Thermo-Mechanical and Thermo-Chemical Processes
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Lecture-10
CDRX and GDRX

Hello friends in dynamic recrystallization there is another topic we are taking today and it is going to be called as continuous dynamically recrystallization and geometry dynamic recrystallization. So, if you remember the previous two lectures were related to the discontinuous dynamic recrystallization and as I told you in that the discontinuous dynamic recrystallization is the nucleation of a strain free grain and the growth of a strain free grain.

So, when you have this kind of process it is called discontinuous dynamic recrystallization. The new terms which have come in dynamic recrystallization is because people have observed some new microstructural behaviour and from there they have said that it is now a different type of recrystallization process and that is why a new name is called continuous dynamic recrystallization and another one is geometry dynamic recrystallization.

So, continuous dynamic recrystallization actually is very similar to a dynamic recovery type of process. So, in dynamic recovery also we have we have seen that the material with high stacking fault energy are predominantly they restore their mechanical property through dynamic recovery. And in continuous dynamic recrystallization also high stacking fault energy materials are the one which are predominantly get recrystallized through this particular process.

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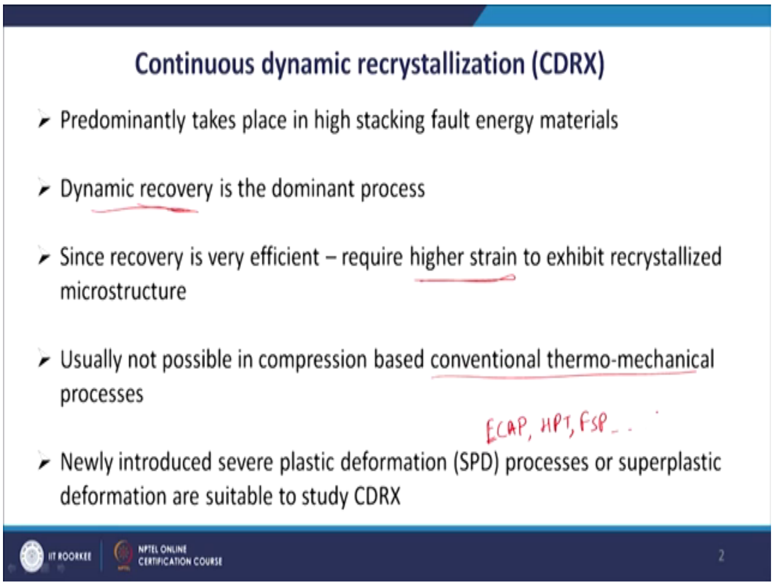

As I told you that dynamic recovery kind of recovery that is a dominant process and because of that, some people also refer to it as an extended recovery process. Means, if you take recovery to a larger strain maybe it will come as a recrystallization process.

So, just to kind of differentiate between recrystallization and recovery, recrystallization means I should have predominantly high angle grain boundary that makes most of the grains should be surrounded by high angle grain boundary, whereas in a recovered grain there are large grains and in within that you have sub grains and these sub grains are predominantly surrounded by low angle grain boundary. So, recrystallization means that I should have finer grains whereas recovery means I can have finer sub grains. So, this kind of classification should be clear in your mind. Why this kind of process takes place, especially in high stacking fault energy material, because recovery is very efficient.

Now, when the recovery is very efficient means dislocation can easily recover, I cannot have a discontinuous dynamic recrystallization which requires certain amount of dislocation density. So, now to have a recrystallization process I need higher strain to exhibit recrystallized microstructure in case of continuous dynamic recrystallization. So, you can say at lower strain you will see the microstructure is a dynamically recovered microstructure but if you go to higher strains, you will start seeing recrystallization taking place.

Now why it was not earlier kind of identified because in our conventional thermo-mechanical processes for example, rolling or extrusion or forging which are based on the compression cycle. In compression, you can always understand that there will be induced tensile stresses also. So, when you apply very large compressive strain there will be a large tensile strain also and you have to maintain constant volume, because of that you will ultimately have cracking in the material.

