Texture in Materials
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Module - 09
Theory of deformation texture evolution
Lecture - 47
A Metallurgist Point of View (Contd.)

Good afternoon everyone and we are doing module number 9 that is a Theory of deformation texture evolution. And this is the lecture number 47 and we will be continuing the Metallurgist Point of View part.

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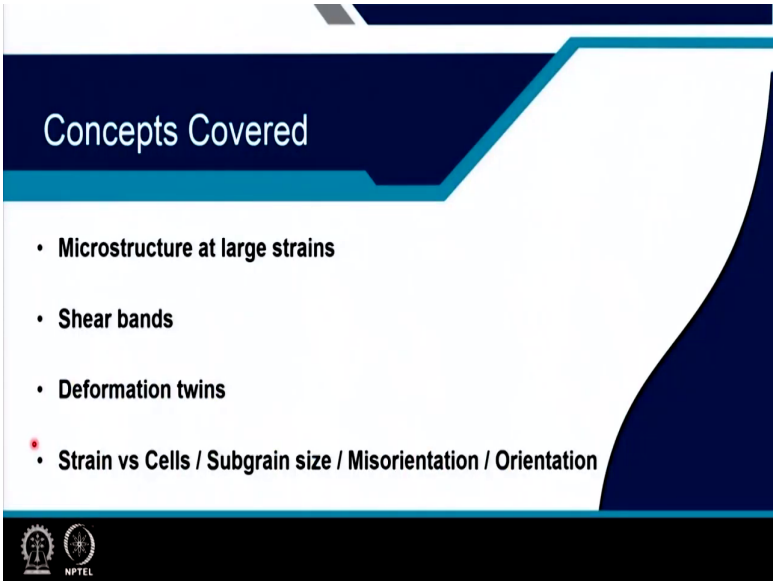

So, the concepts that will be covered in this lecture today are microstructure that form at large strains. We have gone through the microstructure evolution during low strain to moderate to moderately high strain and let us look how this microstructure develops at large strain.

We will look into shear banding we talked about shear banding in the last lecture, but we will look into the microstructure of shear bands that forms. Then deformation twinning that occurs in low stacking fault energy materials. Then we will try to relate the strains with respect to the cell subgrain size, misorientation, orientation and thereby we will try to relate the microstructure with respect to the texture of the material.

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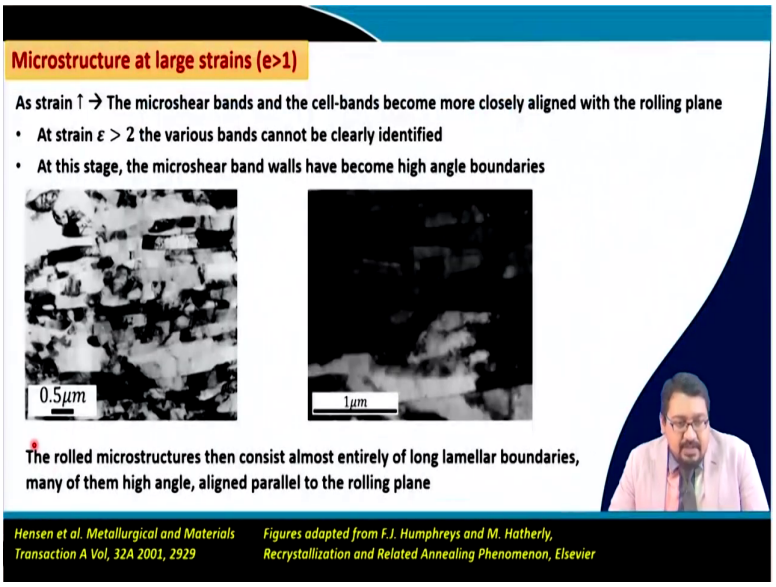

So, if we look into the microstructure of the materials at large strain what we look at lower strain we see that initially dislocation substructure and cell forms and as the material strain increases cell band formation and for larger grains or lower stacking fault energy transition or deformation bands start to develop.

When the strain is large then almost at a angle to the cell band structure other micro shear band starts to form forming an S type band structure. And thereby micro shear banding or S band structure which is different from the S orientation start to develop right. So, do not confuse that with the S orientation I am again letting you know.

