Texture in Materials
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Module - 11
Theory of annealing texture evolution
Lecture - 54
Static Recrystallization

Good afternoon, everyone and today, we will be starting module number 11, which is Theory of annealing texture evolution. So, this is the final week and this is the lecture module for the week number 12. This is lecture 54, Static Recrystallization.

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The concepts that will be covered in this lecture will be annealing; microstructural schematic of recovery, recrystallization, grain growth; nucleation during recrystallization, and continuous and discontinuous recrystallization.

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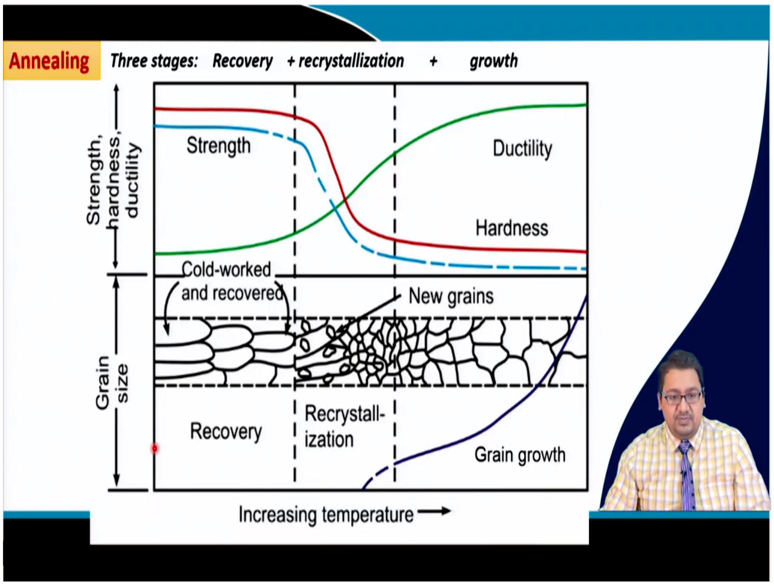

So, let us start with what is annealing and of course, this information is just a revision for all the students, who are doing this course. But let us look into it into in a different perspective. We see that when we deform a material particularly a material, which is cold worked; a cold worked material is having elongated grain, say it is a cold rolled material. Say for example, aluminum, copper, or steel has been cold roll largely and if we look in the transverse direction plane, you will find that elongated grains present in it.

Now, depending upon the stacking fault energy of the material, say we are talking about high stacking fault energy material or medium stacking fault energy material. Where recovery is predominant, then with cold rolling and with a sometimes while doing cold rolling for aluminium, which has a lower you know melting temperature, recrystallization temperature thereby is much lower and much nearer to the room temperature.

Recovery may occur and in case of those materials, where a little warm temperature could be given and then, recovery may take place. So, this is a plot which shows in the x axis with the increase in temperature and we can see that in this part of the plot, we have shown elongated grain and we have observed the transverse direction after cold rolling and after recovery. We can see that with a certain increase in the temperature, there is a recovery going on inside the material. But this will not affect the microstructure at all.

The recovery of the material, we will talk about it in the coming slides. But we when we will look them into the microstructure with the help of optical microscope or with the help of scanning electron microscopy imaging, we will see that the grain boundaries are intact and there is no change in the grain boundary.

Now, in this region, while with the increase in temperature recovery is taking place, you will see that the strength and the hardness of the material slowly decreases; but its decrease is very minimal. At the same time, we will see that the slight increase in the ductility.

Now, when after this cold rolling and recovery stage, there is a point when the temperature of the material is increased. So, what we are doing? We are doing an annealing right. So, when the temperature of the material is increased, slowly slowly smaller and smaller grains starts to nucleate at the grain boundaries; particularly, it starts to nucleate at the most highest strain points of the microstructure, which is the grain boundary and the most strained areas of the grain boundaries are the triple junctions.

So, small equiaxed grains starts to nucleate at the triple junctions of the grain boundary and then, at the grain boundaries and slowly slowly you will find the smaller and smaller grains nucleate and it fills up the microstructure, which initially had larger elongated grains.

Now, this process is known as recrystallization, where we can observe a substantial change in the microstructural morphology, which were initially elongated and now, they are slowly becoming you see initially a bimodal kind of structure and then, it becomes a equiaxed grains with smaller grain size as compared to the initial cold worked and even the recovered material.

At this position, in this position, the position, which is known as recrystallization, we can see that there is a substantial decrease in the strength as well as the hardness of the material. At the same time, there is a substantial increase in the ductility of the material. With further increase in the temperature, we will observe that the grains which are equiaxed and small in this region starts to grow and grow and grow. So, this region where the grain basically grows is known as the grain growth region. We can see that as the grain grows, the average grain size can increases and this is given by this plot here. On the other hand, you will see that there is a slight decrease in the hardness with the increase in the grain size and the there is a slight decrease in the strength with the increase in the grain size and this is relative to the Hall-Pitch relationship and the grain boundary strengthening equation.

