Texture in Materials
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Module - 09
Theory of deformation texture evolution
Lecture - 46
A Metallurgist Point of View

Good afternoon, everyone and we are doing the module 9 which is Theory of deformation texture evolution. So, in the lecture 44 and 45, we try to understand the basics of mechanics or basic principles that involves plastic deformation in terms of polycrystalline plasticity and how in very fundamental manner we try to understand that how the models have been developed.

And, what is Taylor model, what is Sachs models and why Taylor model is full constraint and Sachs model is no constraint model and how in between models are developed by using a interaction parameter alpha and varying that interaction parameter in order to find out you know deformation texture evolution, as well as strain hardening behavior in more realistic manner during the simulation process.

So, today we are going to do lecture number 46 and I am I will try to state the Metallurgist point of view relating deformation texture evolution.

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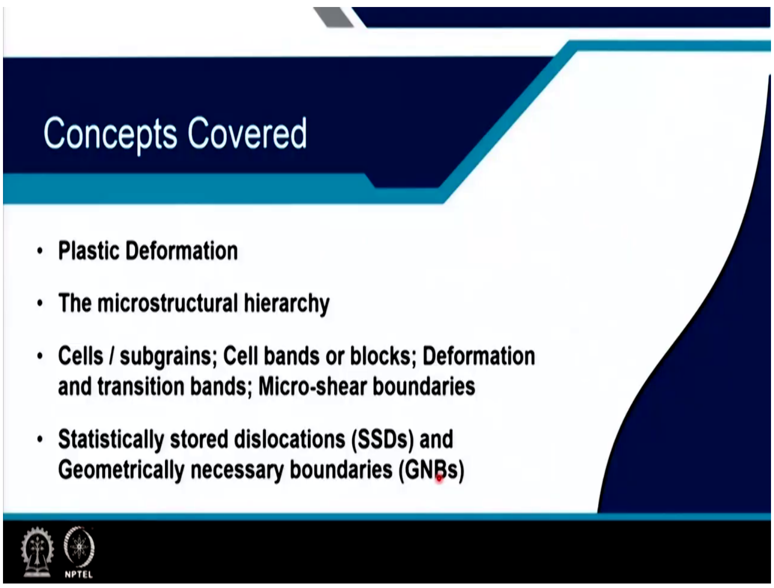

So, the content of this course are plastic deformation relationship; then microstructural hierarchy which includes cell subgrain structure, cell band block structure, cell block structure, deformation or transition bands, deformation bands, transition band, micro shear band boundaries and finally, statistically store dislocation and geometrically necessary dislocations definition and all these things.

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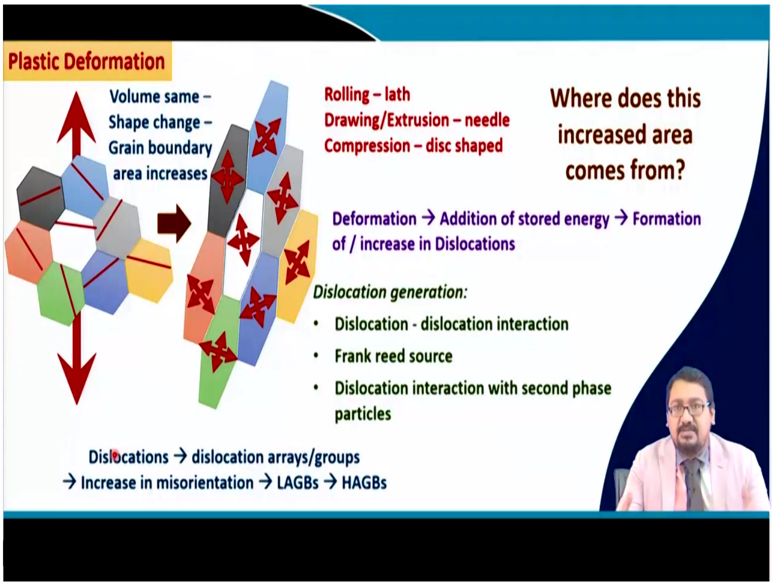

Plastic deformation as I said involves the example that I have given a tensile example involve the shape change of each grain from equiaxed to elongated for this tensile deformation and this is subjected to you know shape change, but volume constant, right. So, the volume remains the same.

Now, if we look into each of these grains, the elongation of each grain due to multiple you know stress state in different stress state in each grain leads to an increase in the grain boundary area. Now, say for example, rolling that will produce lathe type of structure, lathe type of grains from elongated grains, in case of drawing or extrusion needle type structure will develop in case of compression pancakes type structure will develop.

And, all this structure which is forming say from initial equiaxed plane will comprise of an area of a grain boundary much larger than the initial material. Now, where does this increased area coming from? Now, deformation plastic deformation rather is like you know addition of stored energy in the material and this addition of stored energy inside the material is basically in physical form should be addition of dislocation structures in the material, right.

So, the stored energy that is given to the material in terms of an applied stress which comprises of a plastic deformation in the material is stored in forms of defects which are mostly in forms of dislocation in the material, right. So, during plastic deformation see the initial material always contains some amount of dislocations even if it is extremely annealed condition and then also there will be a minimum amount of statistically stored dislocation that will be present in the material.