So, when the strain is quite large and it is larger than 1 nearly say 1.2, 1.5 or nearly 2 then micro shear bands and cell bands. So, cell bands were formed initially at lower strain and micro shear band starts to develop at an angle to them and they meet each other to form an S band structure. And as the strain becomes larger the micro shear band say this one micro shear band and this is cell band they start to elongate and become closely aligned to each other.

And if it is a rolling then it closely aligned parallel to the rolling plane. So, at this point the mis-orientation angle of these boundaries of this micro shear bands and the cell bands become closer and closer to the high angle boundary and it becomes near to the high angle boundaries. So, at strains greater than 2 degree what will sorry at strains greater than 2 the

these various micro shear band and cell band structure becomes very it is not clearly visible cannot be clearly identified in the microstructure.

You see that we have given two example one taken from the paper by Hensen and another from the book of Humphrey and Hatherly and we can see that how this micro shear bands and cell band structure gets parallel to each other too. So, that it is indistinguishable.

So, we do not know which one is the micro shear band and which one is the cell band structure. So, at this stage when these under this situation of the microstructure when it is at high strain or higher strain the micro band walls are basically the becomes the high angle grain boundary or their misorientation becomes greater than 15 degree.

So, rolled microstructures mostly contains these kinds of long lamellar boundaries of high angle which are aligned parallel to the rolling plane. So, we can see that this is the rolling plane, this is the rolling direction and this is the rolling plane and we are looking on the transverse plane of the material as usual as in the previous lecture too.

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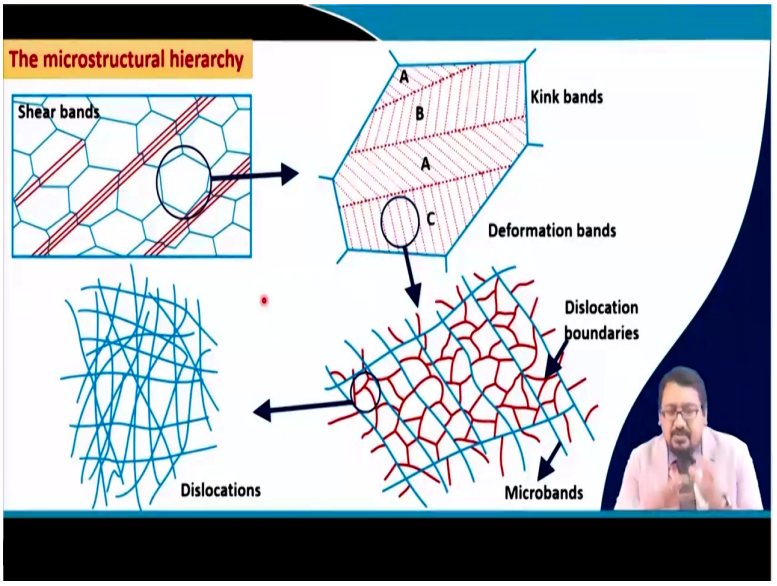

So, we are discussing about the micro structural hierarchy and we have seen formation of shear bands, deformation bands, micro bands or cell band structure. And then the formation of cell sub grain structure from the dislocation arrays.

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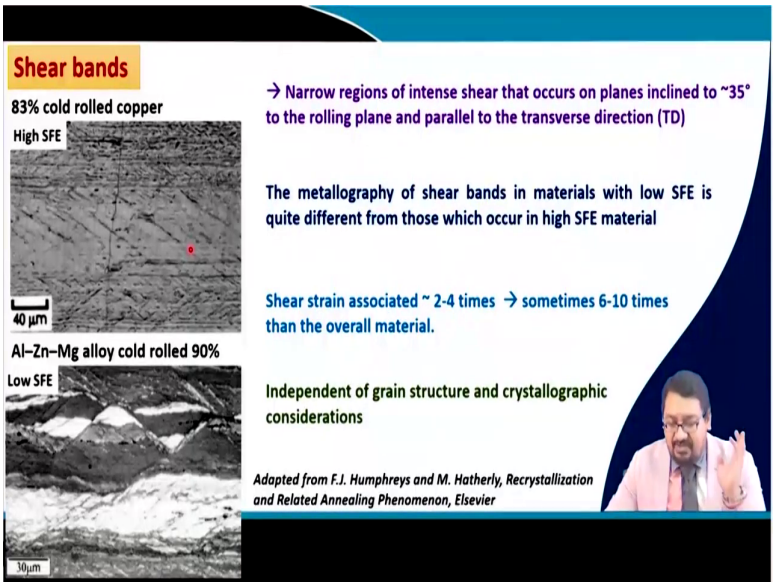

