Texture in Materials
Prof. Somjeet Biswas
Department of Metallurgical and Materials Engineering
Indian Institute of Technology, Kharagpur

Module - 11
Theory of annealing texture evolution
Lecture - 55
Dynamic Recrystallization and Recrystallization Texture

Good afternoon everyone and this is the 2nd lecture of module 11, Theory of annealing texture evolution. This is lecture number 55 and where we will be learning about Dynamic Recrystallization initially and then we will go to understand Recrystallization Texture.

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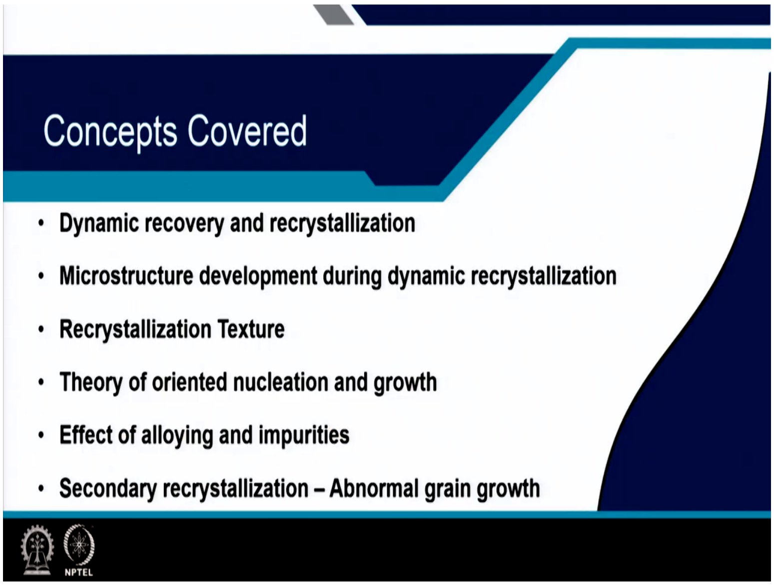

So, the concepts that will be covered in this lecture will be dynamic recovery and dynamic recrystallization then, the microstructure development that occurs during dynamic recrystallization the mechanisms of it then we will go and discuss what are the different types of texture that obtained on recrystallization of FCC, BCC and HCP material.

Then the theory of oriented nucleation and the theory of oriented growth during recrystallization will be you know studied. Following the effect of alloying and impurities on the recrystallization behavior and finally, secondary recrystallization and

abnormal grain growth.

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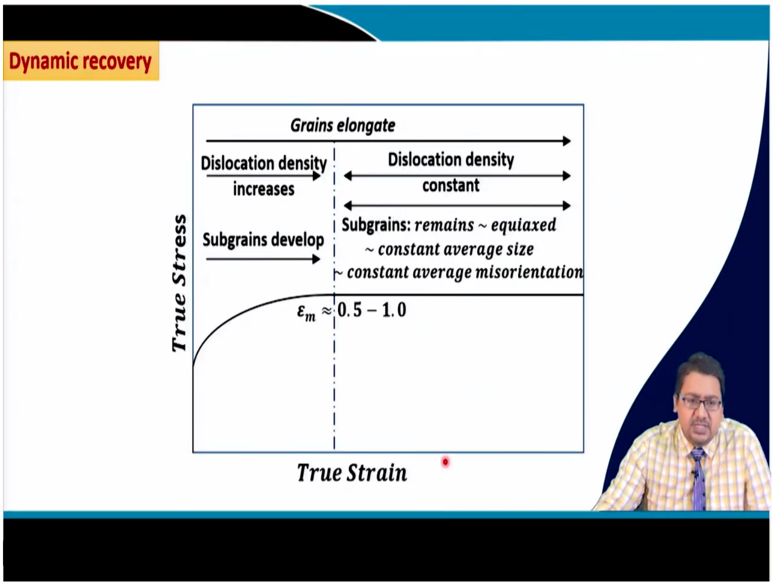

So, let us start with understanding that how recovery takes place during deformation that is why we call it dynamic recovery processes and how the flow curve that is the true stress true strain curves looks like during the dynamic recovery of a material. So, here is a curve in the x axis it is the true strain in the y axis it is the true stress as usual and this curve is known as the flow stress curve right.

Now, after the you know elastic region, while the plastic region starts the strain hardening of the material makes the curve makes the flow curve to grow something like this. Here you will see that the strain hardening rate is continuously decreasing while the strain is increasing right and that is why the curve is slowly going and becoming you know horizontal.

During this region while the deformation is going on let us say that it is a tensile deformation for example, and usually this situation will occur during large plastic deformation scenario like rolling, extrusion, drawing or any other processes right. And during this tensile deformation if we look into it what will happen? That deformation will lead to generate more and more dislocations in the material and these dislocations while they are generating.

They will you know interact with each other to annihilate if they are unlike each other and they will form dislocation arrays and will start to develop dense dislocation walls to form cells and subgrain type of structure while the dislocation density will keep on increasing during the deformation.

Such a situation exist only when that during the deformation the amount of dislocations that are generated are much larger than that which is annihilated due to the formation of cell and subgrain structure and due to the process of dynamic recovery. Such a situation the strain hardening of the material occurs and the because of the increase in the dislocation density right in this region.

