types of contraction twinning.

So, let us go into detail about 101 bar 2 101 bar 1 type extension twinning and why it is called an extension twinning and what is the effect of the c by a ratio on this. Now, to explain in detail the 101 bar 2 101 bar 1 type extension twinning forms by rotation of the crystal structure the hexagonal crystal structure by about 85 degrees to 112 bar 0 axis.

So, this rotation if we look into this hexagonal close packed structure the structure you can see that this is the basal plane containing the atoms in it this is a 1, this is a 2, this is a 3. And now the 101 bar 2 twins forms in K 1 neeta 1 K 2 neeta 2 plane as explained in the previous class, where you see the K 1 plane can be plotted like this.

So, K 1 it is a 101 bar 2 type plane and then K 2 which is something like this right, that is also a 1 bar 012 type plane. So, you see that both these planes both these pyramidal planes are present in this hexagonal crystal structure in this fashion. If we look into these two planes in such a way in a two dimensional manner then it will look something like this.

So, if we look into this figure. If we look into this figure we will see that the this is this one is the K 1 plane which is 101 bar 2 this is the K 2 plane which is 1 bar 012 type plane and the angle between these two plane is 2 phi. If you see that the distance between these two plane is root 3a and how this root 3a comes we can show. Let me take the pen and if you look into this if we if I show you that ok. This is the you know the top view of the C axis. So, this is the C axis and we are seeing this distance which is basically what I am saying root of 3a. So, if you look into let me change the color of the pen to say blue or something. So, if we look if we draw a line these lines and this is the 112 bar 0 directions right. So, this is a, this is a the angle between this is 60 degrees this is 60 degrees.

So, the if this is say this is x this direction is x then x equal to a times sin of 60 degrees right that is equal to a times root 3 by 2, this whole distance is equal to 2 times x and therefore, this is equal to root 3a. So, that is how this is root 3a. Now, if we look into the angular relationship then let us say this the angular relationship between this axis and this axis is theta.

And the angular relationship between K 1 and K 2 is 2 phi, then you will see then that as per the total angles 2 phi plus theta plus theta should be equal to 180 degree for a triangle it is known. So, we get this equation. The second equation that we get is tan of theta that is this theta is equal to c by root 3a, which is also true. So, these two equations if we keep in mind, then we found out that if we try to find out the shear strain, the shear strain. In order to do this kind of twinning or to get this deformation in this twinning is if it is given by the capital S then it is equal to you know 2 times cot of 2 phi.

Now, if you want to derive the value of shear strain for the deformation twinning formation one can see the book of Hertzberg nearly in page number 105 210 the derivation for this shear strain is given. Now, if we derive further the value of S which is equal to 2 cot of 2 phi it becomes equal to 2 divided by tan of 2 phi, which is basically equal to from this equation 180 degree minus 2 theta.

Now, if we solve this we will get S that is the shear strain is equal to tan square theta minus 1 divided by tan theta. Now tan square theta as I said tan theta is equal to c by root 3a. So, we put the value of tan theta from this equation here and we get c by root 3a whole square minus 1 divided by c by root 3a. And so, if we solve it, it becomes S equal to c by a whole square minus 3 divided by root 3 times c by a right.

So, if we look into this equation you will find out that if c by a is greater than root 3 the shear strain is a positive right is positive and if c by a is less than root 3 then S is negative right from this equation. So, the sense of the shear strain for the 101 bar 2 101 bar 1 type extension twinning changes if c by a is greater than S or less than S, for c by a equal to S the shear strain is 0. So, such a condition is the condition where this 101 bar 2 101 bar 1 type extension twinning will not take place.

