Thermo-Mechanical and Thermo-Chemical Processes
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Lecture-08
Discontinuous Dynamic Recrystallization

Hello friends, today we will start with a new topic on dynamic recrystallization. So, we have covered microstructural evolution in this particular module, then dynamic recovery. Very important microstructural change which takes place in the material during hot deformation is through dynamic recrystallization and in that the smaller topic which we will be covering is discontinuous dynamic recrystallization.

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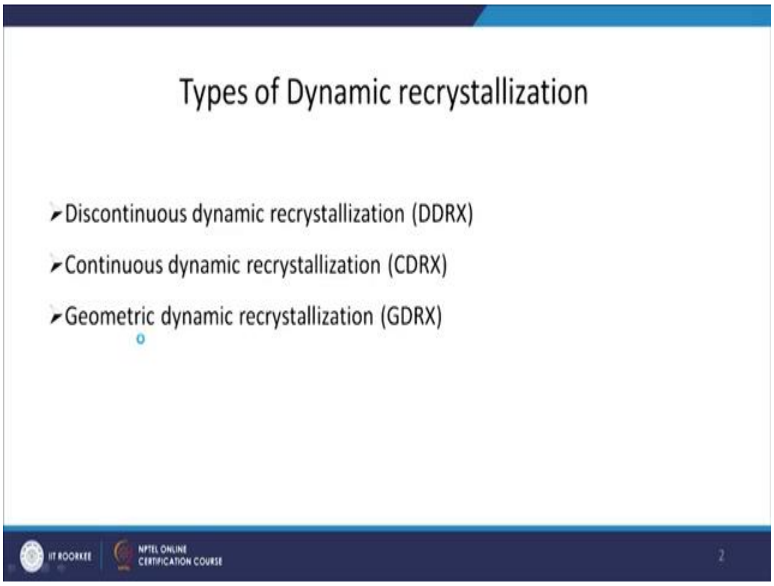

So, basically dynamic recrystallization there can be three types of dynamic recrystallization, which we will be covering one by one. In that discontinuous dynamic recrystallization is the first one which we are going to cover then the next one is continuous dynamic recrystallization and the geometry dynamic recrystallization. Actually most of the studies and the modelling of numerical modelling or analytical modelling is done on the discontinuous dynamic recrystallization.

So, initially that was the most important microstructural changes which people saw and understood. The continuous dynamic recrystallization is a later addition to the dynamic recrystallization and we will try to understand that why now, it has become important.

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So, if we look at the discontinuous dynamic recrystallization of also some time you will come to know it as a classical model or classical dynamic recrystallization. And the difference between the main important characteristic of this kind of recrystallization is it is through nucleation and growth. So, recrystallization means is a new strain free grain will grow in a deformed matrix. So, when we are putting deformation basically what we are doing we are putting dislocations or dislocation density is increasing in the material.

So, the strain energy is increasing in the material and the later material want to bring down its free energy. So, what it will try to do is, it will try to nucleate a new strain free grain within this strained matrix and this will grow and later on the whole matrix should be covered by this relatively strain free new grains. So, this is what is the recrystallization, formation of this new strain free grains in the strain grains.

So, it is not a phase transformation, the same phase will be getting a new set of grain or new set of clothes. So, primary mechanism is nucleation and growth. So, you can kind of compare with or you can easily understand this particular recrystallization with the diffusional phase transformation. So, in diffusional phase transformation also you will see a similar kind of kinetics and the behaviour of how the recrystallization progresses will be similar to how phase transformation progresses.

In phase transformation of course, it will be a new phase which is forming in the older phase as you might be knowing in case of a steel ferrite nucleates from austenite. Similarly, in this case the new strain free grains will nucleate in the strained grains. It is very similar to the diffusional phase transformation. If you remember in dynamic recovery, we said that in high stacking fault energy material the recovery is more efficient means dislocation can be recovered very easily okay, but in low stacking fault energy there is not much driving force for recovery.

So, dislocation accumulation takes place. So, in low stacking fault energy material where the dislocation accumulation takes place recovery is not very efficient then when the dislocation density will increase you will have a recrystallization. So, the recrystallization phenomena you will usually observe in a low stacking fault energy material like copper, nickel and austenitic steels. What is the mechanism of dynamic recrystallization? As I told you basically nucleation of new strain free grain takes place.