And therefore, as the dislocation density increases and increases further the strain hardening rate decreases and decreases right. So, there is an increase in strain hardening in this region. But after a certain strain say a moderate strain of 0.5 to 1, what will happen? That the amount of dislocations which is generated and the amount of dislocation due which annihilates or rearranges to form dense dislocation walls or cell and sub grain structure becomes constant.

That is the amount of dislocations which are generated due to the deformation and the amount of dislocation that is consumed due to dynamic recrystallization sorry dynamic recovery becomes same and therefore, there is no further increase in the dislocation density. So, in this region the dislocation density becomes constant after a certain strain certain moderate strain such a situation is a situation where the strain hardening becomes constant and the strain hardening rate becomes 0 right.

So, in this situation which is known to be dynamic recovery has a horizontal stress strain curve where the stress true stress remains constant the sub grain remains equiaxed, it always keeps a constant average sub grain size. And the misorientation of the sub grains remains in an average same that is constant. So, this is dynamic recovery.

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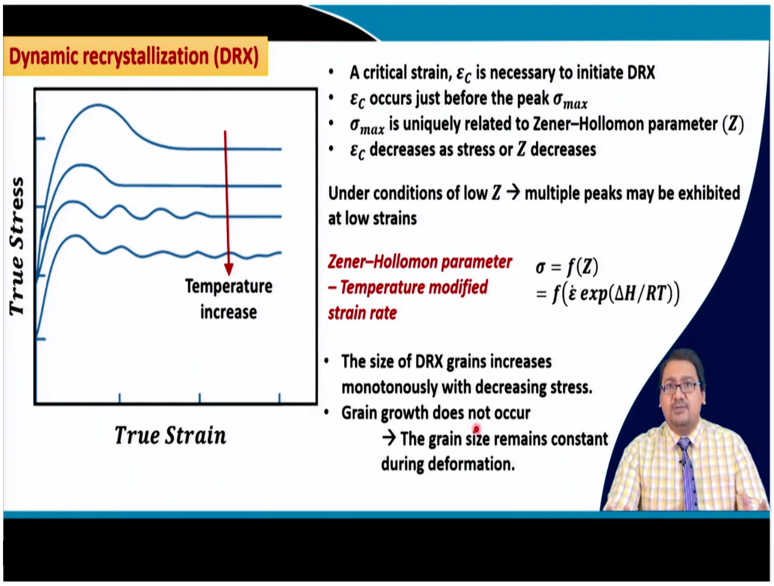

On the other hand during the deformation process, if the deformation is under warm condition or for certain material a larger amount of deformation for those which have low recrystallization temperature could be given at room temperature. Say for example, the true stress true strain curve or the flow curve show is looks something like this if we look into the first curve it looks something like this with a hump. The presence of this hump indicates that there is a dynamic recrystallization going on in this material.

Such a hump will occur when the amount of dislocation density present in the material particularly increases as I said that the deformation is not homogeneous in a poly crystalline microstructure. So, the dislocation density increases in certain high strain energy region to a certain level so that it could not sustain.

And new nucleation of recrystallization may starts to occur at those region and these regions should be first the grain boundary triple junctions and followed by grain boundary regions which are highly strained due to the deformation. Under such situation what happens that once this situation comes that the amount of dislocation density in different different high strain energy regions becomes so high that new recrystallized grains and having no dislocations inside it develops.

And such a situation lowers the dislocation density of the entire material leading to lowering down the stress during the means during this you know for example, a tensile test situation. Such a situation we will occur and if the temperature of this test experiment increases with the increase in temperature.

You will see that initially at lower temperature there is only 1 hump and with the increase in the temperature the number of humps becomes very large. Because this is a situation where the deformation is taking place there is an increase in the dislocation density forming of dynamically recrystallized grains lowering the dislocation density then further deformation leading to the increase in dislocation density again.

And then continuous lowering of dislocation due to another set of recrystallization and this goes on happen again and again at higher and higher temperature for certain materials with particularly say for example, in case of FCC high stacking fault energy materials. And this is a situation that can be explained in terms of stress and Zener Hollomon parameter.

Let us say that this situation exist at a critical strain say epsilon C which is necessary to initiate the DRX, the critical strain occurs just before the sigma maximum. And the sigma maximum is uniquely related to Zener Hollomon parameter which is denoted by z in our case. So, as the temperature is increased the strain required for this dynamic recrystallization process decreases, as this leads to the decrease in the stress and thereby the Zener Hollomon parameter.

So, under the condition of low Z multiple peaks are observed at lower strains right. So, just to give you that what is Zener Hollomon parameter you go back and read the fundamentals of it that it is a temperature modified strain rate and is a function of you know sigma. So, sigma is can be said as a function of Z so, as Z reduces the sigma reduces. So, z is basically a function of strain rate exponential delta H by RT right.

Now, the size of the DRX grains increases monotonously with the decrease in the stress grain growth does not occur and the grain size remains constant during the deformation process.