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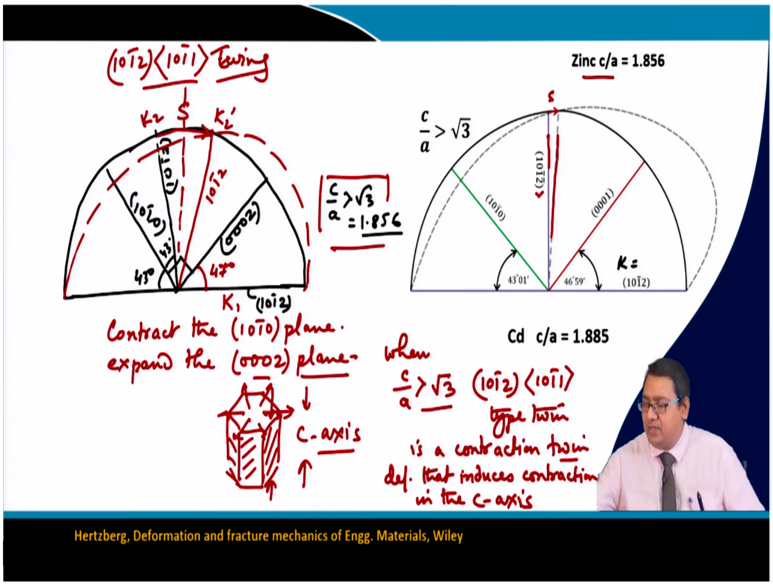

So, if we look into the hexagonal close packed material with c by a greater than root 3 you will find that the materials such as zinc or cadmium has a c by a of equal to 1.856 for zinc and 1.885 for cadmium both greater than root 3 the which is equal to 1.732. Now, under this situation if, let me take the pen.

Under this situation if K is equal to 101 bar 2 and let me draw simultaneously the same drawing. So, if this is 101 bar 2 plane which is you know perpendicular to the plane of this paper and this is the line showing neeta 1 say for example, and initially let us say that at an angle if c by a is greater than root 3. And now in this case is equal to 1.856 this is an example of zinc you can see that the angle at which 101 bar 0 is with respect to 101 bar 2 is ok give me a moment is an angle which is nearly 43 degrees.

So, if this is 101 bar 0 which is at an angle of 43 degrees to 101 bar 2 then the 0002 or the 001 will form at an angle of 90 degrees to 101 bar 2. So, this is the plane 002. So, this is the 101 bar 0 plane. Now another 101 bar 2 which is basically the K 2 will form at 43 degrees to 101 bar 1 and let us draw that and that will be somewhere here and this is another 101 bar 2 type plane.

Now, if we look into the initial material the material will without any strain into it will look something like this pardon my drawing and after a shear strain. Let me change the color of this pen let me change it to say red ok, and after a shear strain S the K 2 will move here and it will go somewhere here right. So, this is the new 101 bar 2 plane right. So, this is the drawing which shows the after a shear strain S the 101 bar 2 moves from this plane to this plane right. Now if we look closely to this situation that when 101 bar 2 101 bar 1 type extension twinning occurs and leads to a shear like this where the K 2 basically, shifts from here to K 2 dash where the K 1 remains same.

The angle at which 002 is there is basically a angle you see 43 and 43 plus 90 a total angle of 180 degree it will come out to be equal to something around you know 47 degrees. So, if we see that the shear strain is pushing the K 2 plane which is at an angle lower than 90 degree from the you see 101 bar 2 in the direction in the plane where 101 bar plane or the prismatic plane, planes direction.

So, with the shear the material will experience you know stress which will be such that; that it will you see contract the 101 bar 0 plane and expand the 0002 plane right. When such a situation appears the such a situation appears when c by a is greater than root 3 and this is the situation for zinc where the 002 plane is expanded and the 101 bar 0 plane is contracted. Now, if we look into an hexagonal close packed structure what does it mean, you see this means that the deformation which induced this 101 bar 2 101 bar 1 type. You know twinning is basically expanding is trying to expand the you know basal plane right whereas, it is trying to contract along the you see the 101 bar 0 plane; that means, these planes.

These planes are basically 101 bar 0; that means, the contraction is taking place along the C axis this indicate that when c by a is greater than root 3 then 101 bar 2 101 bar 1 type twin is a contraction twin because it occurs when deformation that induces contraction in the C axis.

