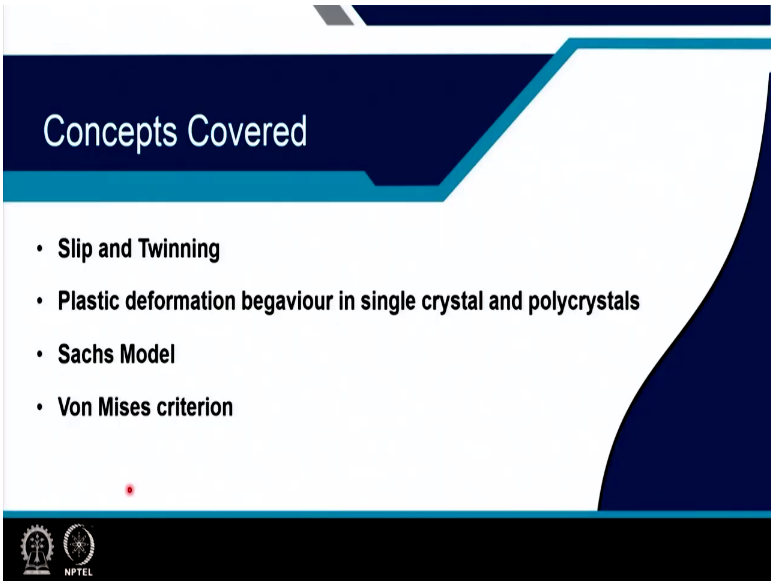
Texture in Materials
Prof. Somjeet Biswas
Department of Metallurgical and Materials Engineering
Indian Institute of Technology, Kharagpur

Module - 09
Theory of deformation texture evolution
Lecture - 44
Basic Mechanics of Polycrystal Plasticity

Good afternoon everyone. And today, we are going to start with module number 9, which is Theory of Deformation Texture Evolution. And this is lecture number 44, and we are going to start Basic Mechanics of Polycrystal Plasticity.

So, in this lecture, we will go through extremely fundamental part of deformation behavior of materials, and we will have 4 lectures. The first two lecture will be mostly based on mechanics, and the last two lectures will be on the metallurgical aspects of deformation behavior.

(Refer Slide Time: 01:17)

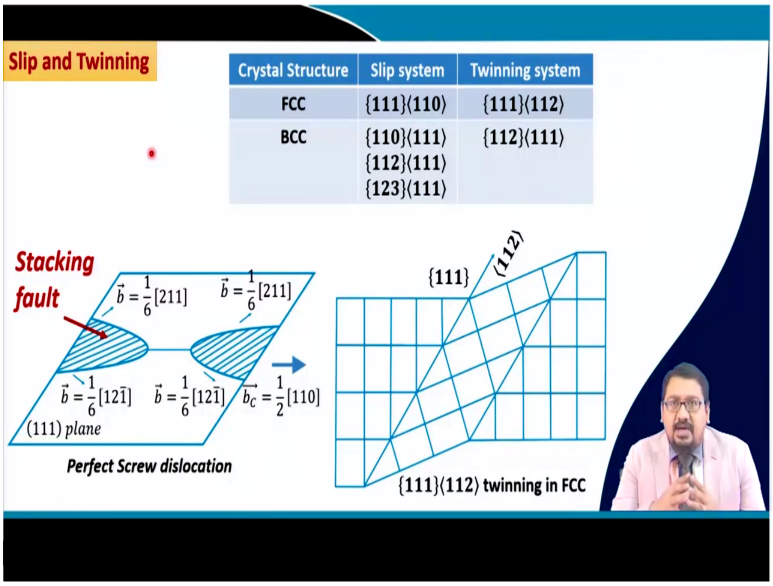


Concepts Covered

- Slip and Twinning
- Plastic deformation begaviour in single crystal and polycrystals
- Sachs Model
- Von Mises criterion

So, the concepts that will be covered in this lecture are slip and twinning mechanism in formation. Plastic deformation behavior in single crystals and in polycrystals. And we will cover Sachs model which is basically comprising of utilizing Schmid factor for a certain Schmid slip system to observe the you know plastic deformation. And then, finally, the Von Mises criterion.

(Refer Slide Time: 01:55)



Slip and Twinning

Crystal Structure	Slip system	Twinning system
FCC	$\{111\}\langle 110\rangle$	$\{111\}\langle 112\rangle$
BCC	$\{110\}\langle 111\rangle$ $\{112\}\langle 111\rangle$ $\{123\}\langle 111\rangle$	$\{112\}\langle 111\rangle$

Perfect Screw dislocation

$\{111\}\langle 112\rangle$ twinning in FCC

So, if you look into the most of the crystal structure in metallic materials are either face centered cubic material or body centered cubic materials. Few, like magnesium, titanium, zinc, zirconium, also have an hexagonal close packed structure.