So, material will crack if you I apply a very high compressive strain. So, I cannot apply very high compressive strain in normal conventional thermo-mechanical processing and that is why maybe people have not observed CDRX before. But when the severe plastic deformation processes come in to Vogue. So, for example, you might have heard about equi-channel angular pressing ECAP or high pressure torsion HPT or friction stir processing FSP , there are a large number of processes are there in this category.

The strain in these cases is usually through shear process. So, shear strain is imposed these are not compressive strain-based processes. So, the deformation is through shear and because of that, you are able to impart a large amount of strain during these processes and because of that, you are able to say CDRX process in these severe plastic deformation process. Another area or another deformation where you can see this continuous dynamic recrystallization is the super plastic deformation.

I will tell you what do we mean by super plastic deformation in a very small section. So, because in Super plastic deformation also you have very high strains you can achieve. So, the CDRX processes people have seen in during super plastic deformation.

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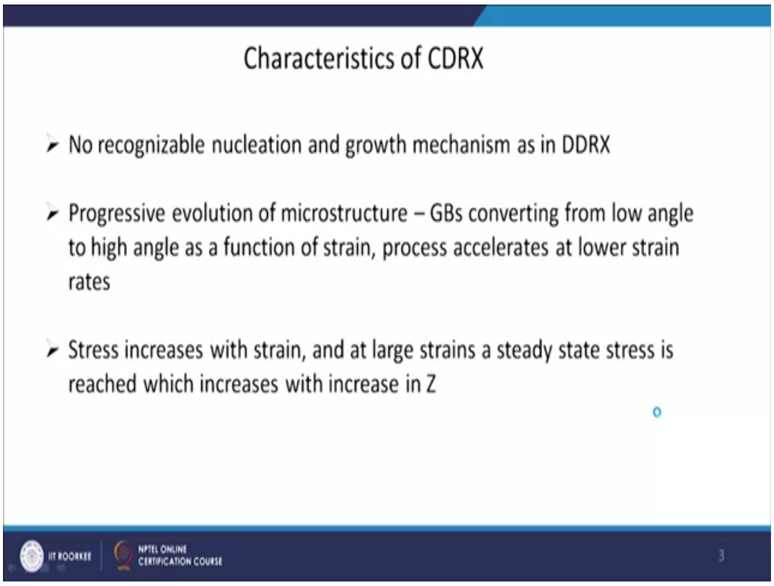

Now, what are the characteristics of continuous dynamic recrystallization, as we have already seen in discontinuous dynamic recrystallization, you have nucleation and growth mechanism whereas, in this case of course there is no nucleation and growth separate as mechanism. In fact, in this you have progressive evolution of microstructure. So, it is a continuous kind of process, where grain boundaries are converting from low angle to high angle.

So, basically low angle grain boundary kind of transform into high angle grain boundary and there are different mechanism people have proposed at how this can happen as a function of strain. So, as a function of a strain low angle boundary convert into high angle gain boundary. So, in dynamic recovery as I was telling you that you have big grains and they have small sub grains. So, this I can kind of make it bold to show that these are high angle grain boundaries and within that you have some grain boundaries and so on (refer to above figure).

So, now, these sub grain boundaries these are all low angle grain boundaries and these will in the process will convert into high angle grain boundary through continuous large amount of strain and as we have seen in dynamic recovery stress increases with the strain and at large strains steady state stress is reached which increases with increasing Z. So, if you see the flow stress curve in this process, it will be like what you see in dynamic recovery it will have a steady state condition and with increasing Z you will have higher stresses (refer to above figure).

So, you can have multiple curves like this. So, in this direction your Z is increasing. For example, this is what I was telling you about super plasticity.