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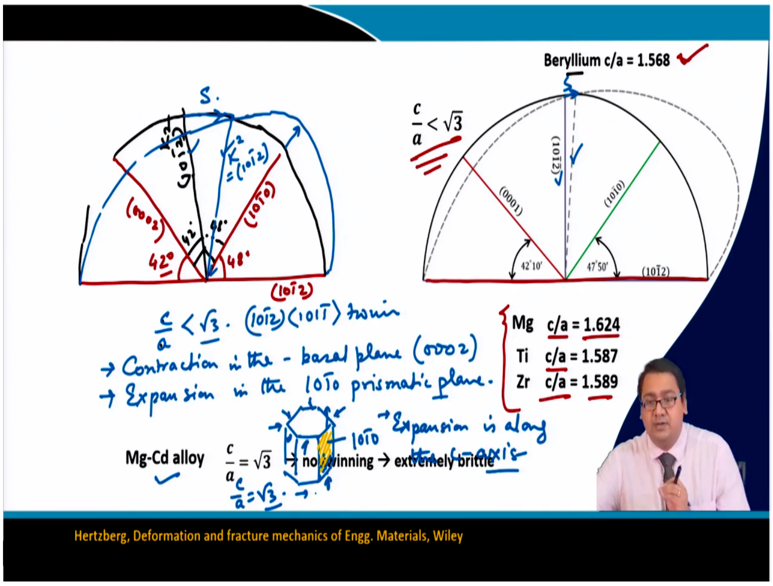

Now, if we look into the situation where c by a is less than root 3. Now, under that situation let us take the example of beryllium which has a c by a ratio of 1.568. Apart from that if you look the c by a ratio of magnesium, titanium, zirconium, magnesium with a c by a ratio of 1.624, titanium with a c by a ratio of 1.587, zirconium with a c by a ratio of 1.589 they all have c by a ratio less than 1.732 that is less than root 3. So, under that situation what will happen, if this is the K 1 plane. So, let me draw it if this is the K 1 plane this is 101 bar 2 and this remains fixed during the process and in the case of beryllium with c by a ratio 1.568 the angle between the 101 bar 2 plane and the 001. You see an acute angle which is nearly 42 degrees and this is opposite of what happened in case of zinc.

So, the angle between 101 bar 2 and 101 bar 1 is basically 48 degrees nearly 48 degrees which is the angle between 101 bar 2 and 101 bar 0. Now, definitely this is the case where, 002 and 101 bar 0 will always maintain the 90 degree configuration and therefore, the K 2 plane which is another 101 bar 2 say it is 1 bar 012 forms at say 42 degree again from 0002, right. So, this will be something like this it will form somewhere here. So, this is one 101 bar 2 another this is the K 2 plane right.

Or one can say at that this forms at 48 degrees to 101 bar 0. So, this angle is also 48 degrees and this is the same. So, under a non-strained condition if the situation is like this under a non-strain condition if the plane are not deformed and in this situation. Then if you see that when there is a stress acted because of the deformation then the stress will change the K 2 from here to you see here right.

So, the new K 2, K 2 dash which is again another 101 bar 2 will form after a shear stresses and this shear stress is shifting. So, this is the S which is shifting this initial 101 bar 2 to this. Now, this will lead to enforce you know this is enforced by deformation right. So, this deformation and the you know displacement of the 101 bar 2 plane from this position to this position will lead to the you know change in the stress straight of the material and this will happen only if there is you know tensile along the 101 bar 0 x plane and you know contraction in the 0002 plane.

So, in this case when c by a ratio is less than root 3 the formation of 101 bar 2 101 bar 1 type twins leads to you know contraction in the you know basal plane that is the 0002 plane and expansion in the 101 bar 0 type prismatic plane right. And let us look again into the hexagonal crystal structure what does it mean. So, if this is an hexagonal close packed structure, this is the structure of that material and we are saying that it is expanding along 101 bar 0. So, let me see. So, if these are the sorry it is changing with the whole color does not matter, let me get back to the same color.

So, if this is the 101 bar 0 type prismatic plane then there is expansion of this prismatic plane right and then there is contraction of the basal plane right, such a situation will only occur together if the expansion is along the C axis. So, 101 bar 2 101 bar 1 twinning is an extension twinning for beryllium, magnesium, titanium, zirconium which has C axis less than root 3.