And, so, this dislocations will interact with each other during the deformation they will interact and annihilate sometimes, they will interact and form dislocation arrays, their mis-orientation will increase. Now, new dislocations will also start to develop we know that there are frank reed source or other kinds of sources which will continuously generate newer and newer dislocations.

So, these new dislocations will also interact with the other dislocations or the dislocation arrays that are present in the material leading to increase in the dislocation sub structures in the material. Thirdly, the dislocations may also interact with the second phase particles which are present in the material.

So, dislocations which are present they interact, they form they interact and they form dislocation arrays, they form dislocation groups and they increase their misorientation. So, the dislocation arrays misorientation will keep on increasing, it will be initially diffused then it will become sharper and it will become a low angle boundary and then it will become you know it will further increase in misorientation and form an high angle boundary.

This way the area of the grain boundary for each grain will keep on increasing during the deformation.

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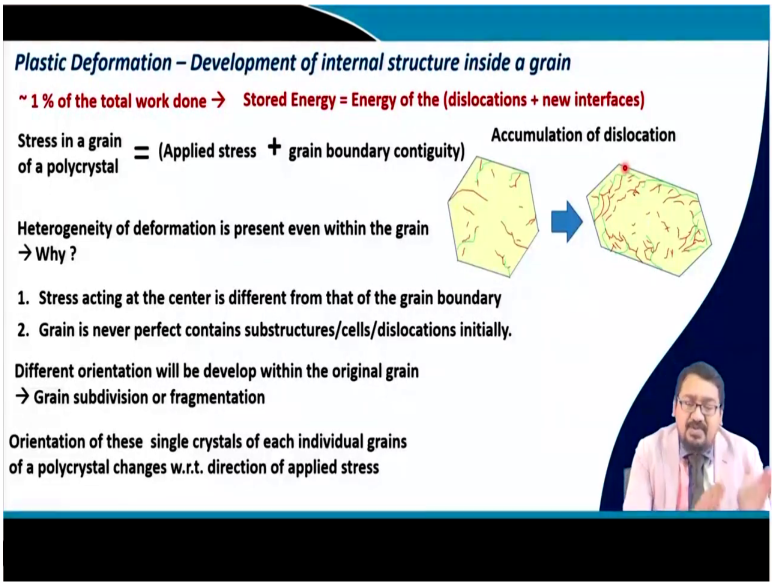

So, as I said the plastic deformation that is responsible for developing the internal structure inside the grain, only 1 percent of that you know work done to the material work given to the material is converted into this stored energy. 99 percent is basically converted into heat and only say 1 percent of this is converted into stored energy, that is the energy which is related to the formation of these dislocations and this dislocation related new interfaces.

So, as you know that in Taylor model and in the plastic deformation of polycrystalline aggregate minimum 5 independent slip systems are needed because not only the applied stress has to be fulfilled, but the complex stress associated with the grain boundary compatibility has to be fulfilled.

So, this situation exists along with this the deformation in the material in the grain will not be homogeneous as assumed in the Taylor model. The deformation within each grain will be rather a heterogeneous deformation. And why it is so? Let us take this equiaxed grain say it is a extremely highly annealed microstructure.

So, this grain will contain the least amount of dislocations or dislocation arrays present in it and let us say that there are dislocations with say the red ones are having misorientation of 2 to 5 degrees. So, low angle very low angle boundaries and the green ones say with 5 to 15 degrees and the blue ones which is comprising of the grain is basically greater than 15 degree greater than equal to 15 degree.

So, when it deforms you can see that this these parts of the grain which are near to the grain boundary and is associated with the other grain by the grain boundary and grain boundary compatibility is the issue in these position. The stress state in this regions of the grains will be more affected by the grain boundary contiguity. And, if we go towards the center of the grain then the stress state will be less affected by the grain boundary contiguity issue and therefore, it will be mostly almost similar to the applied stress state the of the material.

So, stress acting at the center of the grain will be different from that which is which will be acting near the grain boundary. So, there will be always a transition where the stress state will be different at the grain boundary, near to the grain boundary and little far away from the grain boundary and then at the center of the grain boundary. So, there will be difference in the stress tensor in each of this position.

So, grain will face different stress state at different areas of a different volume of it is of itself, right. So, the grain because it will experience different stress state will never deform homogeneously rather it will deform heterogeneously and thereby it will start having formations of substructure such as cell, cell band structure in the material, right in inside the inside them inside the grains.

So, different orientation will develop inside a single grain because of the different stress state and thus the grains will subdivide into you know cell structure, cell band structure, transition or deformation bands and overall we can say that there will be low angle, very low angle boundaries forming in the material.

So, orientation of these single crystals individual you know single crystal within this individual grain. So, there will be many small small single crystals that will form within this individual grains in the polycrystalline material will depends on the you know what you called the different stress state in the material.

Now, because of the different stress state in different regions of the grain orientations an orientation development in this different volumetric regions within the grain will be different. So, as different orientations will start to develop in different once second in different region of that original grain then there will be formation of grain subdivisions and thereby as I said formation of cell, substructure or different kinds of other microstructural features within the grain.