You can see that the ductility increases also slightly with the increase in the grain size. So, what we understand that annealing that is static recrystallization consist of three stages; one recovery, second recrystallization and third the grain growth right.

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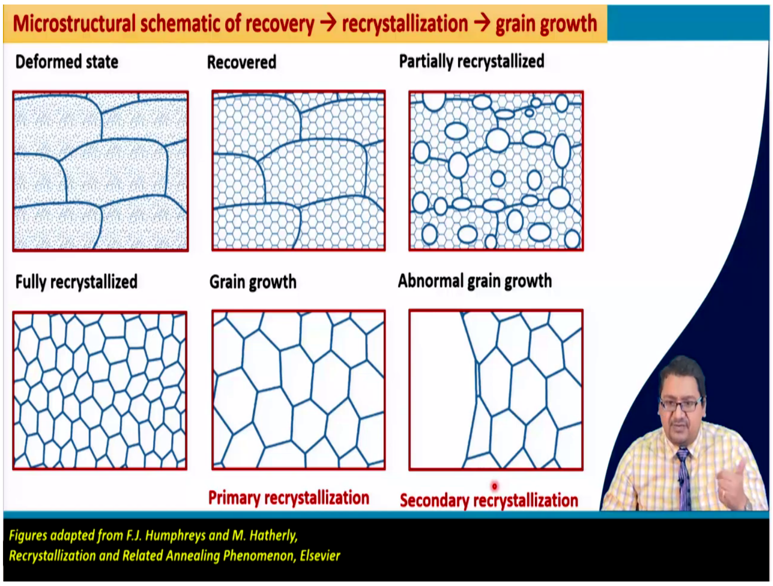

So, if we look into the microstructural aspect of this recovery recrystallization and grain growth in detail, we can see that in the cold rolled state in the cold deformed state, the material as I said we are looking into the transverse direction, we will look elongated grains and say this is the direction of the rolling.

So, this is RD and the direction coming out of this slide is TD and the vertical direction is ND. So, we can see that the grains are elongated along RD and they have dislocations, which are arranged randomly throughout the microstructure. These dislocations are mostly statistically stored dislocations. And apart from that, even in the cold rolled structure, there will be you know geometrically necessary boundaries definitely and there will be other boundaries through, which can occur due to recovery.

But in order to give an idealistic information of the recrystallization stages, let us say that the deformed state contains only statistically stored dislocations, which are randomly arranged throughout the microstructure and they are shown by these dotted points. Now, when the material is put into a little warmer temperature, what happens that these dislocations which are randomly arranged, they try to come together and annihilate each other or rearrange themselves to form dislocation boundaries.

As we have discussed about the formation of dislocation boundaries, dense dislocation wall, incidental dislocation boundaries which occurs due to the formation, such kind of formation. Where the randomly arranged dislocations come together, the unlike dislocation they annihilate each other; the light dislocation, they come together to form dislocation boundaries, dislocations arrays which we are we call it incidental dislocation boundaries or dense dislocation walls. We call them cells and subgrain formation.

This cells and subgrain formation of equiaxed structure inside the grain is known as the process of recovery right, and when after this recovery, we can see that there is no change in the microstructural features that is the grain boundary remains same as that of the initial you know cold rolled structure. But as we increase the temperature further, we can see that mostly in the most highest strained region, that is the grain boundary triple junction first and then, comes the grain boundary and then, even the other positions. Where there is high stressed region may be because of the presence of second phase particles and there will be other aspects, where there could be high strain regions in different parts of the microstructure, new grains nucleate.

And these new grains which nucleate in the grain microstructure, they are known as nucleation due to recrystallization phenomena. And this kind of a microstructure, where the new smaller equiaxed and sometimes elongated grains that develop and this elongation is developing.

Because say for example, instead of a static recovery or recrystallization dynamic recovery and recrystallization is taking place, so the equiaxed grains that are forming are continue are forming in a continuous manner in a dynamic manner during the deformation. So, equiaxed grains are forming and they are deforming; so, they are getting elongated.

So, the point is that such a situation, where in the large elongated grains, the presence of small equiaxed grains are there, this situation in the microstructure is known as partial recrystallization. So, this could be a partial static recrystallization or a partial dynamic recrystallization depending upon the situation.