In case of you see; that means, that whenever the material with c by a ratio greater than root 3 is there a compression along C axis will produce 101 bar 2 101 bar 1 type twins. And that becomes a contraction twinning whereas, in case of these materials magnesium, titanium, zirconium and beryllium and tension or an extension along the C axis will produce the same twin and therefore, it becomes an extension twin in this case.

Now, if we look in for magnesium cadmium alloy a magnesium cadmium alloy has a c by a ratio equal to root 3 exactly root 3, under that condition 101 bar 2 101 bar 1 twinning does not occur. And thereby magnesium cadmium alloy is extremely brittle, let us take these information and look into a small work on titanium.

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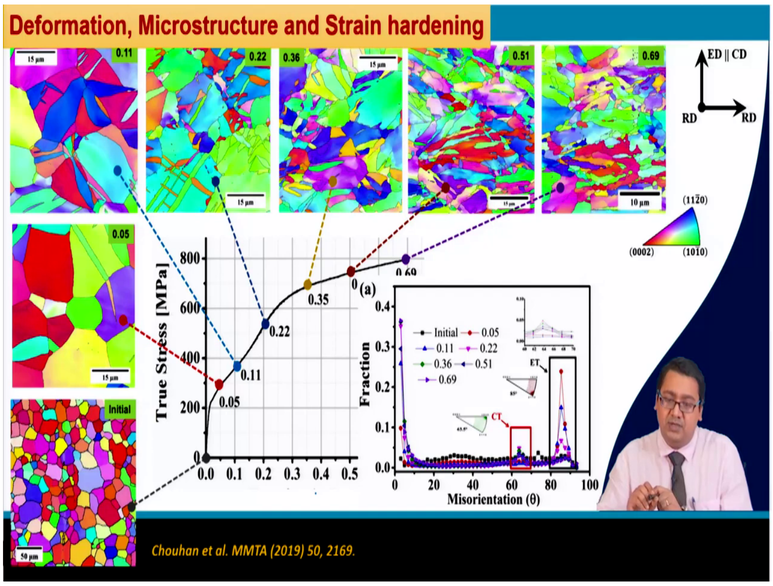

And this is the work where we will show that how the material titanium behaved when it is compressed perpendicular to the C axis. You see that we have taken an extruded material, let me take the laser pointer, the material is extruded and we are looking it from one of the radial direction.

So, we can see the arrows where we can see that the upper side the vertical arrow shows ED which means the extrusion direction and we are looking in one of the side one of the radial direction out of this. So, the horizontal line shows the radial direction RD and this is also the radial direction, the compression has taken place along the extrusion direction.

Now an extruded titanium has it is C axis you know perpendicular to the extrusion direction. So, if there are many grains you can see the red grains are there the red grains have their C axis. So, this is the initial microstructure the red grain has the C axis you see coming out of the screen whereas, the green or the blue grain have their C axis you know horizontal to the screen.

Now, there are other grains which have C axis at an angle but that all of the C axis are perpendicular to the vertical direction which is the extrusion direction. So, when the material is compressed along the extrusion direction, we are compressing the material in such a way that the C axis is getting extended. So, there will be a situation where extension twinning will starts to develop.

So, after a strain of 0.05 we can see that extension twins starts to develop and this is the strain hardening curve the true stress true strain curve where we can see that at this position this is the position where this microstructure has developed. And thereafter after a strain of 0.11 you will see that a lots of extension twin and even large extension twins have started to develop in the material.

If we look into the strain hardening curve from 0.05 strain true strain to 0.11 true strain from up to a true strain of 0.22 you can see a large fraction of extension twins not only have developed it has changed the texture of the material you know significantly. And this we can see by looking into this inverse pole figure you know color key code where we can see that initially the grains were having the colors and now it is little different.

But ok, we cannot say much of this change in texture with respect to inverse pole figure maps when we see it, but at least we can talk about the microstructure evolution. Now, we see that up to 0.05 to 0.11 and 0.22 true strain there is a lot of extension twin develops in developed in the microstructure. So, the when this extension twin develops in the microstructure if we look into the misorientation angle distribution function we can see that there is from 0.05 to 0.11 to 0.22. Strain there is a large fraction of you know misorientation angle forming at nearly 85 degrees, now this is the angle where 101 bar 2 101 bar 1 type extension twins basically develop.