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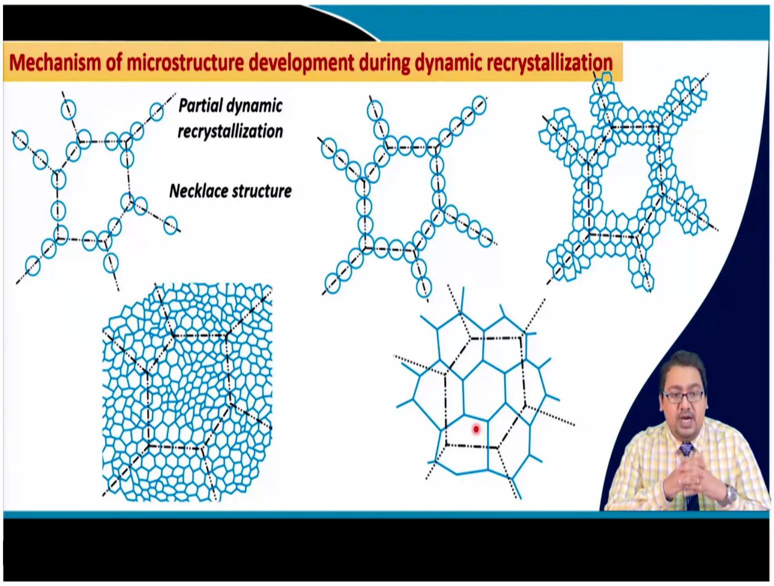

Now, if we look into the mechanism that occur during dynamic recrystallization that is the mechanism of the evolution of the microstructure. One can see that if we look into the first figure as I am showing using my pointer. The grain or the grains that are present in the microstructure they elongate.

And while they elongate during the deformation at highly stressed region small small grains equiaxed grains seem to develop and such small grains developing in the high strained region triple junctions and grain boundaries in the microstructure in such a way looks like that partial dynamic recrystallization is taking place.

Such a situation where this kind of discontinuous nucleation takes place is known as discontinuous dynamic recrystallization. While if we are unable to look into the microstructure at this stage of deformation and looks at a certain higher strain then what we will find that there are grains present throughout the grain boundaries as a necklace type of structure. Such a structure is observed over the whole boundary then such a situation may be considered as a continuous dynamic recrystallization process.

With the increase in the amount of strain the deformed grains starts to elongate and deform and deform further. Thus further increasing this dynamic recrystallization processes and the grain boundary area containing this dynamically recrystallized grains become thicker and thicker hitting away the initially deforming grains which are getting elongated and elongated with the deformation.

Such a situation at which such kind of situation will be observed at a little higher strain than this one and this is still a continuous dynamic recrystallization process having a necklace kind of a structure, now its a thick necklace right. Now, under this kind of condition where the deformation may exist further and a situation may come in such a way that the grains may become equiaxed as a whole and the initial deforming elongated you know grain is totally gone.

Such a situation is usually carried out during means we usually use it to you know engineer the microstructure of the material to obtain ultrafine grain structure by modifying the thermo mechanical situation temperature and the amount of loading condition or the plastic deformation that is given to the material.

Such a material when kept under a temperature so that it recrystallizes. It forms you know larger grains of equiaxed type irrespective of the initial cold rolled microstructural condition. And now we have an idea about it and how this thing works because we have studied in the last lecture 2 similar condition for the static annealing condition. So, the final what we have shown is for the static annealing condition.

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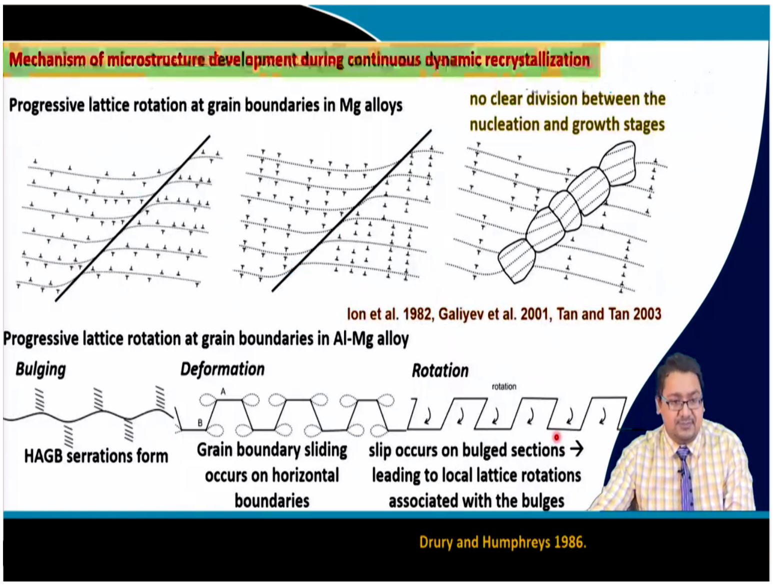

Now, the mechanism of developing of the microstructure is called discontinuous dynamic recrystallization or continuous dynamic recrystallization. By the microstructural feature we observe at a particular after a particular deformation or after a particular strain Now, there are many research work on this issue and it was found out that most of the cases the microstructural development during dynamic recrystallization could be shown by the situation of progressive lattice rotation of the grain boundaries.