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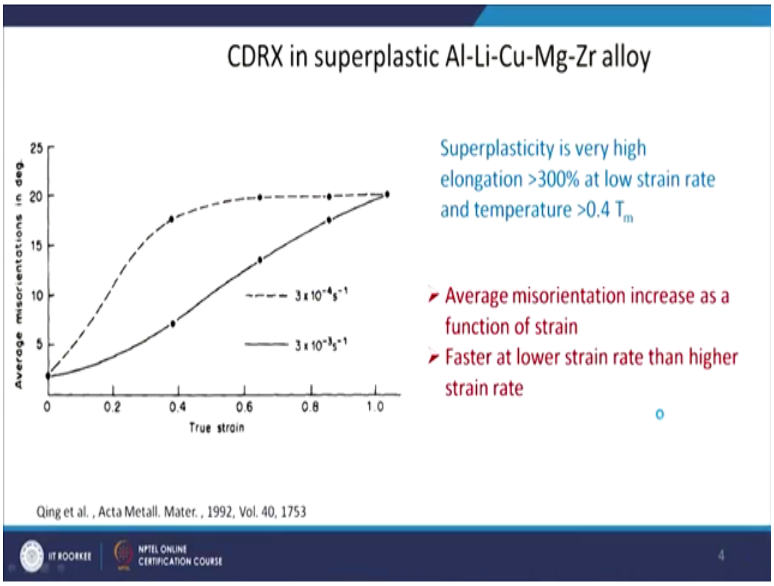

So, this is a very old paper (refer to above figure) 1992 CDRX in super plastic aluminium lithium copper magnesium and zirconium alloy, this aluminium lithium 8090 alloy. Basically super plasticity is very high elongation more than 300% at low strain rate and temperature of more than .4 T_m. So, the conditions are typical of any recovery recrystallization process high temperature. However, the strain rates are low in case of super plasticity as compared to other conventional or SPD processes.

However, the elongation is very high you can achieve elongation of 1000% and even more than that. So, in their work they showed that as a function of true strain, average misorientation of the whole microstructure is changing as a function of strain. Because the average misorientation is low that means, it might have high angle grain boundary and low angle gain boundary.

But if you combine all and take advantage of that, it is very low less than even 5° that means predominantly the material has low angle grain boundaries. So, already sub grains are there and so on. And as the deformation is progressing you can see that the slowly the average misorientation is increasing and reaching some steady state kind of condition at around 20° or so.

It is not a sharp change from one average misorientation to another one, but it is a gradual change in the average misorientation in the microstructure with the strain and these (refer to above figure) two curves one you can see the bold one is at 10^{-3} whereas, the dotted one is at 10^{-4}. So, another interesting thing is that at lower strain you are able to get the more high angle grain boundaries. I think I have mentioned that also in the earlier slide. So, the effect of a strain rate is at lower value of strain you are able to achieve very high average misorientation, So around 17 ° or so, you are able to achieve at around 0.4 strain.

Whereas, in case of higher strain rate condition almost a strain of 1 is required to achieve that kind of average misorientation. Now, how the CDRX actually takes place it is gradually increasing misorientation of low angle grain boundaries as we have just discussed and to kind of remove all the other effects of grain boundaries and so on.

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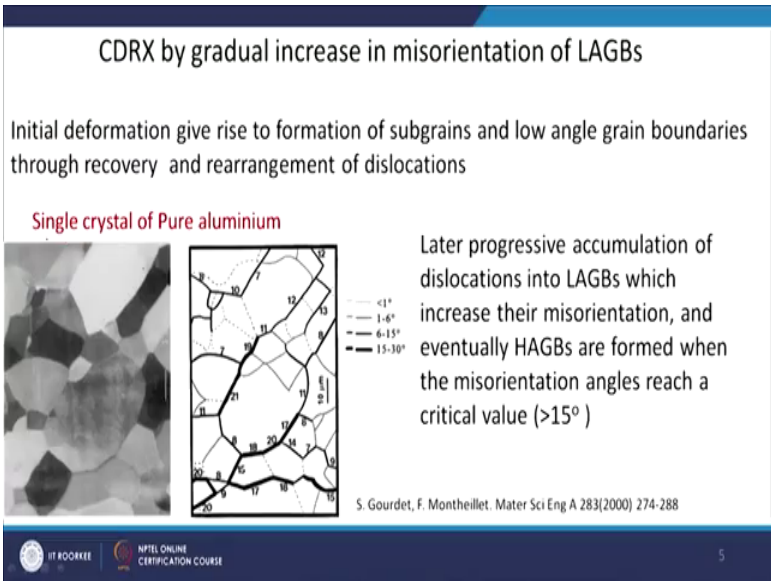