Like you know low angle boundaries may develop and thus this grain subdivision will finally, lead to grain fragmentation while this misorientation angles of this dislocation arrays will increase and will become greater than a certain value that is in our case we always say that 15 degrees or greater are equivalent to high angle grain boundaries and then therefore, the grain basically fragments into more than one grains.

So, now, orientation of this single crystals present within this whole grain will or will be different and thereby it will be subjected further to different stress states in the material.

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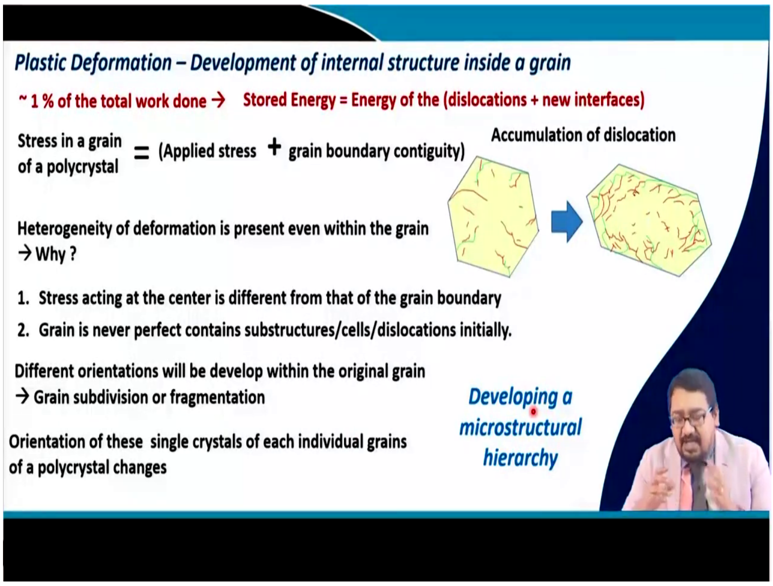

And, thus this situation basically leads to the development of a microstructural hierarchy in the material.

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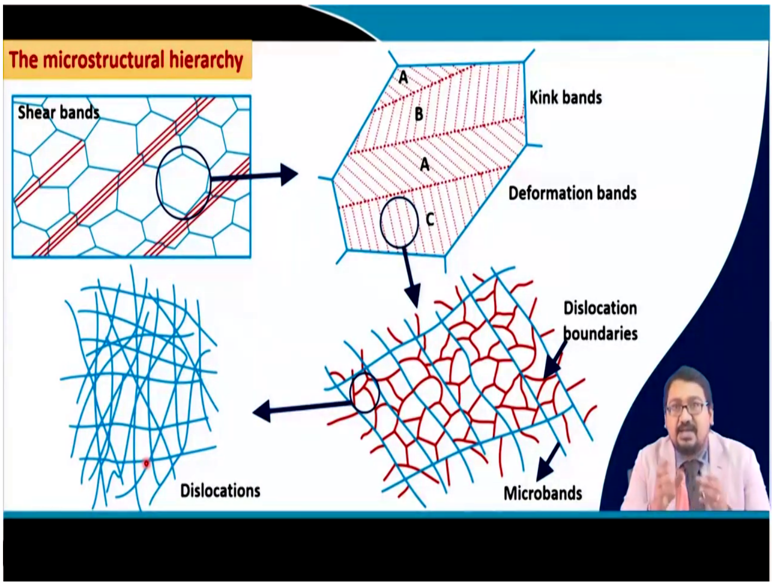

So, when we are talking about microstructural hierarchy if we look into a microstructure a less magnified microstructure after a certain deformation let us say that we have taken a polycrystalline material say for example, a face centered cubic aluminum and rolled it and if we are looking along the transverse direction then let us say that we have rolled under warm condition and so, that all the slip systems are fully activated.

And, if we are looking into the transverse direction of the microstructure and let us say that this direction horizontal direction is the rolling direction. And, if we look above is the normal direction so, you know that perpendicular to the normal direction is the rolling plane and so, this microstructure is of the transverse direction. So, plane perpendicular to the transverse direction when we are looking into this we will see that apart from certain elongated grain may be sometimes equiaxed a little elongation will be definitely there because it is a rolling.

There are band kind of structure which are formed which forms at a certain degree to the microstructure and irrespective of the orientation of these grains or the size and the shape of the of these grains such kind of shear bands develop. These shear bands are basically intensely strained areas of the microstructure which are at least 2 to 4 times more strained than the overall microstructure.

If we look deeper into this microstructure into a single grain say for example, this one then we will see that inside the grain there will be various kinds of structure like these bands which are known as deformation band and which will have this orientations which are different from the orientation of the neighboring bands, right.

Now, these orientations if it has a orientation of say C and then an orientation of A and then a orientation of B then these are deformation bands, but if the orientations are such that between two orientations A if there is another orientation B then such kind of situation is known as a kink band formation.

Now, if we look into this region inside a single deformation band, we will find that the microstructure is further divided into smaller areas and these areas are basically known as cell block structures. Now, if we magnify this area we will see that there are structures which are you know like this parallel lines, but not exactly parallel, but almost parallel lines which are known as cell blocks or cell bands or you know micro bands and within this cell blocks or cell bands there are other dislocation boundaries present.