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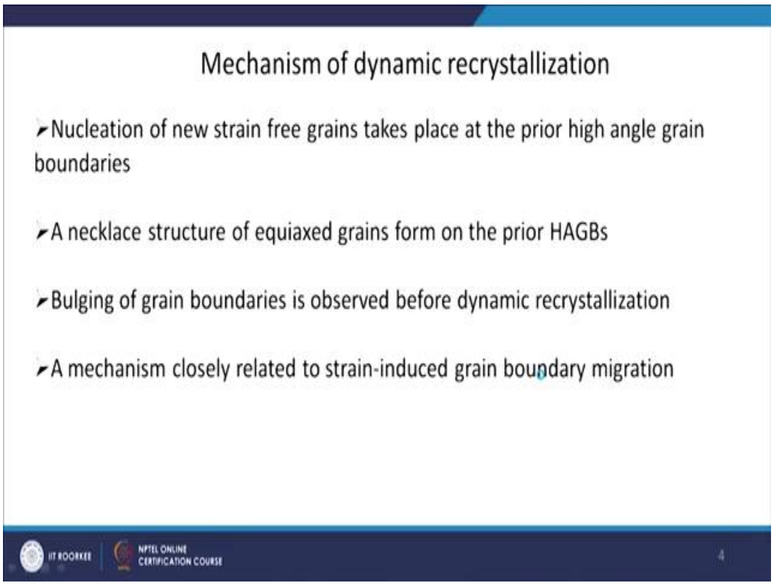

And where it will nucleate or where this will nucleate as in case of phase transformation if you know the new ferrite grains will nucleate at the prior austenite grain boundaries. So, similarly in this case nucleation of new strain free grains will take place at the prior high angle grain boundaries and around that you have dislocation density, so that is where it will start. And because it will start at those boundaries it kind of form what people call it as a necklace structure.

So, if you can understand suppose we if we take only the equiaxed kind of grain something like this (refer above figure). So, if you can nucleate the high angle grain boundary like this okay, you can see there that it looks like a necklace. So, this is what we call as a necklace structure of equiaxed grains form on the high angle boundaries and how you will absorb that if nucleation is started that the bulging at the grain boundary starts first before dynamic recrystallization.

You will have a kind of a bulge on the boundary and that particular new strain free grain then we will grow. So, you will have a bulging at the grain boundary and this bulging and this strain free grain will then grow in the strained matrix. So, that way it looks very similar to strain induced grain boundary migration. So, strain induced means, you have a driving force for this high angle grain boundary migration.

Because of the difference in the strain energy where you have a higher dislocation density and where new strain free grain is starting nucleating and then growing, that will be a dislocation free kind of grain. So, this is strain energy difference is the driving force for the more mobility of the grain boundary and that is why it is also similar to a strain induced strain boundary migration.

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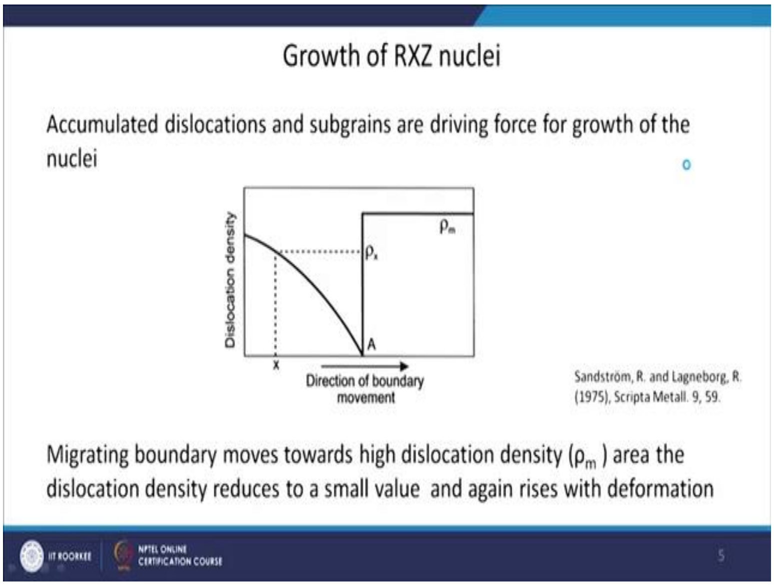

Now, growth of recrystallization nuclei if you see the growth schematic diagram is there (refer to above figure). So, at A is your the newly formed recrystallized grain, the boundary of that which is growing. So, if you see in terms of dislocation density where this grain boundary is, the dislocation density is very low. Just ahead of this boundary which is moving, you have a dislocation density of the matrix.