And if we look into it you will see this is really extremely small inverse pole figure map this is an angular inverse pole figure map which is angled at 85 degree. So, this is an 85 degree angular inverse pole figure which shows that at 85 degree the angle at which these boundaries are forming are you know sorry the axis at which these boundaries are forming are 112 bar 0.

So, this is the specific axis angle pair that is 1 bar 112 bar 0 at 85 degrees which relates the you know special boundaries or the coincident side lattice boundaries that forms during an extension twinning. Now you see that whenever the extension twins develop the stress strain curves shows a sigmoidal shape, the sigmoidal shape of the stress strain curve indicates that the strain-hardening rate is increasing rather than decreasing while the deformation process is going on.

So, if you look into this part of the material we see that extension twin occurs from 0.05 to 0.1 to 0.22 strain and this leads to strain hardening a sigmoidal shape in the microstructure and an increase in the strain hardening rate. Thereby what happened, I am not going extreme details to show all the results and analysis, but there by with the increase in strain contraction twins starts to develop inside this extension twin you know domains. Now, up to 0.22 most of the microstructure is basically covered with extension twin no part of parent microstructure will remain and then contraction twin will develop at the same time slip activities and involvement of you know ternary extension twin formation inside the contraction twins will lead to further microstructural refinement.

And thus when a compression is taking place perpendicular to the C axis first extension twin develops and then contraction twin develop and then a small fraction of contraction twin also develop a ternary extension twin and side by side simultaneously slip deformation also takes place refining the microstructure. We can see that contraction twins basically develops at nearly 62 degrees of misorientation angle.

And in order to see whether this is the contraction twinning if we look into the 63.5 degree you know inverse pole figure angular inverse pole figure we see that a high fraction of grain boundaries have their axis at 101 bar 0, which indicates that this is contraction twinning. So, this unusual sigmoidal shape curve occurs, because of the formation of extension twinning and we call it stage 2 of deformation, where it is known as textural hardening. As we have seen in the last few slides that when 101 bar 2 101 bar 1 type extension twins develop the rotation of the HCP crystal structure occurs at nearly by 85 degrees.

And when the HCP structure if it is something like this with the C axis in this direction and it rotates and becomes like this with C axis horizontal then there is a textural hardening this microstructure this sorry this with the C axis horizontal. And a compression like this is a softer oriented you know hexagonal material, whereas, with C axis like this the material become texturally hard the Taylor factor of the material becomes very high under that situation. So, texturally harden texture hardening leads to the formation of sigmoidal shape and a positive strain hardening rate.

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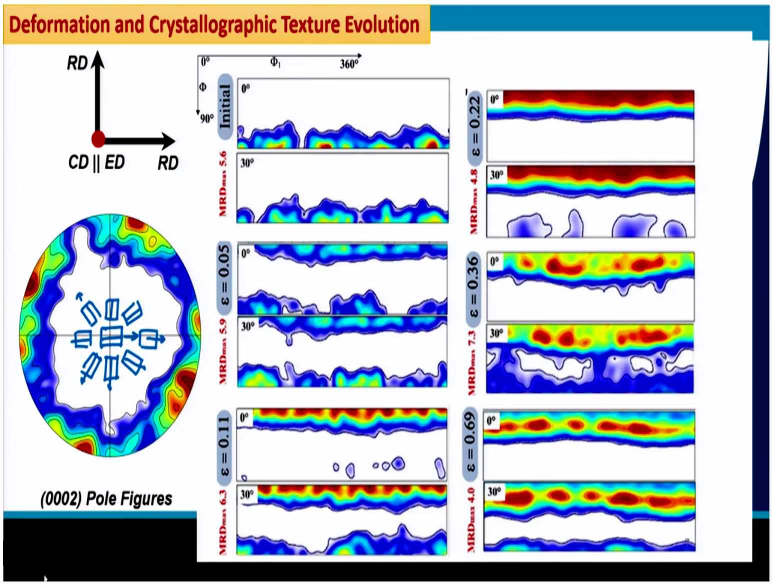

We will look into this in the next slide too if we look into the development of you know pole figures and orientation distribution function during this deformation. The reference is reference direction is CD now coming out of the screen, RD is here and here. And you see the initial material contains you know the C axis in the periphery of the pole figure and this is the 0002 pole figure.