And, this dislocation boundaries as you see contains a high dense dislocation boundaries in red color and inside that boundary the dislocation presents are in quite less amount. Now, if we look into this blue colored parallel lines which are known as cell band or cell block or micro band boundaries they have a misorientation slightly higher than the red color dislocation boundaries or the cell or the substructure boundary present in the material.

So, if we look inside this cell you know cell structure or dislocation boundaries we will find you know dislocation structures randomly oriented randomly present in the material like this; dislocation array is present in the material. So, this kind of microstructural hierarchy is present in almost all the material and this aggravates during the plastic deformation, and other dynamic recovery and recrystallization scenario during plastic deformation and even under static annealing scenario.

And, these microstructural hierarchy present in the material affects the properties of the material and they are affected by the different stress state at different positions of this these grains and relating to formation of a lattice curvature due to which different orientations developed in different region.

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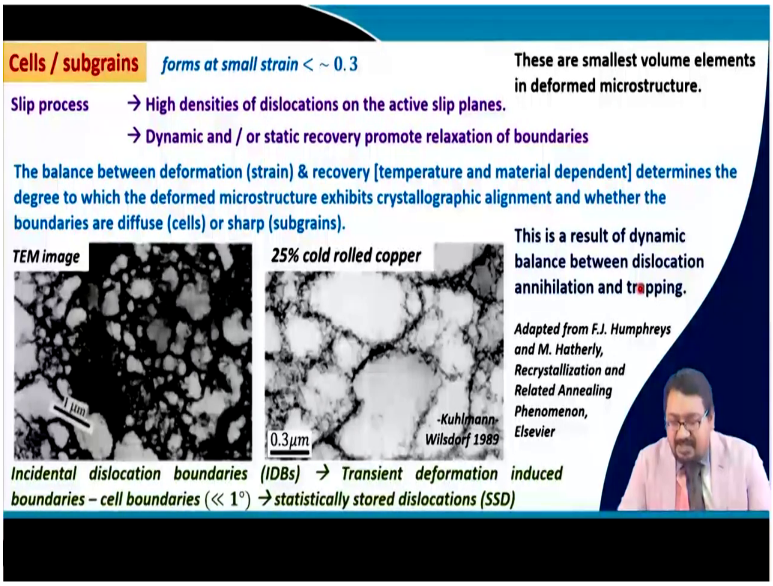

So, let us start with what is you know a cell structure or a subgrain structure whenever a material is slightly deformed say we have taken a high stacking fault energy face centered cubic material we I always say a high stacking fault energy face centered cubic material because you see these materials say for example, aluminum or copper have all the slip systems present in it.

And, there is no way in which the slip is restricted because of the high stacking fault energy and the less distance between the partial, the cross slipping of screw dislocation because the partial can meet and it will cross slip into another 111 plane as I said earlier in another lecture that and it will the screw dislocation will be enabled to cross slip whereas, the S dislocation will you know climb simultaneously to make the deformation possible make the material malleable, right.

So, cells and subgrain structures starts to form at very small strain say for example, 0.03 of points sorry 0.3 strain and these are basically smallest volume element of the microstructure. If you look into the TEM image and this is pure copper or 25 percent pure copper and this is from the paper of Kuhlmann and Wilsdorf. And, I have adapted these figures from the book of Humphreys and Hatherly.

And, you see that the TEM image of 25 percent rolled copper is given. In one position we can see that the strong you know dense dislocation boundaries are forming due to this presence of this dislocations, inside which it is mostly dislocation free. If we look into the another structure which is you know at a high magnification we can see that these dense dislocation boundaries either forms a cell or a sub grain structure.

Now, to tell you what is the difference between a cell and subgrain is; cells are those which have mostly a diffused boundary of dislocations. If the boundaries become more sharp it is known as subgrain structure. These boundaries basically have a misorientation angle much lower than say it is around 1 degree or less than 1 degree.

So, that it is very difficult to capture in electron backscattered diffraction in an SEM, but TEM images can not only capture them, but also can give the information about the small angular difference that is the misorientation of this boundaries if it is done under controlled condition in high resolution.

These boundaries are also known as incidental dislocation boundaries or they also known as transient deformation induced boundaries, they are also known as cell band boundaries and you have you see that these are less than 1 degrees. They are basically called statistically stored dislocations. We will come in the next slide may be to show the definition of statistically stored dislocation and geometrically necessary dislocations.

Now, during the plastic deformation the slip process in which you know high density of dislocations forms on active slip planes and then as I said that because of say as I said this is a copper. So, it is a medium to high stacking fault energy material, cross slipping of screw dislocation is not prohibited.

So, dynamic recovery or static recovery promotes a relaxation of boundaries to form such kind of cell subgrain structure. So, during the deformation the there is an increase in the dislocations in the microstructure as said earlier that during plastic deformation dislocations will increase.

And, with dynamic or static recovery which is associated with temperature increase and also material dependent as I said high stacking fault or low stacking fault which determines the degree to which the deformation you know microstructure exhibits crystallographic alignment and whether the boundary that forms will be diffuse type; that means, cell structure or sharp type; that means, a subgrain structure.