Ion et al Galiyev and tan and tan they all separately and a different situation, ion in 1982 Galiyev in 2001 Tan and Tan in 2003 showed that in case of magnesium alloys single phase magnesium alloys there is progressive lattice rotation because of the absence of five independent slip systems.

And this progressive lattice rotation leads to formation of equiaxed grains in the grain boundary and it does not have any clear indication of nucleation and growth stages and so, this is a process of continuous dynamic recrystallization. Here we will show you that if this is the initial state of the microstructure where a grain boundary is being shown there are a presence of large amount of statistically stored dislocation in both sides of the microstructure.

And during the process of deformation these statistically stored dislocations they arrange themselves in a fashion so, that the unlike dislocation annihilate and the like dislocation becomes dislocation array near the grain boundary. And such a situation may lead through the formation of small equiaxed strains at the boundaries where there is large amount of these dislocation arrays present.

Now, this is this situation exist because the well there is a deformation the grain boundary if it is like this is try to slightly rotate. Say for example, I am showing by the pointer that this part of the boundary is tried to being rotated in this direction and this part of the boundary is try to be rotated in this direction.

Leading this kind of a rotation cannot take place because there is presence of grain in both the side and therefore, it could lead to serration bulging and strain induced boundary migration kind of phenomena leading to the formation of this kind of you know equiaxed grains in the grain boundary without any division between nucleation and growth stages.

Showing that this is continuous dynamic recrystallization phenomena right and we will discuss about this in the next lecture in a little detail where we will look into a case study of dynamic recrystallization in magnesium alloys. Drury and Humphrey in 1986 also showed progressive lattice rotation behavior in case of aluminum magnesium alloy and as we know aluminium magnesium alloys and high stacking fault energy material poly crystalline material.

They showed that because of the progressive lattice rotation there is bulging and the bulging occurs in the same way as the SIBM mechanism strain induced boundary migration mechanism where the bulged part of the grain boundary is towards the high dislocation region right.

So, say for example, a microstructure with two grains and this is a boundary and the grain which is above is say grain 1 and the grain which is below is say grain 2. As the deformation is not homogeneous all over the deformation is heterogeneous. Say the dislocation density in this area of grain 1 is higher these areas are higher. And in these areas of grain 2 the dislocation density is lower.

Whereas, in these areas of grain 2 this and this the dislocation density is higher and in these areas of grain 1 the dislocation density is lower. Under the situation of deformation the serration of the grain boundaries will take place because the grain boundary will shift towards the direction of the high dislocation region.

And thereby there will be a formation of bulging and then the situation will become something like this as shown where my pointer is right. And such a situation we will exist and there is horizontal boundaries they are said to do grain boundary sliding and thus the situation will exist where this boundaries will become something like this. And this will occur due to you know rotation of the crystals in between these boundaries because by the phenomena of slip.

So, slip occurs after this bulging process on this bulged section leading to local lattice rotation associated with the bulging. So, these are the mechanism of you know dynamic recrystallization and continuous dynamic recrystallization that occurs in poly crystalline material.

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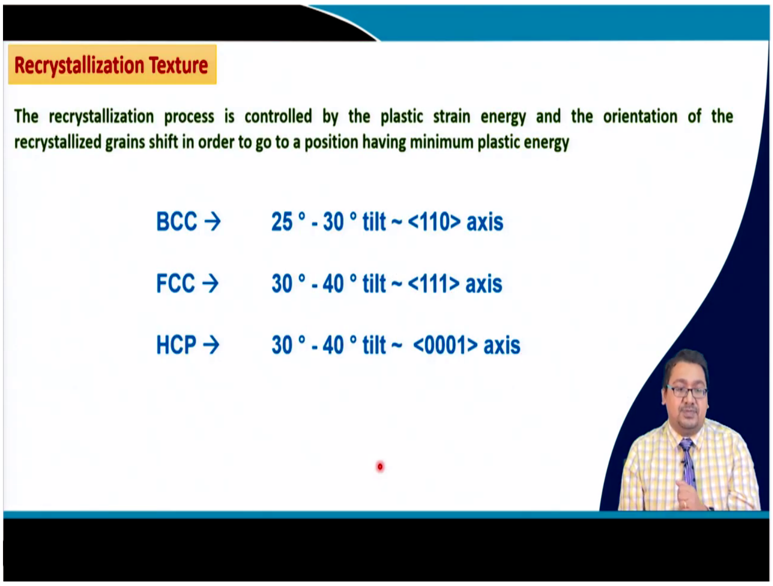

Now, we will come to recrystallization texture. The recrystallization process is controlled by plastic strain energy. So, we deform a material we introduce a lot of plastic strain in the material and so, the energy of the material is very high in the physical form which is present physically in form of dislocations in the material. Therefore, by increase in the dislocation density of the material also in terms of increase in the dislocation arrays and also in terms of increase in the grain boundary area right.

So, the orientation of the deformed microstructure will be related to the strain energy of the material right. Now, when the material is recrystallization the orientation of the recrystallized grains will be shifted to a certain position which should have the lower or the minimum possible plastic strain energy right.