And we have not shown the shear banding formation up till now. So, if we look into the shear banding formation for high stacking fault energy this is 83 percent rolled copper and this is for the low stacking fault energy material, specifically if aluminum zinc magnesium rolled up to 90 percent of the deformation. Both the figures adapted from Humphrey and Hatherly Recrystallization and Related Annealing Phenomenon by Elsevier.

So, these band structures which forms at a certain angle and they occurs mainly at 35 degree to 40, 45 degrees to the rolling plane when we look in the transverse direction. These bands have you can see this band they the formation of these bands occur at these angle irrespective of the stacking fault energy, but the there is a specific you know micro structural feature difference between the formation of these bands for high stacking fault and low stacking fault.

From which one can distinguish that whether this material is high stacking fault energy or low stacking fault energy. Now, the metallography of the shear bands in the material with low stacking fault energy as I said is quite different from that of the high stacking fault energy material. Now, shear strain which is associated with this you know band structure is usually in the range of 2 to 4 times than of the overall shear strain of the material or the microstructure.

However, sometimes it can reach up to 6 to 10 times of the overall material. So, these shear band formation are independent of the grain structure, shape and orientation. So, they are not related to the shape, size, grain structure and the crystallographic orientation of the material.

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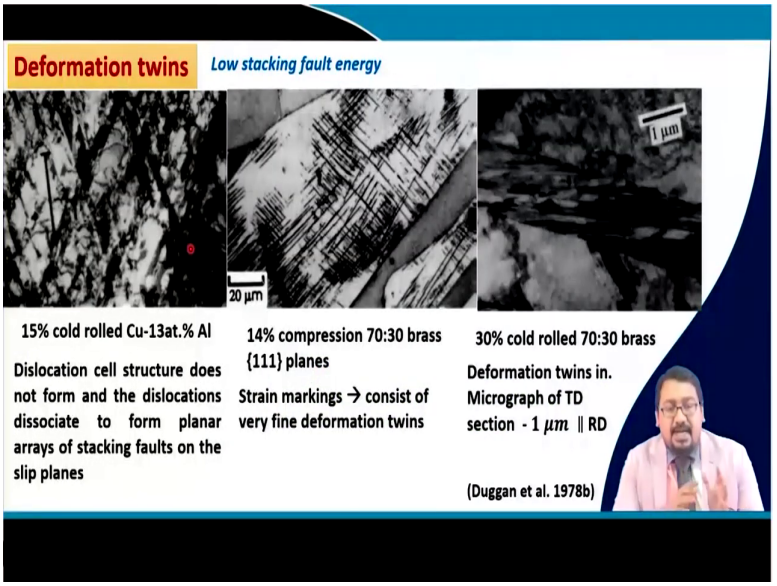

On the other hand, materials with low stacking fault energy can develop deformation twins because of the absence of the required minimum 5 independent slip systems. Now, because of the large distance between the partial 112 dislocation in case of FCC in case of low stacking fault FCC material.

The cross slipping of screw dislocation do not take place because the large distance of the low stacking fault energy material between the partial do not allow by how much large the deformation given that this two 112 partial cannot come close together to become a perfect 110. So, that it can cross slip to another 111 plane thus cross slip becomes restricted and therefore, they climb.

And thus because the 5 independent slip systems cannot be fulfilled the deformation actually progresses by the formation of deformation twin or twinning. So, there are various kinds of twinning's that can form and you can see that one twin in case of FCC is 112, 111 type. Here, from the publication of the Duggan we have shown three microstructure one copper 13 percent atomic weight percent aluminum, one and another two of 70:30 brass.

The second figure is for 14 percent compression and the third figure is for the 30 percent cold rolling. Now, we can see that from the first figure we can see the twin structures which develops in the microstructure looks like crisscross type of structure and we can also see that the dislocation cell structure is does not even form and the dislocation dissociate to form planar arrays of stacking faults on the slip planes.