So, this is very high dislocation density which is in the matrix, this interface is seeing these kind of high dislocation densities. At the grain boundary of course, because it is a strain free grains which is supposed to grow and that boundary is growing. So, it is having the low lowest dislocation density and as you can see the dislocation densities again increasing. So, what happens if you are keep deforming the material and recrystallization is happening in the material so these new strains free grains, they will again accumulate the dislocation. So, it is not like that once this strain free grains are growing and you have a recrystallized microstructure.

Again, if we keep deforming, if we have not stopped the deformation at that point and we are still deforming what will happen that these new grains now will start having deformation and because of that the dislocation density will start increasing. So, just at the grain boundary which is moving in the strain matrix you will see that the dislocation density is very low and at any particular distance x you will see that the dislocation density is ρ_x.

And of course, the dislocation density will again keep increasing and then maybe it will reach the present dislocation density of the matrix as it is shown here (refer to above figure). Now, what is the condition for nucleation?

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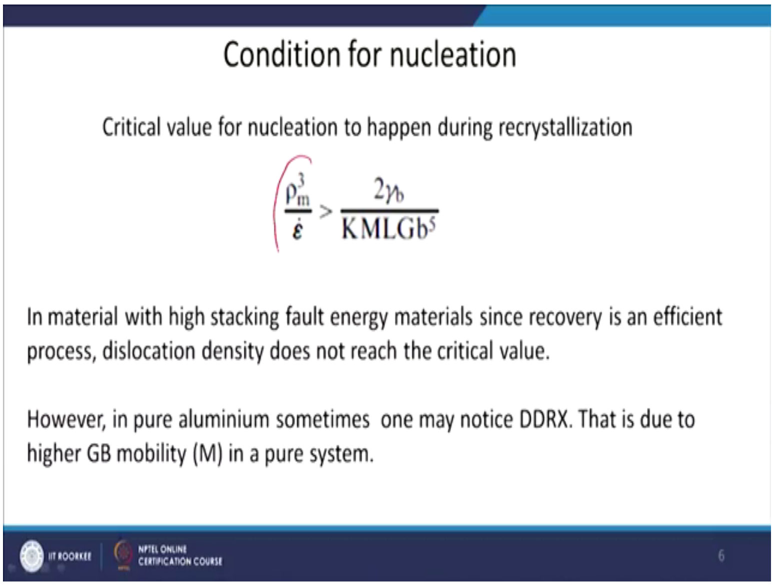

So, critical value for nucleation to happen during recrystallization is this particular ratio that is the dislocation density in the matrix raise to Q divided by the strain rate (refer to above figure). This particular value should be more than the material properties here for example, this gamma b is your grain boundary energy, M is the mobility of the grain boundary, L is the slip distance of the dislocation so I will just write it down here mobility of the grain boundary, L is your slip distance of dislocation, G is your shear modulus b is of course, your Burgers vector and this is your energy of grain boundary. So, as we can understand that in material with high stacking fault energy they have a better recovery, the dislocation recover very efficiently. That is why you can see that the dislocation accumulation is not there and the dislocation density will not reach the critical value which is required for nucleation. So, however, as we already know that aluminium is a high stacking fault energy material and it should show efficiently dynamic recovery.

But sometime some researchers have seen in pure aluminium also they have seen the discontinuous dynamic recrystallization that means recovery has not taken place the dislocation has accumulated and then the new strain free grains are growing through nucleation and growth mechanism. This is usually people have observed in very pure aluminium, maybe 99.999% purity.

So, in those materials actually the mobility of the grain boundary is very high because there are no solute atoms or precipitate to pin the grain boundary. So, again boundary can move very easily ok. So, the mobility term there is very fast. Because the M is in the denominator this value of this ratio will be lower. So, you will require less dislocation density also to start the nucleation process.

So, either it can be that you have a lower efficiency of recovery so, that you can easily reach the high value of dislocation density or you can have a higher mobility of the grain boundary so that this ratio itself has lower value so, with a smaller dislocation density also I should be able to reach the that critical value of nucleation. Sometime it happens in the high stacking fault energy material also that you can have dynamic recrystallization instead of dynamic recovery, but those are very specific cases.