So, in case of body centered cubic material it was found out that a tilt of 25 to 30 degrees usually takes place along the 110 axis. We know there are 6 110 axis if we add plus and minus then there are 12 110 axis. So, there could be a rotation of 25 to 30 degree tilt rotation along this axis. In case of FCC you see it was found out that 30 degree to 40 degree tilt is usually observed in about 11 axis and in we know that there are 4 111 axis.

So, 8 plus and minus 111 axis out of which it is said that at least 6 of them could be activated right. In case of hexagonal close packed material it was found that 30 to 40 degree tilt along the 0001 axis could be observed.

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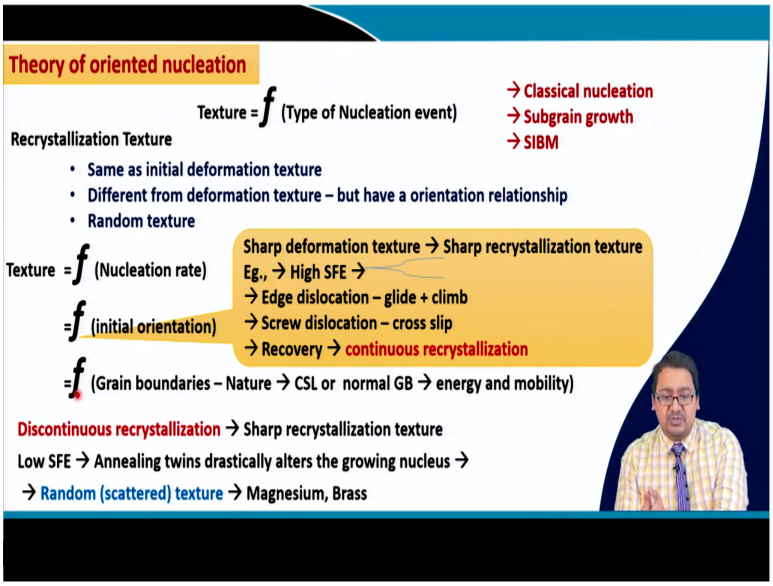

Now, there are two theory of recrystallization texture the first theory is the theory of oriented nucleation. The theory of oriented nucleation states that the texture of the recrystallized material is a function of the nucleation event. And as we have discussed in the earlier lecture that the nucleation event could be the classic Volmer Becker nucleation or the sub grain growth mechanism or the strain induced boundary migration mechanism.

Leading to nucleation of a certain grains with certain texture and that decides the texture of the recrystallized material because as I said the recrystallized material or the recrystallized grains has a texture which is related to the minimum plastic energy situation.

Now, the recrystallization texture that is observed in these case depending upon the type of material materials property materials characteristics may be same as the initial deformation texture, may be different from the deformation texture, but having an orientation relationship that I showed in the last slide.

And it may also have random texture right. So, there are three possibilities. Now, texture as I said is a function of the nucleation event; that means the nucleation rate right. So, higher nucleation rate of a certain type of component having minimum plastic energy so the texture will tend to be like that. Of course, the texture will be the function of initial orientation.

Now, the initial orientation of the material we if it is in a largely deformed state for a certain material will have a certain deformation texture. If that texture component is very strong, then the recrystallized texture will be rotated along that particular axis about that particular angle to get the minimum plastic energy so, a strong initial orientation will give a strong initial texture right.

Say for example, a sharp deformation texture will give a sharp recrystallization texture in case of high SFE material, because the high SFE material has a lower distance between the dislocation partial. Say for example, FCC material 110 splits into 112 types of dislocations and these partials are closer together. And therefore, these materials are easier to cross slip of particularly screw dislocation which simultaneously will lead to climb of edge dislocation and then there will be recovery processes associated with it.

So, the recrystallized structure will be in relation to the deformed structure, because such a situation will lead to you know such initial orientation will affect the formation of recrystallized texture by the process mostly which is known as continuous recrystallization.

Now, texture is also the function of grain boundary the nature of grain boundary. So, either the grain boundary is normal grain boundaries right random high angle grain boundaries or if these grain boundaries are coincident site lattice boundaries. So, the energy and the mobility of the grain boundary will affect the recrystallization texture evolution and this will also depend upon the say stacking fault energy.

Now, higher stacking fault energy there will be initially no CSL boundaries there will be no restriction of recovery. And thus the texture formation will be different whereas, in case of say for example, low stacking fault energy material. Annealing twins drastically alter the growing nucleus because of the presence of CSL boundaries present due to deformation induced twinning.

So, in case of magnesium and brass sometimes random or scattered textures are also observed. Now, this does not mean that discontinuous recrystallization processes cannot produce sharp texture. There are situations where discontinuous nucleation lead also to sharp recrystallization texture right.