Once this temperature is increased in case of the static annealing or static recrystallization, these equiaxed grains starts to grow right and they more equiaxed grains like this nucleate in the grain boundaries and they form throughout the microstructure. Such a microstructure is shown here, where a lot of recrystallized grains nucleate and the initial cold rolled structure is completely gone, such a situation. Where the microstructure which was initially cold rolled and elongated grains having elongated grains, they form a microstructure which is like this equiaxed smaller grains as I was talking about in the last slide is known as full recrystallization.

Following the full recrystallization, there is a process, which is known as grain growth. So, certain grains grow in the expense of the other grains and then, such a situation is shown in this microstructure, schematic of the microstructure which is known as the grain growth. So, the condition of deformed state, which leads to recovery partial recrystallization, full recrystallization and grain growth is known as primary recrystallization process.

Continuing the temperature increase, we can see that there is a secondary recrystallization, which could be observed by abnormal grain growth of certain grains in the expense of the other and we can see larger grains forming in various parts of the microstructure and this abnormal grain growth, secondary recrystallization could be observed, when primary recrystallization is sometimes restricted right. So, this is the whole microstructural schematic of recovery recrystallization and grain growth.

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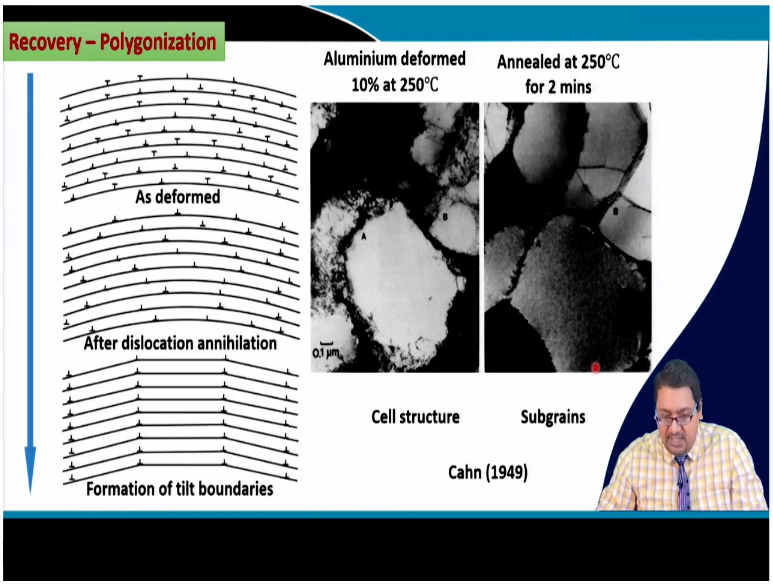

So, recovery as explained earlier is a process of polygonization. So, polygonization is a process, where you see any deformed material contains statistically stored dislocations. So, you can see there is there are lots of dislocation present throughout the microstructure and now, because of the plastic deformation induction in the material and the presence of multiple grains to maintain the grain boundary contiguity, the lattice of the grains becomes you know becomes curved; you see curved.

So, presence of deformation induced lattice curvature in the material leads to rearrange the, you know dislocations in such a way that the unlike dislocations when they come together, they annihilate and when the light dislocation, they come together, they arrange themselves in such a way so that to lower their energy and to form dislocation arrays.

So, as deformed material, when it gets recovered, some dislocations get annihilated and then some dislocation, they arrange themselves in a fashion so that to lower the overall energy of that portion of the microstructure and form you know dense dislocation walls or incidental dislocation boundaries. So, such a situation of polygonization is known as the recovery process.

If we look into two figures microstructure shown by Cahn et al in 1949, we can see these are aluminium, which is deformed at 10 percent at 250 degree centigrade. You see that when the such a situation occurred, the dislocations arrange themselves to form you know dense dislocation structures, which are the boundaries, which are in a diffused form and this kind of a situation, you can see the one grain and the other sorry, cell structure, this is within a grain ok.

So, the grain will have a much larger size and then, when it is annealed at 250 degree centigrade for 2 minute, we can see that sharp boundaries develop. So, this is the way when the diffused cell boundaries which are known as the cell structure, forms sharp boundaries which is known as the subgrain structure, during the process of annealing with the increase in temperature or keeping the temperature same with the increase in time right.