So, we are looking on the TD section once again where we can see this planar arrays of stacking fault which are basically the twin structure of the material. If we look into the 70:30 brass compressed up to 14 percent. And we are looking basically on the TD plane again which comprises of the 111 plane in this case you can see strain markings which are similar to this because this is at a lower magnification and it looks something like this.

And these strain marking are consist of very fine deformation to information. One can see another example of 70:30 brass which is basically a single phase brass of FCC crystal structure of low stacking fault energy as say earlier and we are again looking at the TD plane. And this direction is basically this arrow micron bar is basically showing also the direction of rolling and we can see formation of dense twin structure in the microstructure right.

So, deformation texture develop due to you know slip twin activities and all these micro structural features shows that different types of deformation texture will develop because of the formation of this micro structural features and micro structural hierarchy in the microstructure.

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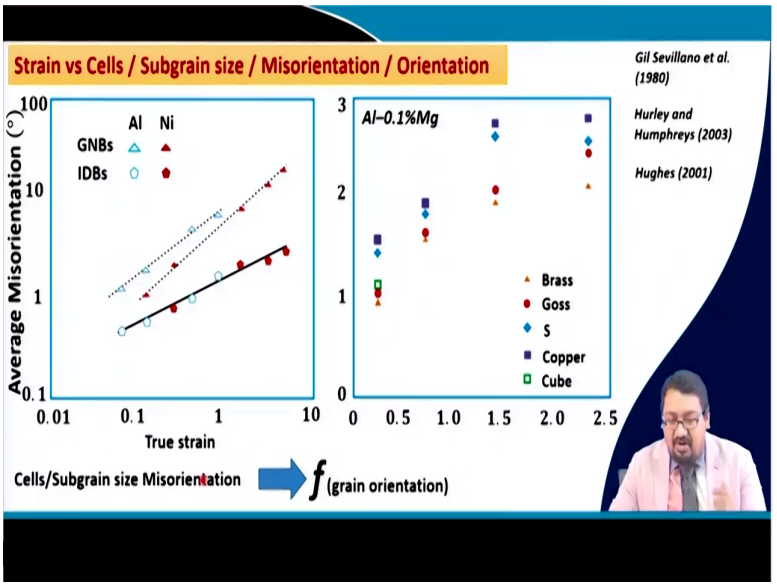

So, let us look into detail a little that how the amount of strain will affect the cell size and the misorientation angle of the IDBs and the GNBs and how it will affect the orientation and how the orientations are related to this. So, these are few examples from work done by Gil Sevillano, Hurley and Humphreys and Hughes you see at different time lines.

If we look into the first graph we can see that there are it is on aluminium and nickel and we see that the blue colored triangle and the pentagon shows you see aluminium GNB and IDBs. And if you look that the GNBs of aluminum increases the IDB of the aluminum.

So, GNBs are geometrical initial boundaries IDBs are basically related to statistically stored dislocations. We can see that the relative increase in the GNB is much higher than the relative increase of the IDBs. In case of nickel also if we look the red triangle which shows GNBs and the red pentagon which is the IDBs related to SSDs, we can see that the GNB increases higher in a much larger rate with the increase in the true strain than the SSD.

So, this work shows that the misorientation angle either it is of the GNBs or it is of the SSDs they both increases average misorientation angle, both increases with the increase in the strain of the material. So, misorientation of the cell and the sub grains basically is a function of strain and; however, we would like to state that this is also a function of grain orientation.

So, another work which shows for aluminum 1 percent magnesium which is a high stacking fault energy material. So, in this material when it is rolled what happens that with the increase in the strain, copper texture, brass texture Goss, S and cube component starts to develop. It is well known that the copper texture is the deformation texture that forms due to slip activities because of the high stacking fault energy of the material.

After that it is known the other component that forms are the S component, the brass component, the Goss and the most recrystallized component is the you know cube. So, Goss and the cube are the most less component which must contains the least amount of stored energy because it forms due to dynamic recrystallization processes. So, if we look into the component copper which is given by the violet square we can see that with the increase in the strain.

All these components average misorientation value which is given in the y that is this one vertical axis increases. Now, if at a lower angle at a sorry at a lower true strain we can see that there is a presence of cube orientation also, but as we go we at the higher strain the cube

orientation becomes completely absent. So, we can say that at lower strain the cube orientation possessing low average misorientation inside those micro structural part which has this cube orientation are present.