So, mainly there is a competition in the microstructure between the dislocations that is deformation is forming more and more dislocations, and recovery processes is balancing by forming dislocation with high dense region and low dense region in order to conserve the energy or lower the stored energy of the material affected by deformation strain rate temperature and the materials own property.

So, this is the result of dynamic balance between the dislocation which is created during deformation by dislocation annihilation and dislocation trapping, right.

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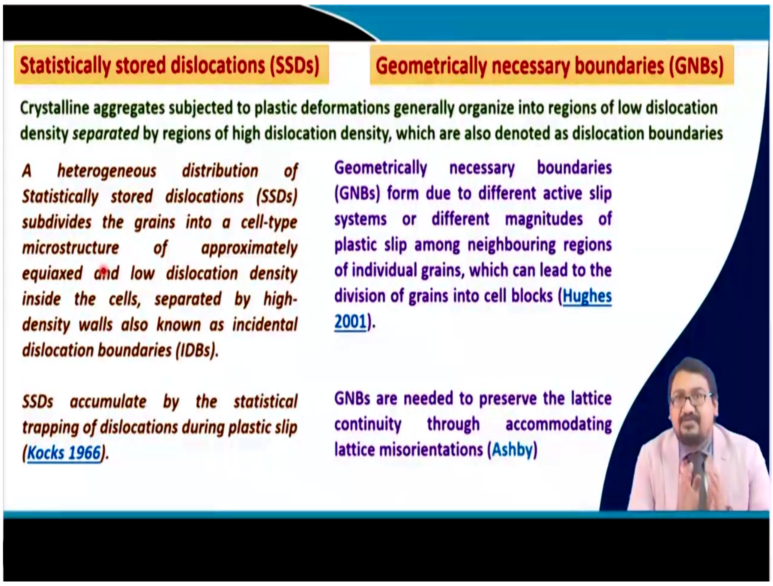

So, as I said there are two types of dislocations which are considered in metallurgy. One is the statistically stored dislocations and another is the geometrically necessary boundaries.

Now, crystalline aggregates which are subjected to plastic deformation generally organize themselves as I said in the previous lecture slide that it generally they generally organize themselves into regions of high dislocation density and low dislocation density, right. So, density that separates by regions of high dislocation density and low dislocation density and these high dislocation density regions are basically denoted as dislocation boundaries.

Now, a heterogeneous distribution of dislocations are known as statistically stored dislocation. If it divides if it subdivides the grain into cell type of microstructure of approximately equiaxed and having very low dislocation density inside these cells and the boundaries having high dislocation density and therefore, they are called high dislocation walls. These boundaries which are formed by statistically stored dislocations are known as incidental dislocation boundaries.

These boundaries have misorientation or disorientation angle which are quite less than 1 degree and they are having very that means, they are having very less orientation difference between two cell structure present specially together separated by this IDBs or incidental dislocation boundaries.

So, statistically stored dislocation is accumulated by statistical strapping of dislocation during the you know plastic deformation by dislocation slip process is was shown by Ashby et al in 1966. On the other hand, geometrically necessary boundaries formed due to differently active slip systems or different magnitudes of plastic slip among neighboring regions within the individual grain which leads to the division of grains into cell block structure.

So, if you remember the red colored cell structure and the blue colored parallel cell box structure is difference. The cell blocks are basically geometrically necessary boundaries they have misorientation angle greater than 1 degree, 2 degree or 3 degrees and statistically stored dislocation which are formed because of the necessary necessity to have dislocation statistical necessity to have dislocation in the material, having dislocation arrays, high dislocation boundaries of misorientation angle less than 1 degrees, right.

So, GNBs are needed to preserve the lattice continuity through accommodation of lattice misorientation. So, if you if I say how does statistically stored dislocation form and how does geometrically necessary dislocation forms; geometrically necessary dislocation forms because of the stress state heterogeneity present inside the grain at the grain boundary it will have the effect of grain boundary compatibility.

So, the stress state will be different and as we go away from the grain boundary towards the center of the material the stress state will continuously change and at the center of the material the you know nascent applied stress, Cauchy stress tensor will be more effective.

So, such difference in the stress state will lead to formation of slightly different – different orientations in different volumetric regions of the grain leading to produce a dislocation sub structural boundaries which is known as geometrically necessary boundaries. The geometrically necessary boundaries will have at least 2 to 3 degree misorientation thereby the region on one side and the other side of the boundary will be quite differently oriented.

Whereas, in case of statistically stored dislocation which forms by statistical strapping of dislocation during plastic deformation has orientation on both side of a SSD IDB boundaries almost same and thereby GNB boundaries are we are able to notice the GNB boundaries in EBSD SEM as very low angle and low angle boundaries, but not the statistically stored dislocation ones.