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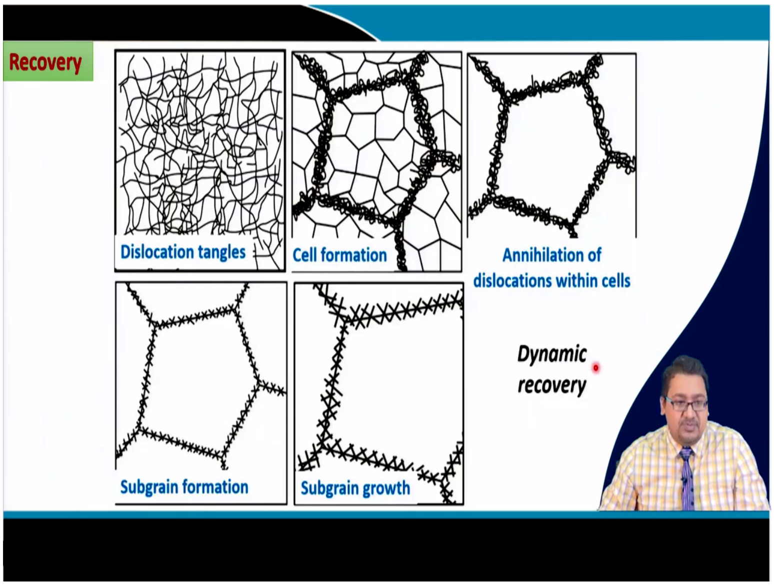

So, recovery process; so, recovery process consists of basically the presence of dislocations or dislocation tangles being randomly present throughout the cold deformed cold plastically deformed microstructure and the formation of cell structure with diffused dislocation wall ok having a high density of statistically stored dislocation at the boundaries, and the low density of statistically stored dislocation inside the cell.

And then, with the time or with the increase in slight increase in the temperature, these boundaries becomes more, dense and more sharper and the annihilation of dislocations within the cells takes place. Because this situation slowly reduces the, you know overall energy of the microstructure to form sub grains.

These subgrains with time, keeping the temperature same or with the increase in temperature, they grow and this is known as subgrain growth. The same situation which occurs in recovery can occur both in the static recovery situation and also in the dynamic recovery situation. However, in the dynamic recovery situation, the presence of subgrain growth is not there.

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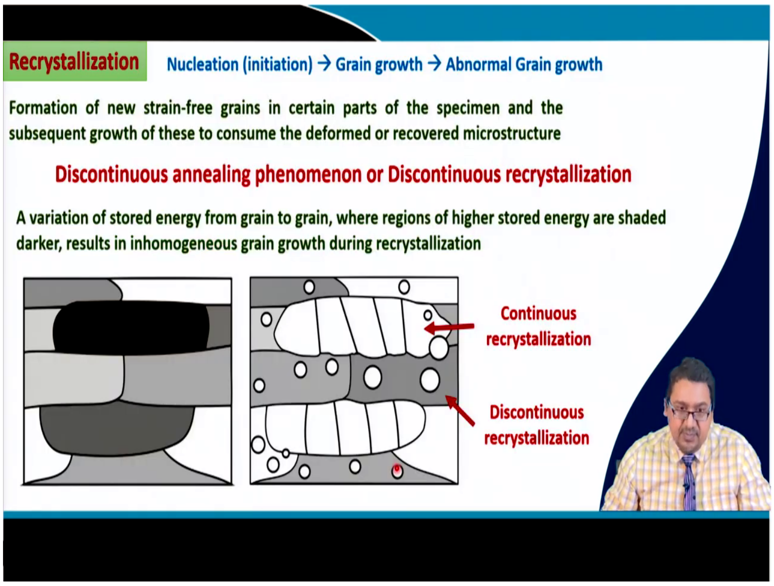

So, recrystallization. So, we have understood that what is the recovery; now, the second stage of recrystallization, which itself known as the recrystallization. So, the recrystallization basically consists of the nucleation or initiation of new grains right and that as we can see can only occur at the presence, where there is a very high stress concentration and that could be the triple junctions of the grain boundary, when it is deformed. So, nucleation or initiation is a better word for that and then, followed by grain growth and abnormal grain growth occurs. So, the formation of new strain free grain in certain parts of the specimen and the subsequent growth of these to consume the deformed or the recovered microstructure is basically recrystallization phenomena right.

So, there could be you know two types of recrystallization; two types of static recrystallization. So, discontinuous static recrystallization or continuous static recrystallization, one can say discontinuous annealing phenomena or continuous annealing phenomena.

Now, you see this discontinuous annealing phenomena may occur you will see most of the time. But when it occurs? When the deformation is less and the temperature to anneal the material is given is large, when the material is less (Refer Time: 20:29), then there are certain portions of the microstructures and certain triple junction areas only in the microstructure which is highly strained right.

So, the grain forms, it nucleates on those strained regions only. So, newly equiaxed grains forming at different regions of the microstructure. While it forms we can see the initially cold rolled deformed material tube, such a situation is known as a discontinuous recrystallization. In case when there is a large amount of deformation and the whole microstructure is heavily strained, a small amount of temperature if given to the microstructure, there is no division between nucleation, partial recrystallization or full recrystallization. And the whole microstructure converts into in to a different microstructure initially, which were elongated grains and it is now fully recrystallized equiaxed grains, without any division between nucleation and growth.