But, at higher strain this cube orientation is completely absent. On the other hand, if we look as I said if we look into the violet square points which represents the copper texture which is the highly deformed structure formed in forms in high stacking fault energy material we see that the with the increase in the strain that is with the increase in strain the average misorientation inside the copper increases.

And in all the strains if we look that this deformation texture that is the copper texture those part of the microstructure containing this copper texture has the highest average misorientation which is followed by the misorientation of the S type component and which is followed by the misorientation of the Goss component and then the brass component.

So, if we look that the deformation those part of the microstructure possessing deformation texture has higher average misorientation than those part of the microstructure which possesses which possesses dynamically recrystallization texture has lower average misorientation. So, one can say the cell sub grain size and the misorientation are basically the function of grain orientation.

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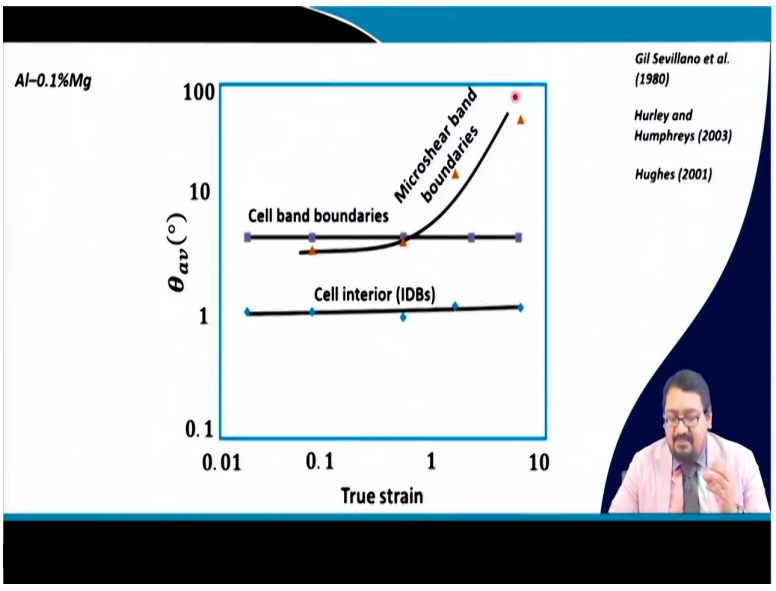

So, if we look into another curve which shows the average misorientation on the in the y axis and the true strain in the x axis. We can see that that the IDBs which is basically related those to the stacking fault energy sorry sorry IDBs which are related to the statistically stored dislocations does not increase much with the increase in the strain in this another example of aluminum 0.1 percent magnesium.

And if we look into the cell band boundaries also it does not increases with the strain even though the cell band boundary is related to the geometrically necessary boundaries. But, if the micro shear band boundaries are observed it was observed that after a certain deformation after for certain strain the micro shear band boundaries basically increases.

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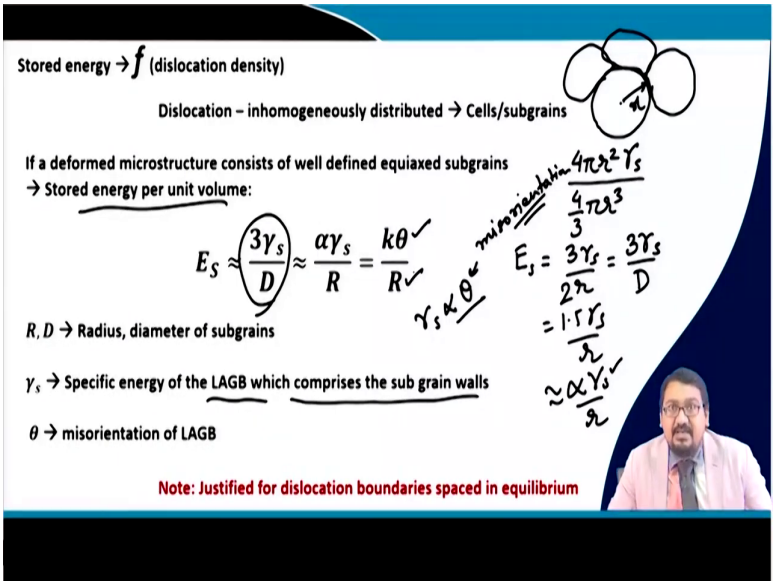

Now, if we look into this overall information and try to find out an empirical relationship between the you know stored energy and the dislocation density we can relatively say that ok stored energy is a function of dislocation density right. So, the dislocations which are present in the microstructure are always present inhomogeneously and they are inhomogeneously distributed because if you look a cell and substructure may contain high dislocation dense region in the cell boundaries.