There is some work on the single crystal of pure aluminium was done. And their people have seen that the microstructure initially is getting divided into sub grains and that is slowly converting into high angle grain boundaries. So, a single crystal now is dividing into some low angle grain boundary areas. So, this dotted one is even less than 1°, the lighter ones are 1-6°, slightly darker ones are 6-15° and very bold ones are the 15-30°(refer to above figure).

So, they are able to show that how the microstructure is evolving through deformation in a single crystal. So, how it takes place is that initial deformation give rise to formation of sub grains. So, initial deformation when you are giving, so, through dynamic recovery processes, the sub grains form and these sub grains are of course surrounded by low angle grain boundaries. And later, these sub grain boundaries are low angle grain boundaries and there is a progressive accumulation of dislocation in this low single grain boundaries.

So, dislocation recovery is continuously going on. So, all these sub grains which are formed because of the continuous recovery you are continuously deforming and there is a continuous recovery of dislocation, this low angle grain boundaries are progressively changing from low angle grain boundary to high angle grain boundary. So, progressive accumulation of dislocation into LAGBs (low angle grain boundaries), increase their misorientation and eventually high angle grain boundaries are formed.

When the misorientation angle reaches a critical value of more than 15°, so, in general around 15° is what we take as the demarcation between a low angle and high angle grain boundary. So the continuous recovery of this dislocation changes the low angle grain boundary to high angle grain boundaries. Another mechanics which is proposed for the CDRX process is through lattice rotation.

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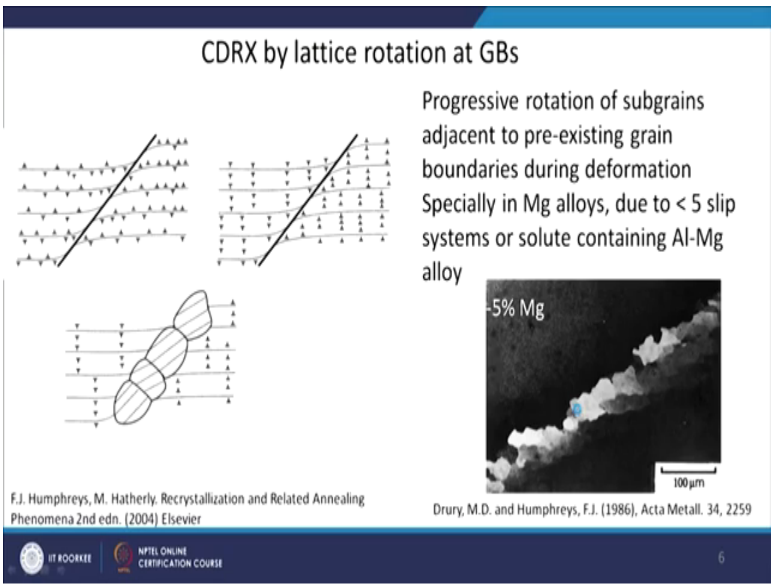

And that is actually more visible in magnesium alloys or solute containing aluminium magnesium alloys. So, magnesium has good solubility in aluminium. So, the magnesium alloys because it has hexagonal close packed structure thre are only 3 slip system out of which only two are independent. So, you don’t satisfy the Taylor criterion of 5 independent slips, in HCP materials.

So, you have less than 5 slip system in case of magnesium alloys and because of that, you have predominantly dislocation only in one plane. Because of that the when the dislocation accumulate you can see that on the pre-existing grain boundary these dislocations are coming and they are accumulating and because of that, you have this (refer to above figure) kind of grain rotation. So, there is a lattice rotation because of the very high amount of dislocation density in the vicinity of the grain boundary.