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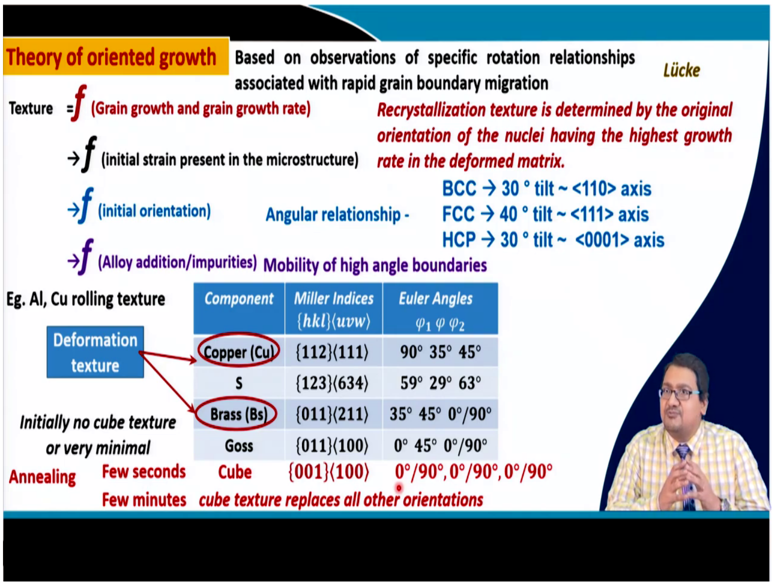

So, another theory of recrystallization is the theory of oriented growth. So, it is said that the recrystallization process is not controlled by the theory of nucleation, but it is controlled by the theory of oriented growth. So, nucleation of all possible texture components occur in the material after the deformation, but those orientations which grows and could be observed in the microstructure has a volume fraction in the microstructure are having certain texture.

And because they are of the preferred texture, which grow, which leads to the theory of oriented growth for recrystallization. So, based on the observation of specific rotation relationship associated with rapid grain boundary migration by lucke. So, you see recrystallization texture as I said is determined by the original orientation of the nuclei having the highest growth rate in the deformed matrix right.

So, texture is a function of grain growth and grain growth rate. So, those nucleus which grows right at a higher rate they are only determined factor for recrystallized texture. The second thing is the function of initial strain present in the microstructure. So, as you I said that the larger initial strain in the microstructure the formation of newly formed nucleus or the newly or the initiation of recrystallization without any nucleation or growth stages are more if the deformation strain is more.

Such a situation where there is no deviation of nucleus formation of nucleus and the growth stages is basically related to the theory of oriented growth right. Secondly the texture is a function of initial orientation. So, as I said that of course, the angular relationship of BCC FCC and HCP which is 30 degree tilt about 110 40 degree tilt along 111 30 degree tilt along

001 axis is admissible in this case. So, the fourth one is the presence of alloy addition or impurities.

So, you see addition of alloys whether the alloys are you know solid solution alloys or you know presents in form present in form of you know second phase precipitates or dispersed side. So, the mobility of high angle grain boundaries will alter right and even you see the presence of these alloys will lead to alloying additions will lead to change the stacking fault energy of the material. And thus may change the dynamic or the static recrystallization mechanism by altering the grain boundary mobility right.

Say for example, about the how the theory of oriented growth is actually occurring say for example, the aluminium copper rolling texture the components that we have seen is the copper component, the S component, brass component and the gauss component usually form after a cold rolling or the warm rolling.

The most deformation texture are basically copper texture and the brass texture right and it depends upon various alloying right not considering high or low stacking fault energy, but a medium stacking fault energy material where the brass component is also coming. Now, when the material is annealed what will happen that once it is annealed for a few seconds cube texture will start to initiate the cube texture which is 100001 type of texture will form at Euler angle 000 90 90 90 positions.

And as explained in few lectures before you can go and see that how and where the cube textures are generated. And once it is anneal for a few minutes the whole microstructure is replaced by grains having cube texture components. So, it can be said that even though there are presence of copper, S, brass, Goss component initially and the cube texture was entirely absent.

So, cube texture formed by the rotation of 40 degree along 111 because this is the case of FCC material and then preferential cube texture developed and it grew in the expense of this copper, S, brass and Goss type of textured grains. And then this growth preference of this cube texture leads to the conclusion that the theory of oriented go growth really occurs and really matters as compared to the theory of oriented nucleation.

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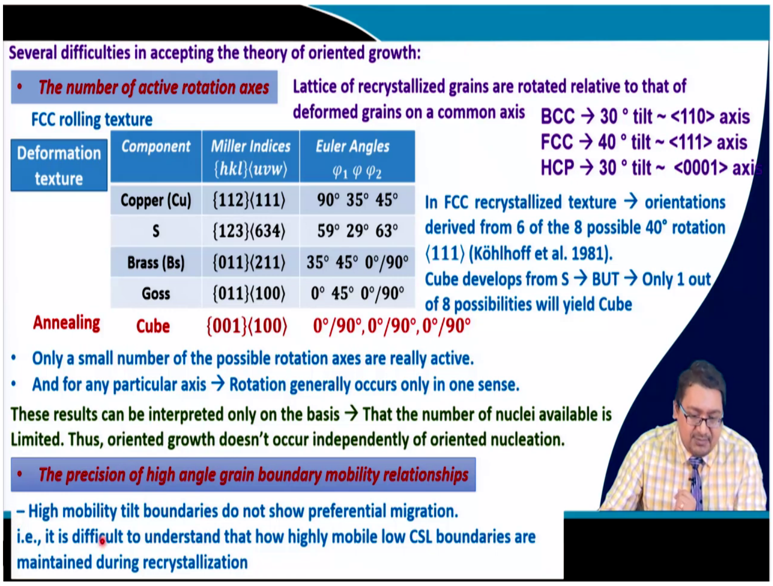

But you see, but there are several difficulties in accepting the theory of oriented growth. The first one is the number of active rotation axis. Now, lattice of the recrystallization are rotated relative to that of the deformed grains along this common axiss right like 30 degrees tilt along 110. So, there are 12 situation 40 degree tilt along 111 there are 8 situation and 30 degree tilt along 001. So, there are two situation 001 and 00 minus 1 right, 000 bar 1.