So, dense dislocation walls and the region of less dislocation density are the cell interior right. So, cell and sub grain structure is present. So, if the deformed microstructure consists of well defined equiaxed sub grains then stored energy per unit volume which is given by E S can be given by 3 gamma s by D. So, let us show that how this is calculated.

So, let me take the pen and you see that if we have a sub grain which is nicely equiaxed and the specific energy of the low angle grain boundary which comprises of the sub grains wall is gamma s then you see this area the surface area of the sub grain can be given by 4 pi r square.

Where r is the radius of this sub grain right and if we want to calculate the stored energy per unit volume then the gamma s is a specific energy. So, the gamma s the energy stored energy for this sub grain is 4 pi r square times gamma s. And now, if it is per unit volume then it becomes 4 by 3 pi r cube.

So, this energy E S that is the stored energy per unit volume becomes equal to 3 gamma s by r right. Now, you see that a sub grain boundary is always shared by another sub grain boundary wherever we look right. So, each sub grain boundary is shared between at least two sub grain boundaries. So, we can divide it by 2 and therefore, the stored energy per unit volume is basically given by 3 gamma s by D which is this one right.

So, as this 1.5 gamma s by r is a roughly calculated value. So, one can say that yes relatively it is E S is equal to stored energy per unit volume is equal to some function alpha which is nearly 1.5 times gamma s which is the specific energy divided by the radius r. So, one can say that if this is so, the specific energy. So, specific energy of the sub grain structure is basically related to the sub grain walls that is the dense dislocation wall that is the sub grain boundary.

So, it is basically will be you know proportional to the misorientation right of the boundary right. So, one can write that alpha gamma s by r is equal to some constant k times theta which is misorientation divided by the R that is the radius of the sub grain right.

So, the stored energy is the function of misorientation of the sub grain and is basically proportional to it and it is also inversely proportional to the radius or diameter or the size of the cell or the sub grain. So, note that this is justified for dislocation boundaries which are spaced as equilibrium right. So, definitely this calculation is for a very ideal situation.

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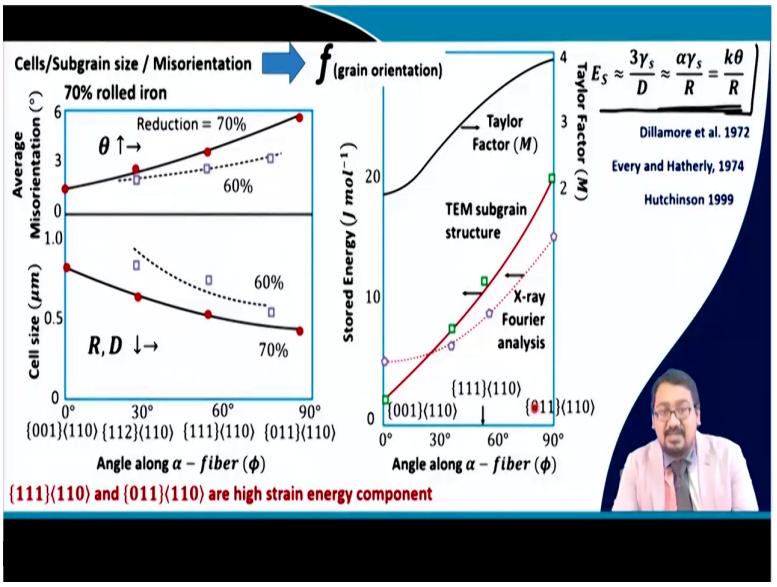

Now, thus if we look into the you know cell, sub grain size, misorientation and if we try to relate with function of grain orientation what we can find out we can definitely find out this relation to be correct ok. Let me take the pointer laser pointer. So, if we look into the first graph this one ok.