If we if I try to show you that how this C axis is basically forming this C axis is basically forming in this manner you know so, the C axis is forming in this direction something like this ok. So, in this way it throughout the C axis is developing as I am giving the arrow right and this is the initial material where the C axis basically develops like this, let me rub this down the eraser.

So, as I was saying that this is the situation of the initial material the initial material when we look into the 0002 pole figure will look like the intensity is only at the periphery of the pole figure. The same can be observed in the phi 2 equal to 0 and 30 degree section as I said in hexagonal close packed material phi 2 equal to 0 and 30 degree section is only shown. So, the intensity of this initial texture fiber forms at phi equal to 90 degree and from phi 1 equal to 0 to 360 degree you can see this. So, it is a continuous fiber.

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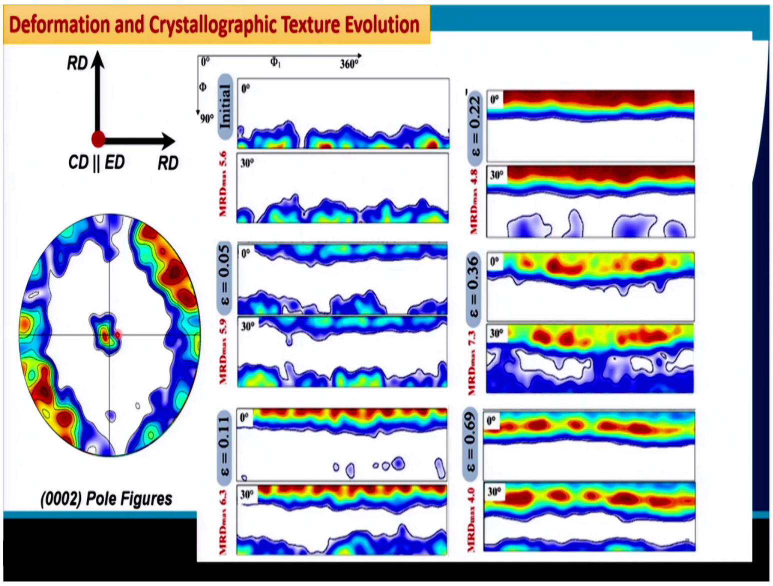

Now, once the deformation takes place you can see that a small intensity develops at the center. And this intensity is also reflected and this is after the strain of 0.05 is also reflected from the intensity presence at phi equal to 0 and phi 1 equal to 0 to 360 at both phi 2 equal to 0 and phi 2 equal to 30 degree which is this one right. So, this happens because of the formation of the extension twinning which is 101 bar 2 101 bar 1 for this case of titanium.

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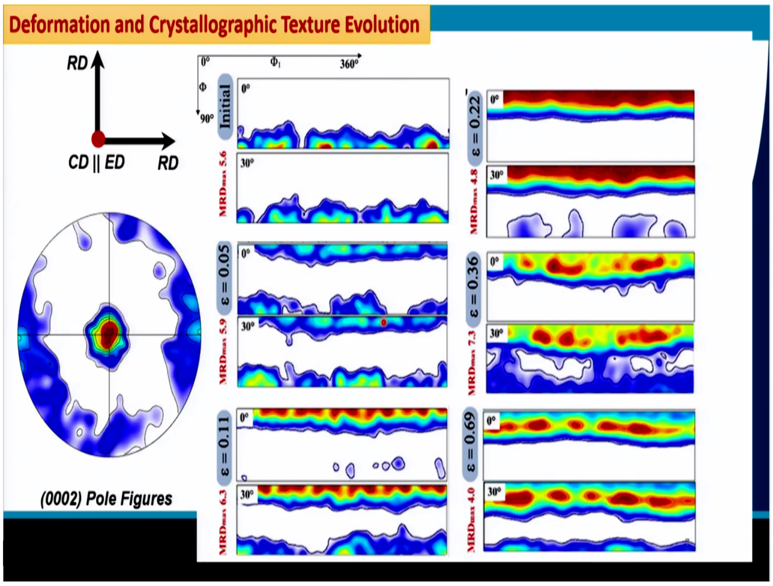