Such a situation is known as continuous static recrystallization or continuous annealing phenomena. If we look if we look into this schematic of the microstructure, you will see that the microstructure has been made in such a way that the colour, the darker colours, they show that the most deformed or the most strained grains the lighter the colours of the grain, those grains are less strained. So, during a plastic deformation, the deformation in the microstructure will not be homogeneous. So, there will be heterogeneous deformation present in the microstructure. Certain grains will definitely deform more and certain grains will definitely deform less and of course, it will also depend upon the initial texture of these different grains.

And so, when these grains which have deformed to a larger extent will recrystallize with a little amount of temperature in such a way that the whole grain is now subdivided into smaller equiaxed grain as shown here and it will be the least strained region after the recrystallization. Such a phenomena that can be observed in a high strained region of the microstructure is known as continuous recrystallization. While those grains which are moderately strained or less strained have only very high strained energy associated with the triple junctions of the grain boundaries. Under such situation, what will happen that the newly equiaxed grain will form at the grain boundaries or the triple junctions.

And as you can see that few of the newly formed grains are also forming at the centre of the grain, they indicate that there is a grain boundary which is coming from below or above this microstructure. Because we should always remember that the microstructure is not a two-dimensional structure. We observe this because we it is easier for us to observe this microstructure on the piece of the paper; but basically it is a three-dimensional structure right. So, the grains are volume and the grain boundaries are not like lines, they are like areas right.

So, these equiaxed grains which are forming in the microstructure are forming because there is a presence of grain boundary maybe on the top or bottom of this you know slice of the microstructure.

So, we understand that a variation of stored energy from grain to grain, where regions of higher stored energy are shaded darker and results in homogeneous grain growth during recrystallization like continuous recrystallization and, where there is you know the grains are forming separately, they are known as discontinuous recrystallization.

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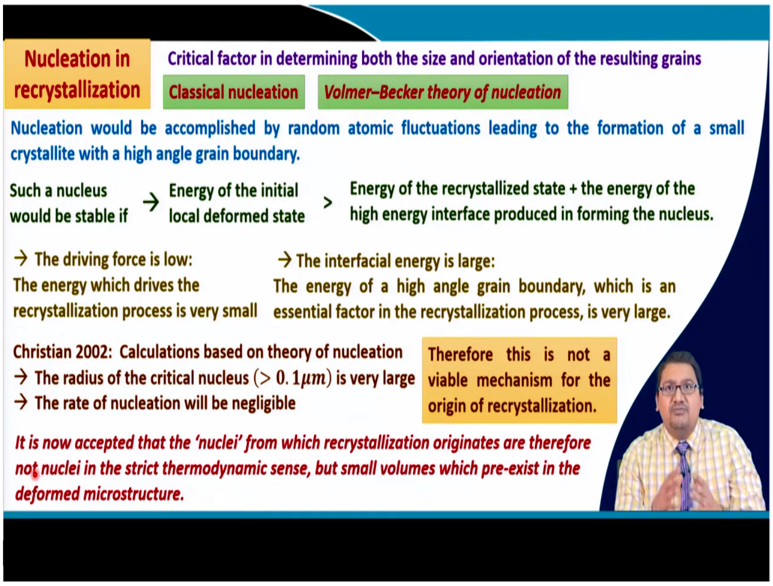

So, recrystallization; as I said consists of nucleation. So, giving emphasis on nucleation during recrystallization phenomena; so, nucleation in recrystallization. So, the critical factor to determine both size and orientation of the resultant grain. So, nucleation is the critical factor that determines both the size and the orientation or the texture of the resultant grain.

So, let us talk initially about the classical nucleation. Classical nucleation is the Volmer Becker theory of nucleation. So, nucleation would be accomplished by random atomic fluctuation leading to the formation of a small crystallite with a high angle boundary right. Now, such a nucleus will be stable, if the energy of the initially deformed material; so, the local area of the initially deformed material. Where this recrystallization or nucleation phenomena will take place will be greater than the energy of the recrystallized state; that means, the energy of the newly nucleated grain at that position plus the energy of the high energy interface produced by the formation of that nucleus right.

So, if there is a highly strained region say for example, the region of the triple junction which is highly strained and so, the energy of that local deformation region will be very high and the nucleus will only take place or only evolve at that position. When the energy of that local deformed area will be greater than the energy of the newly formed nucleus plus the energy of those high energy grain boundary surrounding that nucleus, which is forming in that strained energy situation right. So, if we look that the interface energy that is the energy of that grain boundary, the interface between the deformed state and the new nucleus that has formed is always very high. So, the energy of a high angle grain boundary which is an essential factor of the recrystallization process is actually very very large. So, this is what we should understand. So, the driving force for such a nucleation should be usually very low.