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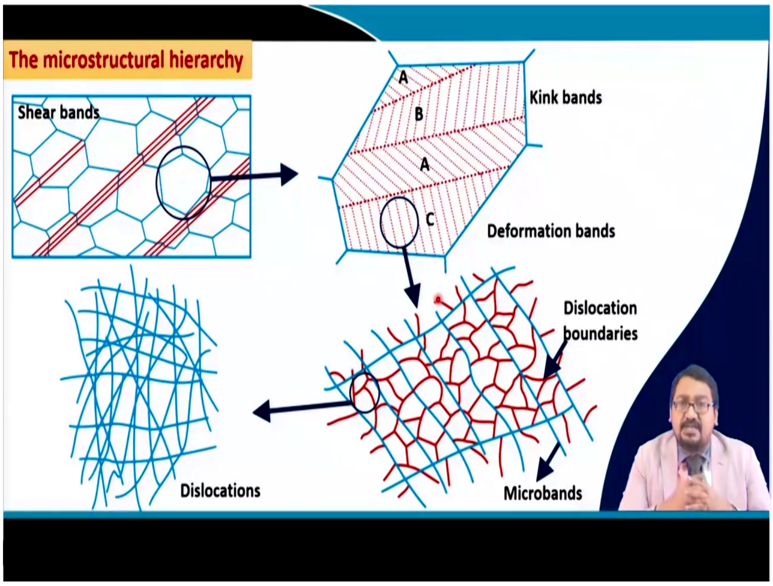

So, as I said that microstructural hierarchy shear band form and then deformation band form and cell band structure form.

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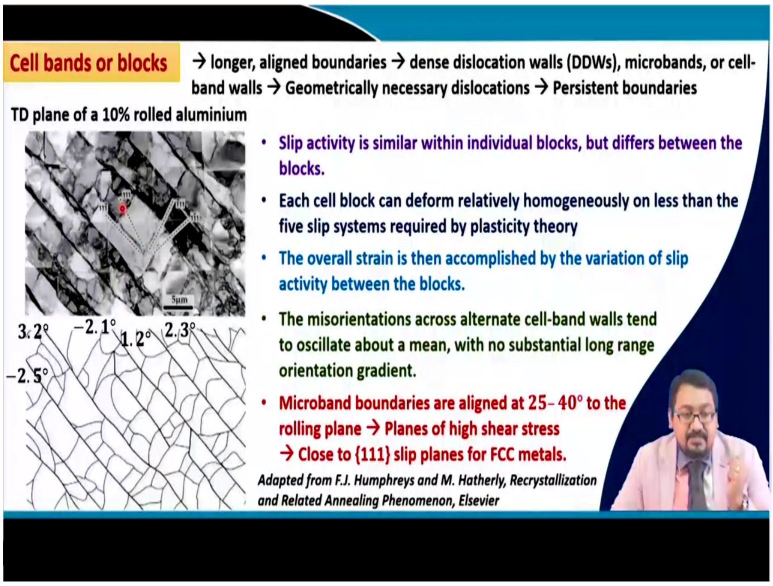

Let us look into the cell band or the block structure that developed in the microstructure. A cell band and block structure if develops in the microstructure look something like this and it will form at strains as I said less than 0.3 of the plastic deformation. So, a TD plane has been shown with the 10 percent rolled rolling reduction in case of aluminum as an example.

We can see that cell band structure parallel structure develops in them and in between this cell band structure we can also observe the formation of substructure subgrain or cells and as I said this cells and subgrains comprises of IDBs which are basically statistically stored dislocation with very low misorientation angle, non detectable using EBSD, but the cell band structure which will be having a 2 to 3 degree misorientation angle will be detectable through an EBSD.

We can see that if these are various cell band structure of the material then these schematic or the this is a schematic of the you know microstructure inside a single grain showing cell band structure and also showing cell structure and subgrains in it we can see that this misorientation of this band is about minus 2.5 degree and then it is 3.2 degree, minus 2.1 degree for this band and 1.2 degree and 2.3 degree for it.

So, this is just to show you that the misorientation angle of these bands are just above the range where the orientation difference between the two regions. For example, if this is the band this region and this region is detectable, but the misorientations are not very high in them. So, longer aligned boundaries these longer aligned boundaries or dense dislocation walls or microbands or cell band wall as these are the names of these geometrically necessary boundaries. They are also known as persistent boundaries, right.

So, you see slip activities will be similar in each individual you know blocks of this boundary. So, if this is a boundary and this is another boundary so, slip activities will be similar here right, but it will differ the slip activity will differ between this bound this in this band and in this band and in this band, right.

So, you see each cell block will deform you know relatively homogeneously on less than five slip system required for plasticity required by the plasticity theory like the Taylor’s model. Now, why it is so? Because of the shape of this cell bands which are parallel and straight, this geometry helps the material to deform at a lower number of slip systems than it is required for the plastic deformation of the usual you know equiaxed grain type structure or you know spherical grain type structure or dodecahedron type grain structure right.

So, the overall strain is then accomplished by the variation of slip activity between this blocks. So, the as I said that the stress state in these different blocks will be different and so, the overall strain will be accommodated by the variation of the strain state right by the slip by varying the slip activity within this within the different blocks.

So, misorientation across alternate cell band wall tend to oscillate about the mean if you see that the misorientation. If you add them they will not become very high for example, if we plot a point to point misorientation you will see that there is a peak of 2.3 degree then at minus 2.5 degree then 3.2 degree then minus 2.1 degree, 1.2 degree, 2.3 degree.