And another nice micrograph is shown here also (refer to above figure). So, and this must be some prior grain boundary and around that you have this small grains which have nucleated through lattice rotation. This lattice rotation give rise to this kind of dislocation at the grain boundary. So, this is usually you will see in magnesium alloys or aluminium magnesium alloys when you deform to very high strains.

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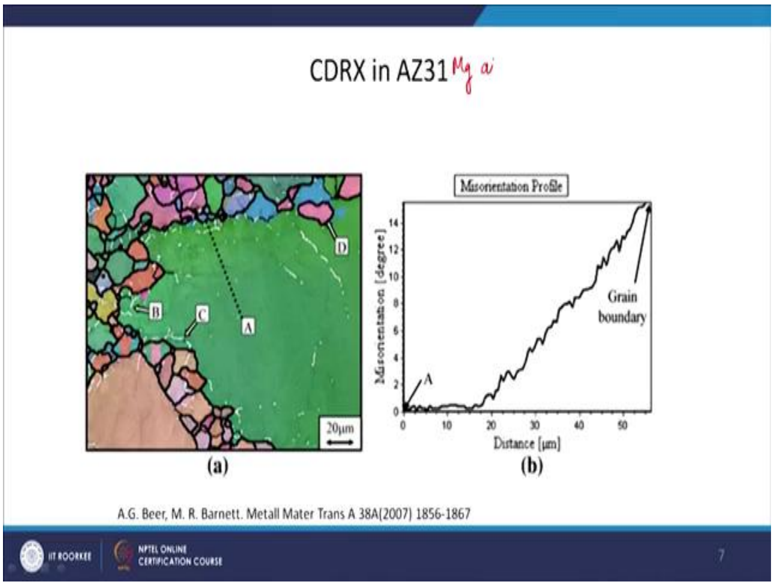

Another example is CDRX in your AZ31 magnesium alloy. So, this (refer to above figure) is also a magnesium alloy where they have tried to show that how the grain boundaries are getting converted. So, the B grain boundary here which is shown with a white colour are the low angle grain boundary and the dark black ones are the high angle grain boundary there is another grain boundary C at here again a low angle grain boundary (refer to above figure).

So, what they are trying to say that these small grains which have formed at the grain boundary is through changing the misorientation of this low angle grain boundary. So, earlier this also must have been a low angle grain boundary, but continuous deformation converts this now low angle grain boundary into high angle grain boundary. So, if we keep deforming later on you will see that this B boundary here and C boundary here both will convert from low angle which is shown with the white colour right now into a high angle grain boundary (refer to above figure).

And the reason to give this kind of argument is that if you kind of plot how the misorientation is changing within the grain. So, this if you see this (refer to above figure) curve, this is misorientation on y-axis and this distance on x-axis and we are starting from A here and going from A towards the grain boundary. So, if you see the misorientation development. So, in the interior of the grain up to some distance you will see that there is hardly any misorientation development.

What does it mean that the dislocation density is low here in the in the interior of the grain and as you are going towards the grain boundary there is large number of dislocation density as well as there may be some sub grain boundaries are forming or very low angle grain boundary are forming. And that is giving rise to this misorientation development as you go from point A towards the grain boundary.

So, this misorientation development is as I am telling you that it will be because of the dislocation density. So, you have higher dislocation density very close to the grain boundary. So this dislocation will now as you can see will be getting absorbed in the this low angle grain boundary of B and C (refer to above figure) and this will be converting into high angle grain boundary as the deformation progresses. So, this is an another way of looking at how the continuous dynamic recrystallization takes place in the material.

Now the next type of dynamic recrystallization. So, we have seen till now, discontinuous dynamic recrystallization, continuous dynamic recrystallization and this is another one which is called geometry dynamic recrystallization.