So, such a situation if exist then any kind of strong texture copper brass or any kind of strong texture which forms may lead to this rotation these all possibilities and therefore, may should end up to get a random kind of texture right. And if you see the work of Kohlhoff in 1981 in an FCC recrystallized texture orientation could be derived from 6 out of the 8 possible 40 degree rotation along 111.

And secondly it is also understood that cube mostly developed from the S component, but if you see that S component is not a very strong component as there are other components like copper and brass components are also present in the material. And cube texture can only develop from the rotation of a certain about a certain 11 axis right. From this 8 or 6 11 axis about only 111 axis that can give the cube texture.

So, you see that only a small number of possible rotation axis is seen to be really active to obtain the cube orientation right. So and any particular axis rotation will occur only in one sense. Now, this results can only be interpreted on the basis that the number of nuclear available is really limited.

So, the theory of oriented growth cannot occur it does not occur without or independently of the theory of oriented nucleation. So, oriented growth does not occur independently without the oriented nucleation. On the other hand if we look the precision of high angle grain boundary mobility relationship.

Now, if we look into detail of it high mobility of tilt boundary is there, but there is less mobile twist boundaries are also present. So, the high mobility tilt boundary during the recrystallization process must show high migration high movement, but it does not show preferential migration. So, that is it is difficult to understand that how this high mobile tilt boundaries with this low CSL you know value ok.

These boundaries as I said this rotation of 111 110 001 about a certain angle produces a boundaries which is of a special kind. So, these special boundaries either low sigma boundaries they are highly mobile. And these tilt boundaries are much mobile than the twist boundaries which are less mobile.

So, there are presence of both tilt and twist boundary ideally, but even though the tilt boundaries are less mobile, highly mobile they do not show this preferential migration. And it is difficult to understand that how this low CSL boundaries which have very high mobility this tilt boundaries are maintained during the crystallization which are you know shows that difficulty in accepting the theory of oriented growth.

But of course, this is a condition of research and still much research are going on in this area to understand the microstructure development during deformation and recrystallization processes and we are every day every month every week we are getting new work on this which are improving our understanding day by day slowly and slowly.

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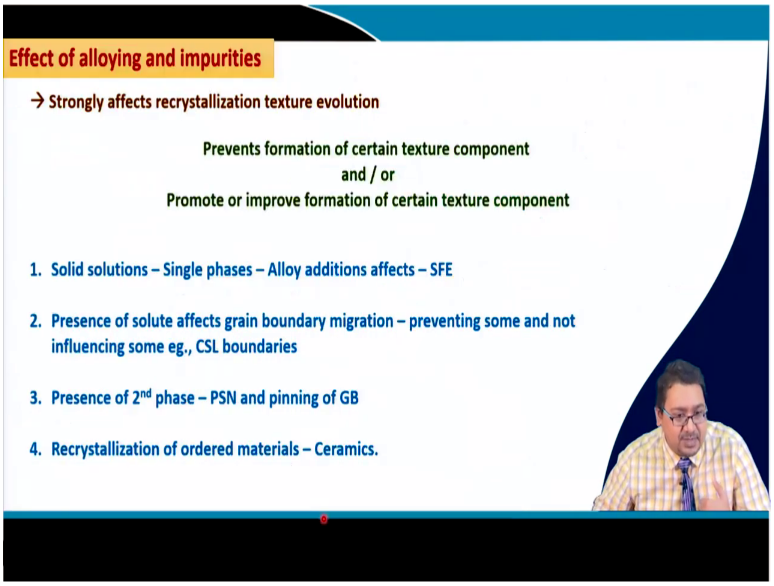

So, now if we look into the effect of alloying and impurities on the recrystallization texture so the recrystallization structure strongly affected by the alloying addition, because if we add certain alloy in form of a solid solution or in form of a precipitate it form dispersoid or it form inter metallic it affects the mobility of the grain boundary of certain grain boundary and it does not affect the mobility of certain grain boundary right.

So, it increases the mobility of certain grain boundary too and it decreases the mobility depending upon the alloying addition depending upon the condition depending upon the material. So, it prevents the formation of certain texture component right and it promotes the formation of different texture components maybe.

So, solid solution single phase alloy addition effects SFE and this effect of SFE leads to the change in the deformation behaviour, recovery behaviour, recrystallization mechanism, formation of CSL boundaries leading to change in the recrystallization texture evolution.

The presence of solute affects the grain boundary migration prevents some and influences some. For example, formation of CSL boundary will entirely change the texture revolution during recrystallization. Third the presence of second phase particle will stimulate you know particle stimulated nucleation and it will also lead to pinning of certain grain boundaries and preferential texture of a different kind may evolve because of the presence of these kind of precipitates.