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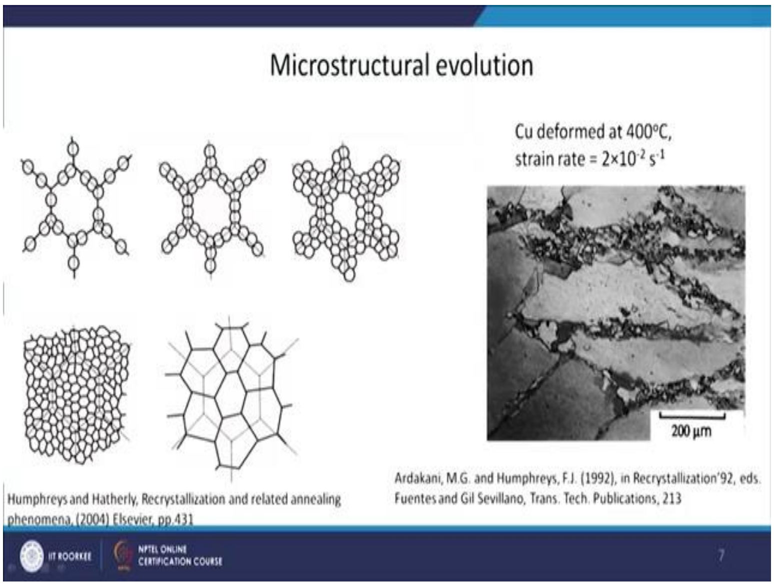

Now, as I told you that microstructural evolution if you see in case of dynamic recrystallization (refer to above figure). So, as I told you the if you take a particular grain. This is the prior grain which was there before the deformation started. And now, as the deformation is progressing you have more dislocation density and also there is a higher dislocation density in general if you see how the dislocation are distributed within the grain.

You will know that the dislocation density is closer to the grain boundary as compared to the grain interior. So, there is also a gradient between of dislocation density from grain interior to the grain boundary. That you will know through geometrically necessary dislocation which are has to be there in the material. So, you have a higher distribution density at the grain boundary and the lower dislocation density within the grain.

Now, since the dislocation density is high as well as the you have high angle grain boundaries so, when you start a nucleation process it can be easily done on a high energy site here (refer to above figure). So, because of that you have all the nuclei which forms at the grain boundary and it gives you a typical necklace type of structure. And as it progresses it will completely cover the whole high angle grain boundary.

You have large number of equiaxed nuclei in this second image (refer to above figure) and then it will progress within the grain and after some time it will be able to cover the whole matrix. And then these particular grains also will start growing. So, there is there will be grain growth here after the recrystallization. So, you have very fine equiaxed microstructure here. But as you know the grain growth process is that the bigger grain grows at the expense of smaller grains.

So, slowly you will have a grain growth process also associated with that, so you can see after a certain time the grain growth has taken place and that initial grain is now subdivided into this small grain that is the recrystallization process. You can also see a nice micrograph here which shows the start of the nucleation process at the grain boundary. So, this must have been the prior grain boundary in the material and something like this (refer to above figure).

And you can see that large numbers of nuclei are present here at the grain boundary. So, this is a copper deformed at 400°C at this particular strain rate. And very nicely you can see that how this recrystallization is happening at the grain boundary (refer to above figure). Now, since the recrystallization is taking place.

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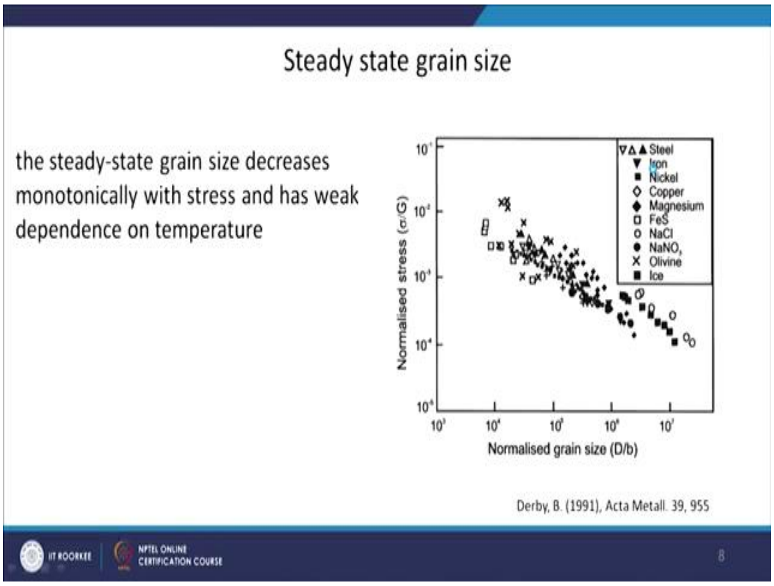