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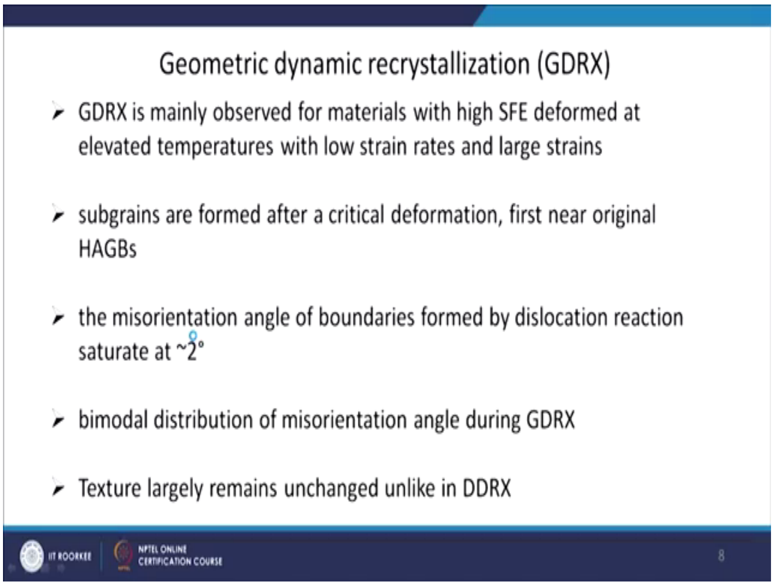

This mainly absorbed for materials with again high stacking fault energy. So, it says in fact, some people are categorising GDRX also within CDRX. So, it is considered as a part of the continuous dynamic recrystallization and of course, it will be also at elevated temperature at lower strain rate and large strains. So, mainly all the; these conditions are also you will find in CDRX, so, only the how the recrystallization process takes place or what is the mechanism that is different than the CDRX process.

So, sub grains are formed as usual after a critical deformation first near original high angle grain boundaries. So, around high angle grain boundaries because that is where you have more dislocation density so near that sub grains will form. The misorientation of the sub grain boundaries is usually is very small actually not more than 2 degree or around 2 degree basically.

And because of that you will see a very bi modal distribution misorientation angle during GDRX, so if I plot frequency here on y-axis (refer to above figure) and misorientation here on the x-axis, you will see some curve like this, a bi model. Predominantly low angle grain boundary and predominantly high angle grain boundary is only two type of grain boundary misorientation will be frequency will be very high.

And texture largely remain unchanged during GDRX process whereas, in DDRX you have a big change in the in the texture of the recrystallized microstructure.

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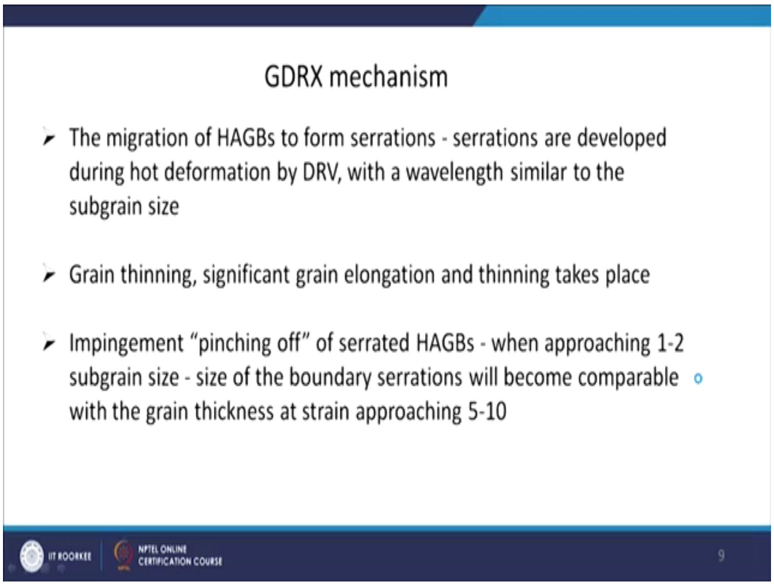

Now, what is the mechanism? So, the migration of high angle grain boundary they migrate to form serrations in the high angle grain boundary. I will show you a schematic for that what do we mean by these serrations (refer to above figure). The serrations are developed during hot deformation by DRV with a wavelength similar to sub grain size. So, as we have just seen that the sub grains will be forming at the vicinity of the high angle grain boundary.