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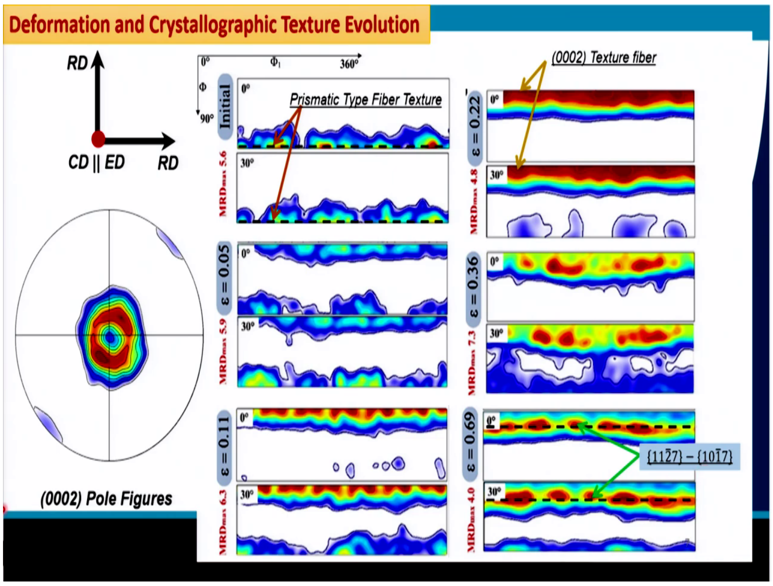

Now, with the deformation further the intensity of this extension twin increases whereas, the intensity of the parent grains start to decrease, at a strain of 0.22. You see that there is no presence of parent grain or a very meager presence of parent grain is present at phi 2 equal to 0 and 30 degree section, you can see this more clearly using the 002 pole figure where there is no intensity of the parent grain texture present.

At this moment one can say that 90 percent 95 percent of the microstructure has been converted into deformation induced extension twinning where the C axis is now rotated by nearly 85 degrees and now which was initially here at the periphery is now at the center. At as the deformation progresses you know from 0.22 to 0.36 to 0.51 to 0.69 the development of texture fiber from the center that is exactly at the CD.

It forms a little away from it and with a little spread and this usually happens in case of titanium because it is c by a ratio is very less 1.56. And therefore, inclusion of deformation induced you know contraction twin along with prismatic, basal and pyramidal slip activity forms various kinds of means reaction kind reaction in a sense that slip induced deformation twin induced deformation.

And leading to formation of you see how we say a 112 bar 7 101 bar 7 type of texture fiber and initial the initial material if you look into it is known as the prismatic type fiber texture. When the texture forms at the compression direction CD it is exactly 0002 texture fiber and when it comes down a little it becomes h k i l type 112 bar 7 101 bar 7 type. And this we will also explain in detail in the next lecture.

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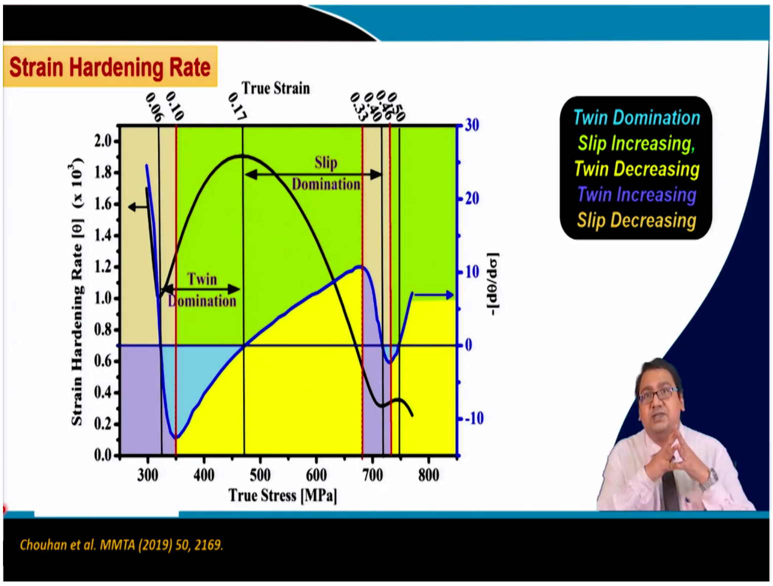