So, of course, it will also affect the grain size of the material. So, if you want to measure the steady state grain size means after the recrystallization the steady state which is taking place. So, a steady state grain size if you measure that decreases monotonically with stress and weak dependence on temperature. So, it is actually strongly dependent on the stress and weak dependent on the temperature.

So, you can see (refer to above figure) on the x-axis I have normalised grain size that is the d divided by b the burgers vector. Similarly, on the y-axis I have normalise stress, stress is divided by shear modulus. This way try to do to kind of bring data of different material in one graph. So, you can see that the material which are plotted here it is steel, iron, nickel, copper, magnesium, sodium chloride, Fe, ferrous sulphide (FeS), $NaNO_3$, olivine, ice.

So, you can also understand that these kind of deformation or recrystallization and all these microstructural changes takes place in case of ice. Olivine is one kind of mineral. So, in different type of materials you can see the same deformation behaviour. The normalised grain size as you can see (refer to above figure) and this is normalised stress, so as my stress is decreasing, the grain size which I am going to get that is increasing.

So, stress is decreasing and grain size is increasing. If you remember earlier also we related the grain size in case of dynamic recovery there we talk about sub grain size that we related with the Zener-Hollomon parameter, and the Zener-Hollomon parameter is also you can relate the stress with the Zener-Hollomon parameter. So, more or less these things are same that when stress or you can say Zener-Hollomon parameter is coming down your grain size is going to be more.

And we also know that when the Z will be low at lower strain rate and higher temperatures. Of course the temperature dependence is weak here but still we can take it as a parameter. So, at lower strain rate sigma value is low and Z value is low that mean low strain rate and high tempreature. So, lower strain rate and higher temperature. So, lower strain rate means that as we have seen the in the nucleation equation also the strain rate was in the denominator that when you bring down the strain rate your generation of dislocation density will be that much slower.

So, you will attain a larger grain size. The steady state grain size will be more. The grain size which you get after recrystallization will be more. Similarly, at high temperature mobility will be more, similarly driving force will be more you will have higher grain size as you go toward the lower stresses. So, this is the dependence between what you get as grain size after recrystallization and the stress values.

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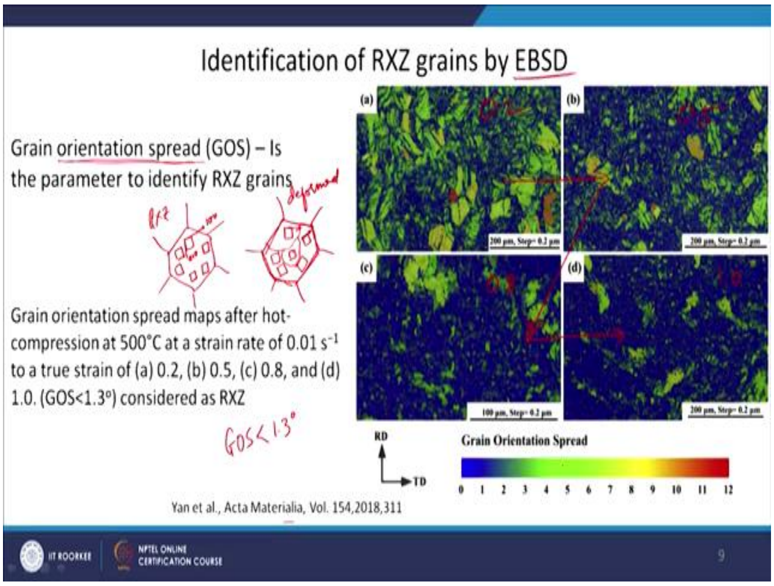

Now, there is another very important characterization technique, is electron backscatter diffraction EBSD and why I was taking that here is because this is one of the very important technique now, to characterise the recrystallization process in the material. And as I told you that in this particular technique, actually you find out the orientation of each grain. So, basically orientation of the unit cell that how the unit cell is oriented in different grains.