Ceramic materials having ordered crystal structure also changes the recrystallization behavior despite of the similar crystal structure compared to non ordered structured material right.

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So, finally, if we look into secondary recrystallization or abnormal grain growth and why secondary recrystallization takes place? So, secondary recrystallization or abnormal grain growth takes place when there is an inhibition of the normal grain growth by the formation of texture and the promotion of the abnormal grain growth.

So, grain growth through secondary recrystallization often have a preferred crystal orientation. When the primary recrystallization process is restricted during the grain growth certain grains are restricted to grow then the secondary recrystallization or abnormal grain growth phenomena occurs.

So, the texture that forms during the secondary crystallization will be different from the primary recrystallization texture right. So, if the primary recrystallization texture may have couple of component. It could happen that the secondary recrystallization will promote only one or few of those components to grow suppressing the other recrystallized component making the entire texture different.

So, abnormal grain growth occurs when strong primary recrystallization texture is already present, but grain growth is restricted particularly if their grain boundaries have lower misorientation lower; that means, greater than 15 degree, but at the lower angle; that means, it must have a lower energy and a higher mobility.

The presence of another weak texture which is introduced in the boundaries of higher energy and higher mobility right. So, copper aluminium when it is rolled and annealed primary recrystallization occurs and cube texture develops right. But in case if this primary recrystallization is restricted and there are other recrystallized components which are present in it like the Goss component or the you know other components.

Then this restriction will lead to develop a secondary recrystallization with an abnormal grain growth following the Kornberg Wilson relationship of 38 degree rotation about the 1111 axis's right. Such a situation exist and leading to the formation of you know secondary recrystallization.

So, the major factor controlling this secondary recrystallization or abnormal grain growth are texture that is it should involve a plastic deformation condition followed by an annealing situation right. Surface effects now surface also affects abnormal grain growth. For example it is easier to obtain abnormal grain growth for a sheet metal than that of the bulk material. So, abnormal grain growths are usually observed in thin sheets.

Secondly, the annealing temperature. So, if the annealing temperature is higher then abnormal grain growth is usually observed. The presence of second phase particle may restrict grain growth due to pinning of the grain boundaries in certain case and particle stimulated nucleation or growth at in the certain case leading to abnormal grain growth too.

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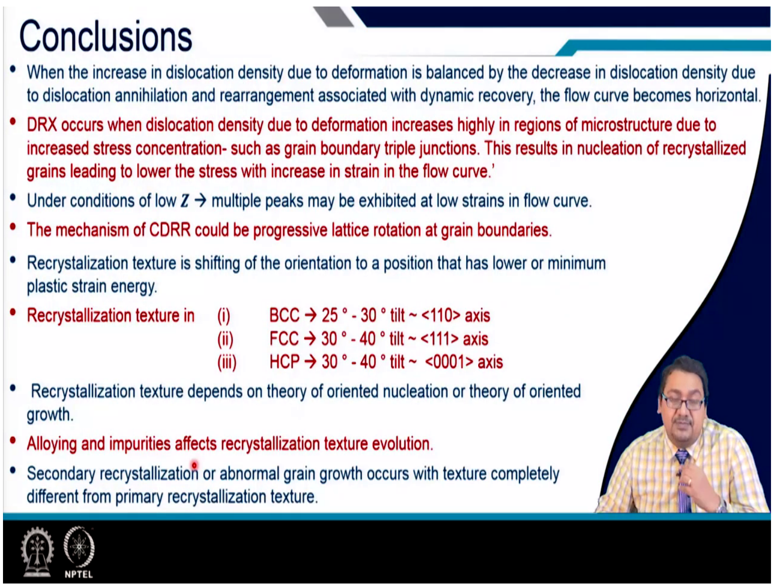

In this lecture we found out that when the increase in dislocation density due to deformation is balanced by the decrease in dislocation density due to dislocation annihilation and rearrangement associated with dynamic recovery the flow curve becomes horizontal such a situation is known as dynamic recovery.

Dynamic recrystallization occurs when dislocation density due to deformation increases highly in regions of the microstructure due to, you know due to heterogeneous deformation. And due to increase in stress concentration such as grain boundary triple junctions etcetera this results in nucleation of recrystallized grains leading to lower the stress with the increase in strain in the flow curve.

The repetition of this occurs under low Zener Hollomon parameter and multiple peaks could be exhibited at low strains of the flow curve. The mechanism of continuous dynamic recrystallization or we can say continuous dynamic recovery and recrystallization could be progressive lattice rotation in the grain boundary at the grain boundary right.

Another conclusion is recrystallization texture is shifted sorry recrystallization structure is shifting of the orientation of the deformed grain to a position of lower or minimum plastic strain energy right. Recrystallization texture in BCC is 25 to 30 degree tilt along 110 axis's for FCC it is 30 to 40 degree tilt along the 111 axis's and for HCP 30 degree to 40 degree tilt along 0001 axis's.

Recrystallization texture depends on theory of oriented nucleation or theory of oriented growth. Alloying and impurities affects recrystallization texture evolution and finally, secondary recrystallization or abnormal grain growth occurs with texture completely different from primary recrystallization texture.

Thank you so much for this class.