So, the energy which drives the recrystallization process is very small. So, you see Christian in 2002 calculated based on the theory of nucleation ok, the radius of the critical nucleus. He found out that it has to be greater than 0.1 and then the, if it is less than 0.1, then the nucleation rate will be very negligible. The rate of nucleation will be very negligible. So, therefore, this Volmer Becker theory of nucleation may not be a very viable mechanism for the origin of the recrystallization process.

So, it is now accepted that the nuclei from, which the recrystallization origin originates are therefore not nuclei in a strict thermodynamic sense; but small volumes which may pre-exist in the deformed microstructure, small volumes which could not be observed using optical microscope or scanning electron microscope. They may be already present or pre-exist in the deformed microstructure.

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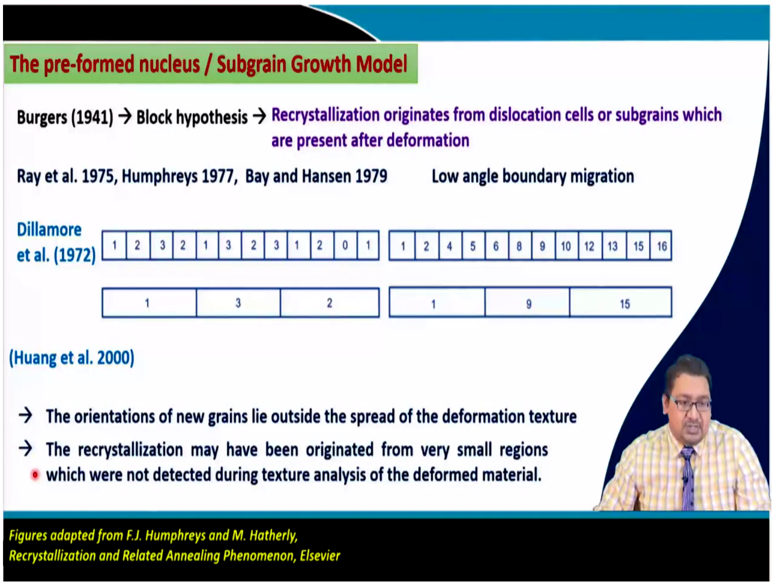

So, the second theory of recrystallization is the pre-formed nucleus or the subgrain growth model. So, considering that the original nucleus is already present inside the microstructure, Burgers at 1941 gave the Block hypothesis. So, he said that recrystallization originates from dislocation cells or subgrains, which are present after deformations; whereas, Ray et al. in 1975, Humphreys in 1977, Bay and Hansen in 1979 showed that low angle boundary migration may lead to the formation of recrystallization.

Dillamore in 1972, showed that if a grain contains you know, if say this is a grain and this grain, if we look at different areas of this grains and if we look into the orientation of these grains in different areas, say the orientation comes 1 and then, the in the next area, it comes 2. Which is very slightly different from the 1 orientation and then, 3 and then, 2 again and 1, 3, 2, 3, 1, 2, 0, 1; that means, there is very less difference between the orientation of the neighbouring pixels within the grain. Then, the recrystallization process will produce you know will produce you see 1, 3 and 2. For example, considering the agglomeration of these four you know subgrains and the agglomeration of this four subgrains and this four subgrains producing a average orientation of 1, 3 and 2 at three different position of that grain.

Now, 1, 3 and 2, the orientation difference is not very high. So, the mis-orientation between 1 and 3 and 3 and 2 will may not make a grain boundary and maybe it is still a subgrain boundary. So, this process may lead to just recovery right. So, that is just like an increase in the subgrain or the growth in the sub grain. So, the process as Dillamore said that if a grain does not contain you know large mis-orientations difference from one area to another that is if the grain does not have large lattice curvature, then the process is still a recovery and not a recrystallization. However, if the grain, if a single grain has a large difference in orientation in different areas of different in its different areas say 1 here and 2, 4, 5, 6, 8, 9, 10. So, there is a change in the orientation slowly slowly slowly; but its gradual and so, the angle between 1 and 2 is a low angle boundary say it is very small, say it is just a dislocation array which is 1 to 2 degrees and like 2 to 4 degree and between 2 and 4 something like that.

So, very small mis orientation angular difference between different areas of the microstructure, which are spatially together and when this microstructure is basically annealed; then you can see that agglomeration annihilation of dislocation and you know agglomeration of dislocation and making a larger single boundaries, the orientation of different areas of that grains will become now 1, 9 and 15.

Such a situation is like this that the orientation difference between the 1 and the 9 is very high and the orientation difference between the 9 and the 15 is also very high. So, that orientation different difference that is the mis-orientation or if you like to call it disorientation becomes higher and it becomes higher than 15 degrees. So, it becomes high angle boundaries or grain boundaries and therefore, such a situation may exist where the subgrain growth model may lead to the formation of high angle boundary.