Now, when I am trying to do that, suppose I take a grain here (refer to above figure), now this grain doesn't have any sub grain, doesn't have any large dislocation density. And suppose I want to know the orientation of unit cell at every point. Suppose I am just looking from the top right now, this is my 100 let say, this is my 010. So. 001 is coming up. So, if I do this measurement and find out the orientation of the unit cell in each part of the grain it will be same. There will not be any change in the way the unit cell is oriented because within a grain it should have the same orientation. But if I do the same measurement now in a grain which is deformed now, you will have sub grain. So, what sub grain will, when sub grain form or sub grain boundary is there, there will be slight change in the orientation of the unit cell.

Right now, I would not be able to do it in three dimensions. So, I am doing in two dimensions that how it will be different (refer to above figure). So, suppose the unit cell is oriented like this here and suppose there is sub grain or maybe the unit cell which slightly miss oriented here. So, the 100 let us, say was here now become like this maybe slowly, slowly, slowly if you see there are some low very low angle grain boundaries or dislocation network maybe after a certain distance it will be oriented something like this (refer to above figure).

So, there is a large number of different variations of orientation of the unit cell. So, this is I would say you will see in a recrystallization grain because you have removed all the dislocation it is now dislocation free grain. So, everywhere if I find out the orientation of the unit cell it should be same. And this is where it is a deformed grain where now, the unit cell has different orientation very slight variation at different part of the grain.

And the grain we have already defined is the one which is enclosed within high angle grain boundary. So, this I will call a sub grain because one part is enclosed with a low angle grain boundary. Within this also you can have some sub grain as like this (refer to above figure), which has all the low angle grain boundaries. So, now the orientation is different at different place. So, this I can characterise what I will call as orientation spread.

So, I can measure the orientation at different place and what is the spread in the orientation. So, if the spread is more that means that there is a deformation in the grain. If the spread is low that means, I have removed the dislocation, I have recrystallized the structure and that is how I can find out the what is the microstructural condition after a particular deformation. So, this grain orientation spread is a very important parameter to characterise quickly the material that how the recrystallization is progressing as a function of deformation.

So, this is one very nice micro structure is shown here taken from papers (refer to above figure). And here they have grain orientation spread map after hot compression at 500°C at a strain rate of 0.01/s and after true strain of after 0.2. So, this is after 0.2 this is after 0.5, this is after 0.8 and this is after 1.0. And the criteria which is they have taken that grain orientation spread should be less than 1.3°. That they will consider as recrystallized.

So, all this blue portion is recrystallized. So, they have taken at 200μ, shown as the scale here (refer to above figure). So, let's say around 400 or 500μ images in x-direction and maybe around in y-direction it will be 300-400μ. And you can see that how it is progressing from here to here to here, that the recrystallization fraction is continuously increasing as you are putting more and more strain. So, you can understand that recrystallization also can is as a function of a strain it will increase.

Lower strain you have a lower fraction as you increase the strain, more and more grains are recrystallizing and later your most of the microstructure will have these blue grains. Blue means somewhere here (refer to above figure), below 1.3 as they are saying that all the grains are now coloured blue. So, this is one of the very important technique to characterise the microstructure in terms of recrystallization. So, I just wanted to tell you this here.

So, what we have discussed now is that what is the dynamic recrystallization and that particularly we have right now seeing that discontinuous dynamics recrystallization, which happens by nucleation and growth mechanics. And we have also seen that the dynamic recrystallization is usually takes place in the material with low stacking fault energy. So, when you have low stacking fault energy material the dislocation density will keep increasing because the recovery is slower recovery is not very efficient in this material.

And then you will have recrystallization process at certain strain and you can also see here there as a function of a strain that how the recrystallization fraction will increase and almost whole of the material will be covered with the recrystallized microstructure. So, with that, I think this particular part is over. Now, in the next lecture we will discuss about that how I can identify the recrystallization from the flow stress curve.

Right now, we have seen the microstructural features and how the microstructure will look like in a dynamic recrystallized material, next we will see the same thing in terms of flow stress or stress strain curve okay, thank you.

Keywords- Discontinuous dynamic recrystallization, grain orientation spread, stacking fault energy.