And, if we simultaneous draw a point to origin map, then you will see that the misorientation angle will not increase very high because of the minus and the plus miss orientation. So, it will be very less minus 2.5 plus 3.2 minus 2.1 plus 1.2 plus 2.3. So, it will not be very high. So, because of such a situation the we can say that the misorientation across alternate cell band wall actually will oscillate about a certain mean which will be not substantially very high and so, there will be no substantial long range orientation gradient.

So, microband boundaries as you are seeing that this is a TD plane and as I said earlier this direction is the rolling direction and this direction is the normal direction. So, the if we are looking in the TD plane this micro band boundaries are formed to be aligned by 25 to 40 degrees to the you know rolling plane if this is the rolling plane, right.

So, it will be 25 to 40 degree to the rolling plane and planes of high shear stress and this will be planes of very high shear stress and these planes will be you see closer to the 111 plane of the FCC metals as aluminium is an FCC material which we are showing for an example, right.

So, if we look further into the microstructural features we will see that at a if the grain size is larger mainly, another feature that develops other than the cell block or cell band is the deformation band or the transition band.

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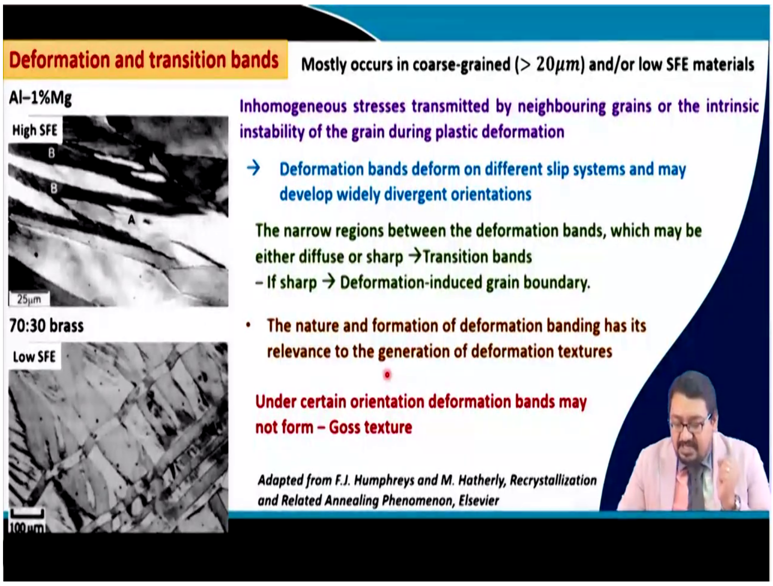

A deformation band or transition band as I said mostly occur in coarse grained material that is the material having greater than 20 micrometer grain size on an average and with mostly it develops in low stacking fault energy material.

Here is an example which is adopted from Humphrey and Hatherly recrystallization and related annealing phenomenon book and is an example of aluminum 1 percent magnesium and 70:30 brass. You can see that in both the cases as the grain size is quite higher and development of deformation or transition bands have taken place.

The orientation of this band if it is B A B A type, then they are known as kink bands and if the orientations of each of this band are not related, then they are you know normal transition bands. We can see that if the microstructure is off from a low stacking fault energy material the deformation band looks entirely different from the ones which develop in a high stacking fault energy material.

So, in these bands inhomogeneous stresses is transmitted by neighboring grains or intrinsic instability of the grains are present during the plastic deformation. So, deformation bands deform on different slip systems and may develop widely divergent orientation.

Now, to explain this what I would like to say is that as the cell band structure we have seen has an orientation difference of 2 degree 3 degree 1 degree from its neighboring bands and then because of this also the stress state is slightly different and the orientation that is forming in between these in between if there is a cell band in between two neighboring orientation will be slightly different quite different leading to a formation of a GNB.

So, the cell band structures are basically GNB the presence of transition band these bands have a misorientation angle much higher than the cell band structure. These bands basically form when the stress state cannot be controlled homogeneously because of the large grain structure or because of the low stacking fault energy of the material.

The stress state in different areas of this band will be substantially different and thereby the orientation that will develop will be substantially different in these you know specially separated bands. So, deformation bands different deforms on different slip systems and they may develop a widely different orientation. So, the if you so, these are deformation bands, right.

So, the narrow region between the deformation bands which could be either diffuse or sharp type are known as the transition band, right. So, these boundaries are known as transition band. If they are diffused then they are usually called transition band and even if they are sharp, but if they are sharp they are also deformation induced grain boundaries.

So, the nature and formation of deformation banding has its relevance to the generation of deformation texture. So, it is more relevant right because these transition bands, these deformation bands have in different regions, quite different stress state associated with it. So, different kind of strain and thereby different slip systems associated with it leading to formation of different texture, different orientation in this regions and therefore, they have more relevance to the generation of the deformation texture.

Under certain orientation conditions like Goss texture it is observed experimentally that these kind of deformation bands do not occur if the material has Goss texture.