It shows in the y axis average misorientation, in the x axis the alpha fiber which comprises of various components containing those components which are highly strained component. So, high strain energy component which are basically 011 110 111 110 and less strain energy component that is dynamically recrystallized components which are cube component like or rotated cube component that is 001 110 or 112 110.

One can see and this is an experimental observation one can see that as the average misorientation that is theta you know increases as the component becomes deformation component right. And if we look in the lower micro graph we can see the y axis which shows the cell size and the x axis is the same. The cell size for the highly deformed or the highly strained component are much lower than the cell size for the dynamically recrystallized or the statically recrystallized component which are 001 110 112 110.

So, the cell size are smaller and the average misorientation are larger that is the theta is larger and the R is smaller for those part of the microstructure which has a higher stored energy. So, if we look into the same alpha fiber and look into the stored energy we can here by from the TEM substructure and from the X-ray Fourier analysis the stored energy is calculated. We

can see that the 110 sorry 011 and 110 and the 111 110 type of material has high stored energy.

So, they are deformed part of the microstructure. And these are of low stored energy that is recrystallized part of the microstructure. So, in case of a certain stress state that is during a plastic deformation of a certain kind maybe it is rolling or extrusion or a certain thing like equal channel angular pressing or a forging process the Taylor factor becomes higher for it is end orientation that is the deformation orientation that forms due to that deformation.

So, you see that those component, those texture components which has high stored energy which are related to the deformation texture component of the material have a high Taylor factor and those component which are basically related to the recrystallized texture component have a low Taylor factor.

So, these components the ones with low Taylor factor with further deformation will be able to you know roll further, deform further. So, that it goes towards the deformation texture component and thereby increasing it is stored energy, thereby increasing the theta that is mean average misorientation and thereby decreasing the R that is the cell size of the cell and the sub grain structure.

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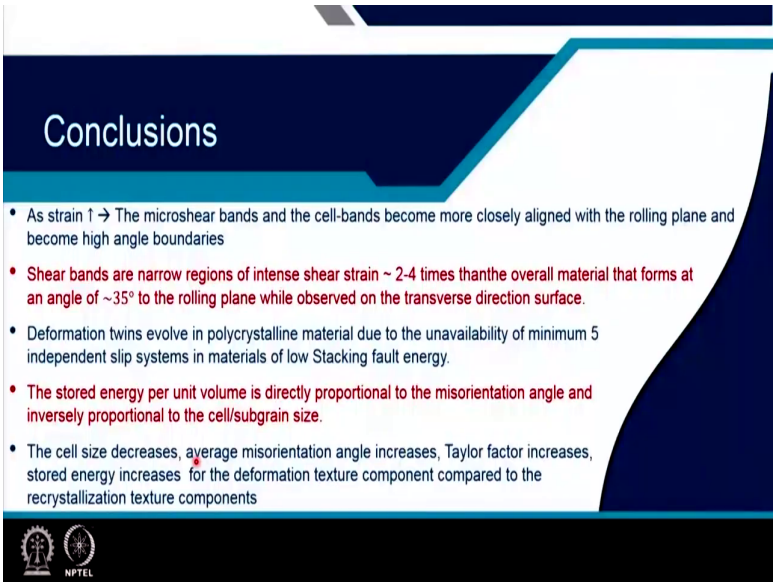

So, we can conclude from this lecture that as the strain is increasing the micro shear bands and the cell bands become more closely aligned with the rolling plane and become high angle

grain boundaries right. The shear bands are basically narrow regions of intense shear strain about 2 to 4 times than the overall material that forms at an angle of 35 degree to the rolling plane and while we are observing in the transverse direction plane right transverse direction surface.

Deformation twins evolve in polycrystalline material due to the unavailability of minimum 5 independent slip systems because the material may have a very low stacking fault energy and therefore, cross slipping or screw dislocation is prohibited. Because low stacking fault energy have large spacing between the partial dislocations which are enabled to come together to form a full 110 type dislocation which is required for the cross slipping of the screw 110 screw full 110 dislocation into another 111 plane.

Now, another conclusion is that the stored energy per unit volume is directly proportional to the misorientation angle and inversely proportional to the cell or the sub grain size. Lastly, the cell size decreases, average misorientation angle increases, the Taylor factor increases, the stored energy increases for the deformed texture component compared to the recrystallized texture components.

Thank you so much.