So, they form serrations and this wavelength of the serration is equal to the size of the sub grains. And of course as we have already seen we have to apply very large strain. It is kind of a flattening of the grain process. So, if you start with an equiaxed grain, progressively it will become more and more flat kind of grain. And of course, it will have these (refer to above figure) kinds of serrations in the grain boundary and the wavelength will be called to the sub grain size.

So, grain thinning will take place with significant grain elongation and when they are getting thinned what will happen is that these two high angle grain boundaries, it keeps getting smaller and smaller So, what will happen you have a sub grain here and sub grain here and this is my high angle grain boundary. And if you keep deforming it what will happen, this will impinge with each other (refer to above figure).

Or also I would call it as a pinching off, you are pinching there and kind of connecting these two grain boundaries. So, at this separated high angle grain boundary will be there will be an impingement here and this will happen when you are approaching 1 to 2 sub grain size. So, this thickness of the or the distance between the two high angle grain boundaries equal to 1 to 2 sub grain size that means only maybe one sub grain will be there and will become comparable with the grain thickness and strain approaching 5 to 10. So, you can understand that the strain has to be very high to have this kind of recrystallization process. Very high strain of 5 to 10 you have to impose to get this kind of process.

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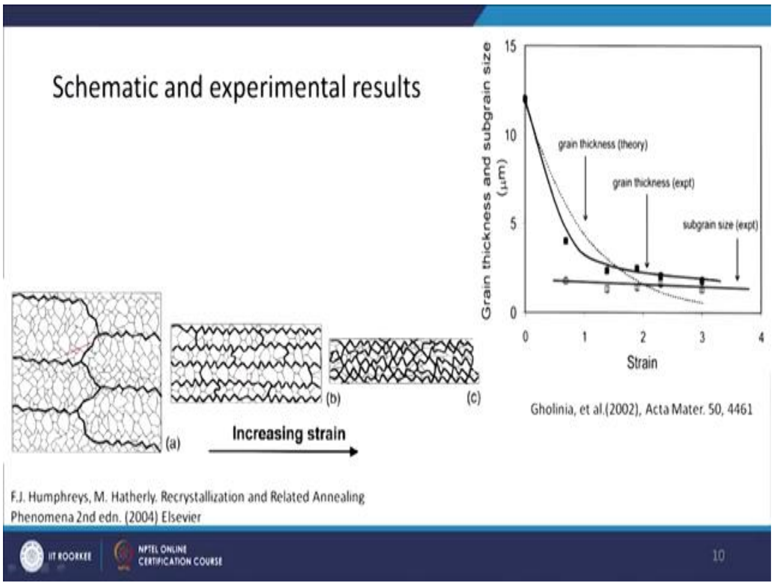

So, this is what is the schematic mechanics. You can see that there are some big grains here (refer to above figure0 and within them there are some small sub grains are formed as you keep deforming. What will happen, these kinds of serrations will form in the high angle grain boundary. And within that you can see the in some cases 1 single sub grain is there in some cases there are 2 sub grains are there and the serration, the wavelength is all most equal to the sub grain size.

So very interesting microstructure. Somewhere you will also see a high angle grain boundary. So, this is the original one which must have been there (refer to above figure). And below that you can see how the spacing between high angle grain boundaries changing. Here there may be almost 10 sub grains are there, now only one or two sub grain is there and even if you keep deforming it what will happen now, this high angle grain boundaries are impinging with each other.

And with only 1 or 2 sub grains are there and the pinching off is taking place, so, now this will convert into smaller grains with surrounded by high angle grain boundaries. So, the recrystallization is completed and it is a geometric process as you can see a very geometry process that how it is taking place that is why it is called geometric dynamic recrystallization.

You can see on this (refer to above figure) curve also as a function of strain on x-axis and grain thickness and sub grain size are plotted on the y-axis.