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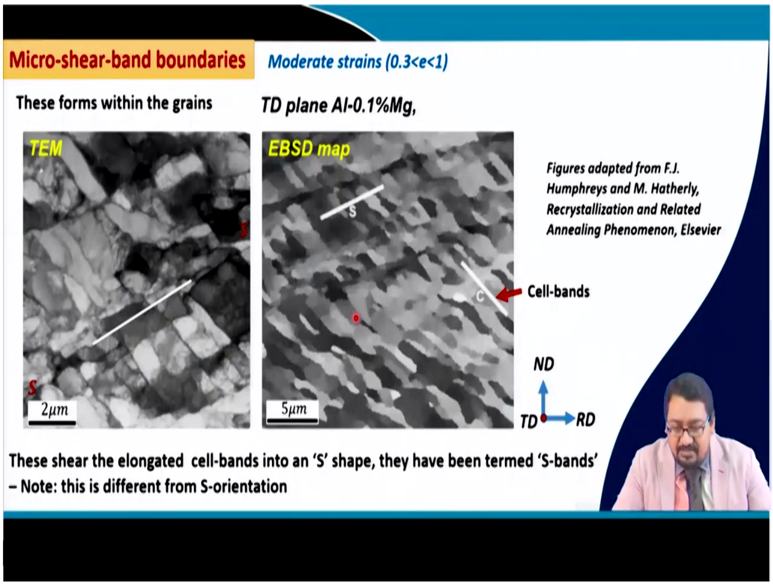

Further, when the strain is increased from 0.3 to 1, and in this range that is in a moderate to higher strain range the apart in the cell band structure a S-band starts to develop. If we look into the TD plane for the aluminum 0.1 percent magnesium which is near to a high stacking fault energy material. The cell band structure which is developed priorly at lower strain could be seen right and this is the TEM image and this is the EBSD image.

We can see the formation of the cell band structure which was developed at a lower strain. But, as the strain is increased a band type structure almost perpendicular to it starts to develop and this structure is known as the S-band structure starts to develop almost perpendicular to the initially formed cell band structure and this structure produces a S type structure in the material and therefore, they are called S-band.

These band which has an S-shaped are known as micro shear band boundaries in the material and these are not related to the S-orientation of the texture. So, note that S-orientation is a different thing than the S band structure that I am showing here, right.

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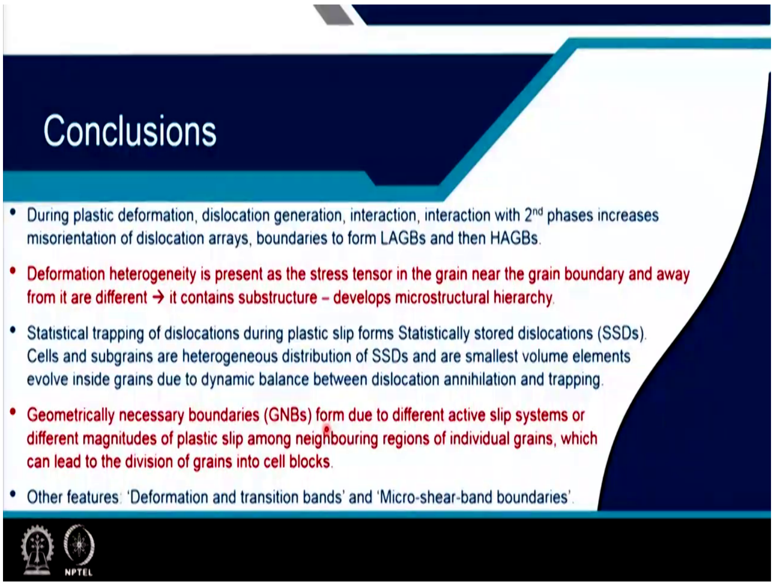

So, we can conclude from this lecture is that during plastic deformation, dislocation generation occurs they interact with each other in they interact with the 2nd phase particles and they increase the misorientation of the dislocation array, forming cell structure and you know cell band structure. So, forming IDBs of related to statistically stored dislocation and GNBs related to LAGBs that is low angle boundaries and further increase in the misorientation produces high angle boundaries or grain boundaries, right.

The deformation heterogeneity is present as the stress tensor in the grain near the grain boundary and away from the grain boundary is different. And, thus the microstructure means the grain in the microstructure starts to produce sub structure and does develop microstructural hierarchy, right.

So, statistical trapping of dislocation during plastic deformation is the basis of the formation of statistically stored dislocations right SSDs. So, cell and subgrains are heterogeneous distribution of statistically stored dislocations and the smallest volume elements that evolve within the grain due to this issue and this is basically by the dynamic balance between the you know because of the dislocation annealing and dislocation trapping, right.

Whereas geometrically necessary dislocations or geometrically necessary boundaries to be more appropriate forms due to differently active slip systems or different magnitude of plastic slip among neighboring regions of a certain individual grain which leads to the division of grains into you know cell block structure that is formation of GNBs inside the grain.

The other features of the microstructure within the individual grains are deformation or transition bands that develop at you know certain microstructure with grain size greater than 20 micron or with low stacking fault energy. Then at higher strain micro shear bands forms with a S-band structure combining the cell band with another cell band forming at an higher strain at a certain angle to the cell band called the S-band and S-structure. So, that is all for today’s class.

Thank you very much.