So, if we look into this situation and if we look into this strain hardening rate for the same material we will see that the strain hardening rate of this material shows a story shows the story more in more detail. So, the black curve you see gives the strain hardening rate that is d sigma by d epsilon whereas, the blue curve this blue curve shows the double derivative of the strain hardening rate, which is d sigma sorry d theta by d sigma.

From this we can see that there are mainly two types of twin dominated the sorry two types of domination or zones that is a slip dominated zone and twin dominated zone which is basically governing this deformation behavior. The stage 2 is the twin dominated zone which is from 0.06 to 0.17 where there is a large fraction of 101 bar 2 101 bar 1 type twins forms which leads to the increase in the strain hardening rate whereas, while the slip dominated zone is here which decreases the you know strain hardening rate.

We can see that the formation of you see the extension twin which is 101 bar 2 101 bar 1 here and here and these two regions are basically the extension twin dominator zone. Whereas, in this region or in the green region this is you know slip increasing. You see the yellow region is considered to be the twin decreasing region whereas, this portion is a slip dominated zone where the extension twin is not taking place, but prismatic, basal, pyramidal, slip is taking place along with contraction twinning inside the previously formed extension twin domains.

So, this is one of a kind of a case study that I like to show you that we did using the information of the texture and on the hexagonal close packed material.

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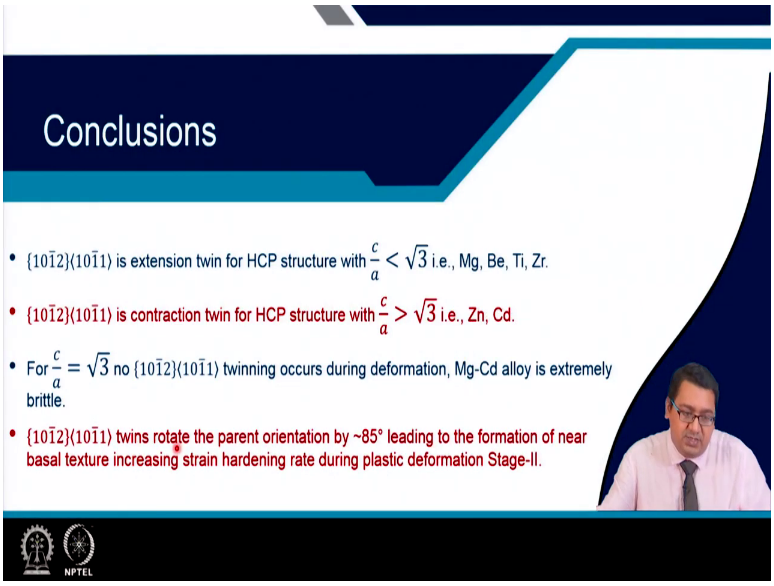

So, we can conclude from this lecture that 101 bar 2 101 bar 1 is an extension twin for hexagonal close packed structured material with c by a ratio less than root 3 that is magnesium, beryllium, titanium, zirconium. Then second conclusion is that 101 bar 2 101 bar 1 is a contraction twin for HCP structured material with c by a ratio greater than root 3, that is zinc cadmium etcetera.

For c by a ratio equal to root 3 no 101 bar 2 101 bar 1 type twins will take place during the deformation the material will be extremely brittle. An example of this material is magnesium cadmium. 101 bar 2 101 bar twins rotate the parent orientation by 85 degree leading to the formation of near basal texture, which increases the strain hardening rate during plastic deformation and this is shown by stage 2 of deformation in a paper a very latest paper in 2009 by Devesh Kumar Chouhan the reference is given in the previous slides.

Thank you so much for this class.