So, now, the single grain is divided into three grain in this schematical example right. So, Haung et al also contributed to this aspect. So, we found out that the orientation of new grains lie outside the spread of the deformation texture ok. Secondly, the recrystallization may have originated from very small regions, which are not detected during texture analysis of the deformed material.

So, there are situations, where even the orientation of the newly formed grain is entirely different from that of the deformed microstructure and such a situation as can be originated only if very very small regions of that microstructure is of that grain is present, which was undetectable, when the material was in the entirely deformed state.

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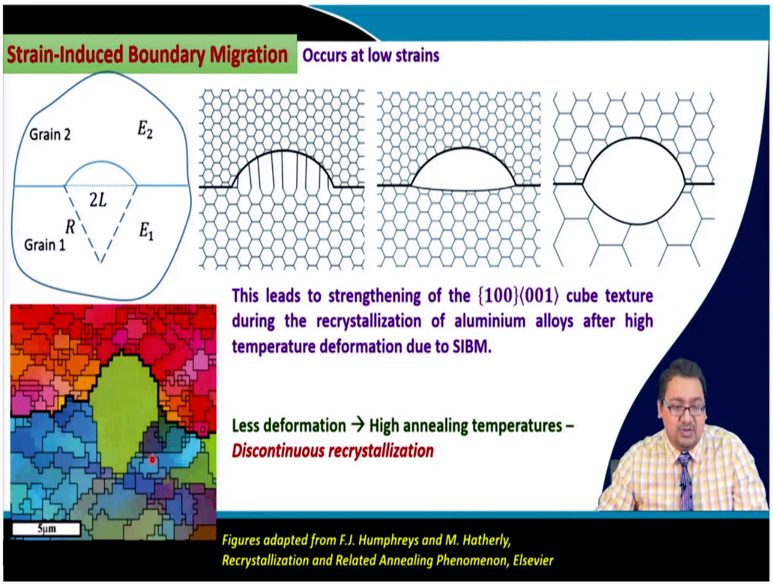

So, you see there is another model of recrystallization and this is a strain induced boundary migration model. And such kind of situation is mostly observed in low initial strain conditions. So, low deformation condition. Such a model states that as the deformation as the deformation is not heterogeneous as I explained in few slides before.

So, if we take a grain boundary, a grain boundary right, a grain boundary which contains two grains; grain number 1 and grain number 2. And if the grain number 2 is deformed more than the grain number 1, then the energy of the grain number 2 is higher than the energy of the grain number 1 that is the plastic strain energy that we are talking about.

So, if we try to give some amount of temperature for recovery and recrystallization to both this grain, then initially, it will form a subgrain structure inside the grain, because initially, it will have dislocations which are tangled and present throughout the microstructure, throughout this these grains right.

So, once a little bit of energy is given in form of temperature, these dislocation in order to lower its plastic energy will form cell and subgrain structure. So, as this grain is more deformed than grain number 1 if as grain number 2 is more deformed than grain number 1, then the subgrains will be of a smaller size in case of grain number 2 as compared to the grain number 1.

So, if we look closely, the dislocation density in the grain number 2 as it is higher than the grain number 1 with in order to reduce the strain energy of the material. The grain boundary will shift towards the higher dislocation area in order to consume the you know the mis-orientation or dislocations consuming that into that bound into this boundary and increasing its mis-orientation.

On the other hand, you will see that these dislocations will you know elongate, the boundary will elongate and slowly these dislocations will also rearrange themselves in such a way such that few annihilate, few dislocations annihilate and few dislocation rearrange to form another boundary here. So, there is a dislocation you know because of the difference in the dislocation density, the formation of this bulge and the formation of this boundary leads to produce a newly formed you know recrystallized nucleus. Which is the could be the initiation of a new grain during the recrystallization process and this process is known as strain induced boundary migration ok.

You can see that here is a schematic, which is adopted from the book of Humphrey and Hatherly, Recrystallization and Related Annealing Phenomena of Elsevier. You can see that there is in the formation of a bulge in this material as this red grain is having a high dislocation density as compared to this blue coloured grain in the inverse pole figure map. And we can see that this bulged high angle grain boundary is forming; on the other hand, still these bound this boundary is in a low angle state, but slowly it will grow and its mis-orientation will increase and it will become a high angle. So, in this way, you know a small nucleation during recrystallization will occur and thus, strain induced grain boundary migration could lead to recrystallization.