So, the sub grain size is shown here which remains almost constant which is what we see in case of dynamic recovery also and the grain thickness is changing like this continuously. So, it is very thick initially and then it is coming down and it is getting very close to the sub grain size. And this is the point where it will start showing that the recrystallization is happening and impinge impingement is happening or pinching off is happening and you can see the strain is almost between 3 to 4 again very high strain.

So, when the sub grain size is equal to the spacing between the high angle grain boundary then you are reaching that condition pinching off.

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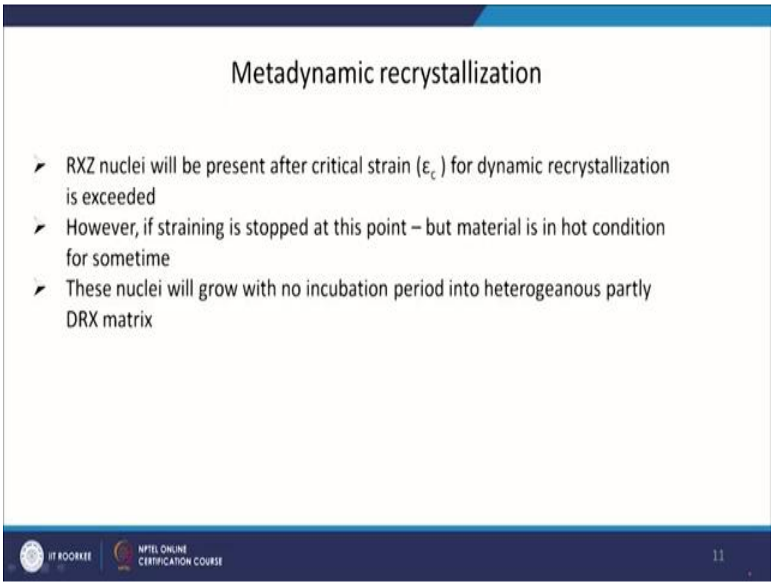

There is another one type of dynamic recrystallization which is called meta dynamic recrystallization a very interesting phenomenon. Basically, it is not a kind of a typical type of dynamic recrystallization it actually happens because suppose a discontinuous dynamic recrystallization is taking place and recrystallized nucleus have already formed at the critical strain.

So, when you have this critical nucleus which has formed after the achievement of the critical strain suppose you have stopped the straining, you are not deforming it anymore. And suppose that the process is like that it is at of course high temperature you are deforming, but you have deformed only up to the slightly above the critical strain and then you have stopped the deformation. If you see the microstructure, you will see a very nice recrystallized microstructure though you have just exceeded the critical strain.

So, in reality it should be only 5 to 10% recrystallized. What will happen that when you are taking it out and if you are not quenching the material immediately that means it is at in hot condition or suppose it is in some furnace it is in annealing condition. So, it is in hot condition after this achievement of the critical strain, then this nuclei will grow without any incubation period and you will have a dynamic recrystallization during the deformation.

So, sometime it actually happens to capture partial recrystallization sometime is very difficult, because in some part recrystallization has happened and some other part where recrystallization is still not started, but during the cooling period when you are cooling the material, and because there is no incubation period that means it can almost happen instantaneously kind of so, while you are cooling the material or you are bringing the temperature down, the recrystallization will happen in the remaining unrecrystallized part also, if you have reached the critical strain or exceeded the critical strain then it is very difficult to capture that how much is the amount of recrystallization after a particular strain. So, sometimes you have to be careful about this Meta dynamic recrystallization when you are studying any recrystallization process that this should not happen during the process that means the material has to be cooled on immediately.

So that you are able to capture the recrystallization process. So, with this our this part of the micro structural evolution in terms of recrystallization and recovery process is complete. And this is one of the very important part because all the hot deformation processes which we do is to get some very fine-grained microstructures. So, we can have better property in the material after processing. So, with that, thank you for this particular lecture.

Keywords- Continuous dynamic recrystallization, discontinuous dynamic recrystallization, geometric dynamic recrystallization and meta dynamic recrystallization.