In our another lecture, I will show you in quite a detail that how strain induced grain boundary migration leads to serration of the grain boundary leading to dynamic formation of this bulge and a nucleus during the recrystallization process for case of magnesium alloy. So, this leads to strengthening of the 100 001 cube texture during the recrystallization process in case of FCC material of high stacking fault energy such as aluminium, aluminium alloys copper etcetera right, after high temperature deformation, the process is SIBM, that is Strain Induced Binary Migration.

Less deformation and high annealing temperature as I said, produces discontinuous recrystallization in such a process; whereas, high deformation and low annealing temperature produces this kind of situation as a necklace kind of structure seems to be like a continuous recrystallization, we will talk about it.

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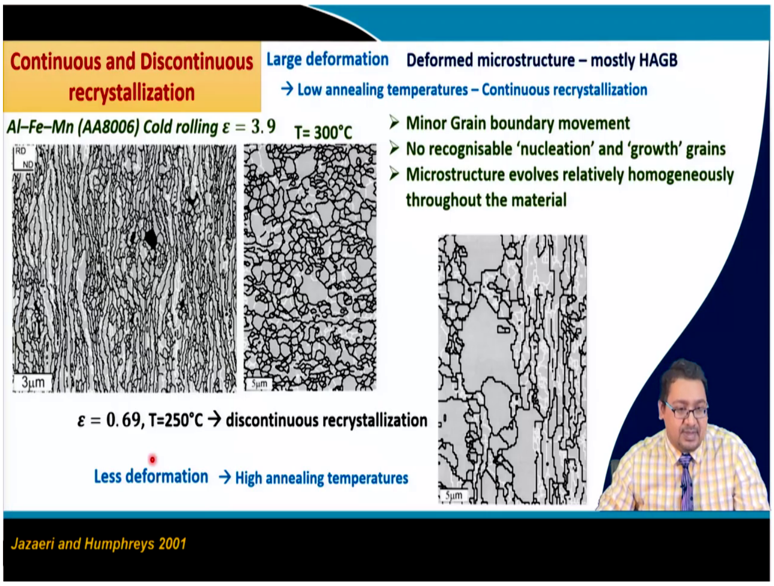

Now, let us say how in static recrystallization phenomena a continuous and a discontinuous recrystallization looks like. Let us take an example of aluminum Fe-Mn known as AA8006 alloy, cold rolled to a strain of 3.9. So, a large deformation is given. So, deformed microstructure, we can see; elongated microstructure could be observed. So, the vertical is the RD and the horizontal direction is the ND. We are looking in the TD direction as usual transverse direction.

And if a low annealing temperature is given to this material, continuous recrystallization takes place and even if the temperature is slightly larger also, then also continuous recrystallization will takes place because there is already a large amount of plastic strain energy inside that microstructure. Now, continuous recrystallization phenomena as given in this example, from the paper of Jazaeri and Humphreys in 2001, we can see the microstructure after a temperature of 300 degree centigrade have no stresses of the initially deformed grains. The RD remains the same vertical and the ND on the horizontal. And we can see that the microstructure is entirely equiaxed.

Such a situation, where there is no division between nucleation and growth stages and there is no stress of the initial cold rolled or the cold deformed microstructure is known as continuous recrystallization. So, we can observe that if we look there is a there is minor grain boundary movement. There is no observation of grain boundary movement. No recognizable nucleation and growth grains. Microstructure evolves relatively homogeneously throughout the material right.

Whereas, if we talk about discontinuous recrystallization, if we take the same alloy and cold roll it to a much lower strain say 0.69. And then, we will get elongated grains. But of course, the elongated elongation in the grains will be much lower than this situation, this situation and the, because the strain is lower and so, the plastic strain energy will also be much lower. So, a larger temperature has to be provided, but because this is aluminum, even if we give a temperature of 250 degree centigrade, we can see that within the elongated deform microstructure, the presence of newly formed smaller equiaxed grains in certain positions like here, like here, here right. But the cold rolled elongated microstructure is still in existence, such a situation is known as a discontinuous recrystallization phenomena right.

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So, what we understood from this lecture class is that one, annealing or recrystallization phenomena consist of three stages right; recovery, recrystallization and grain growth. It should also include secondary recrystallization, which is abnormal grain growth right. Recovery is a process of polygonization, where randomly arranged statistically stored dislocations rearranges themselves to lower the strain energy to form cell and subgrain structure.

So, deformation induced lattice curvature helps in obtaining geometrically necessary boundaries right and then, during the process, this could lead to later static recrystallization with the increase in temperature right. So, recrystallization as I said could be discontinuous process or a continuous process right.

Nucleation of grains in recrystallization, there are three theories; one is the Classical nucleation that is the Volmer-Becker theory; second, the pre-formed nucleus or the Subgrain Growth Model and the third is the Strain-Induced Boundary Migration model.

Thank you for today's class.