Now, in a different model, we will take up each of this structure crystal structure, face centered cubic, body centered cubing and hexagonal close packed structure, and we will see how its behaves and how their texture forms in terms of pole figure and orientation distribution functions. That is in the Euler space.

To start with the very basics that face centered cubic materials like aluminum and copper, they have slip systems which is 111, 110 type. Because the 111, is the closest packed slip plane and the 110 is the closest packed direction in them. There are 4 111, type slip plane in a FCC or a BCC cubic crystal, right. And each 111 plane has 3 110s. So, there are 12 slip systems present in the FCC material and we all know about it.

In FCC material, if we look into it in detail, there is a concept of stacking fault and we all know that in the 111 plane, if there is a fault and then in the stacking it is known as the stacking fault. And we have learned about this, and the very simple book to look upon to this is the book of dieter mechanical metallurgy. And in detail, if you want to look then it is the book of reading.

Now, what is stacking fault and its energy? Now, stacking fault is a fault in the 111, stacking of the face centered cubic material. Now, why it is important the 111 stacking? Because the closest pack slip plane is the 111 plane and that is the plane of our interest. It does not mean that the stacking fault do not occur in the other planes. It occurs. But the plane that is of our interest is the 111 plane, which is the closest packed in case of the face centered cubic material.

Now, if the in case of this kind of material like aluminum and copper, the stacking fault energy is higher. In case of materials, such as brass or other alloyed material, the stacking fault energy is lower. Now, what do you mean by a lower stacking fault energy? We know a complete burgers vector of a slip dislocation for the one for the FCC structure is the 110 direction.

The fault in the 111 plane divides the 110 into 2 partial dislocations, these are 112 types. The distance between these partial dislocations becomes very large if the stacking fault energy is lower and the distance becomes smaller if the stacking fault energy is higher. So, the deformation behavior of a face centered cubic material depends upon its stacking fault energy.

A high stacking fault energy when makes the this distance between these two partial dislocations lower, then the screw dislocation during the plastic deformation can cross slip. And in order to cross slip, the 2 partial 112 dislocation has to come together. So, during the deformation of a high stacking fault energy material, because the partials are closer it is easier for the partial to come together to form a full 110 dislocation to cross slip into another 111 plane, in order to have, in order to sustain the plastic deformation, right.

So, the slip systems the 12 slip systems 111, 110 type slip systems can be utilized, by the presence of dislocation glide and dislocation cross slip of the screw dislocation which allows the edge dislocation also to climb. So, the deformation, plastic deformation of any material does not only need the glide of the slip plane. It also require cross slipping in order to have, in order to activate multiple planes and multiple directions, so that a homogeneous deformation takes place along with which the climb of s dislocation suffice for a proper homogeneous deformation of the material.

So, in case of high stacking fault energy, face centered cubic material, as there are as the distance between the partials are lower cross slipping of screw dislocation is possible. And this allows the material to deform with a multiple number of slip systems and therefore, the deformation of the material is relative to the slip of dislocation slip in the material which is basically 111, 110 type.

In case of low stacking fault energy materials, FCC materials, the cross slipping is prohibited because the distance between these 112 partial dislocations are quite large and a very large deformation could also not able to bring the 2, 112 partial dislocation closer. So, that the it becomes a perfect 110 dislocation, in order to cross slip into another 111 plane.

So, the screw dislocations are restricted to cross slip and thereby the climb of s dislocation also gets restricted. And so, the stress state which is given to the material that is for the plastic deformation could not be sustained through the presence of only a few amount of 111, 110 type slip system.

So, twinning or deformation induced twinning occurs in order to sustain that shape change in the material that is imposed by that Cauchy stress tensor applied in the material. So, the twinning in case of FCC materials, say for example, is the 111, 112 type twinning that occurs, right.

So, here is a example of the 111 plane which shows the presence of the 111, 112 type twinning, that occurs in FCC material, and we can see that how the atoms basically displace itself during the twinning process. And as I said in the previous lectures, that twinning is a displacive mechanism and it is not a diffusion control or thermally controlled mechanism that occurs, right.

Now, of course, twinning may occur also in case of static annealing or under thermal activation which includes diffusion mechanisms, now because the twin boundary is a fully coherent twin boundary. Now, in case of body centered cubic material you know there are no closest pack plane. So, the most closed pack plane in case of the body centered cubic material is the 110 type. So, most of the deformation, basically takes place in the 110 plane.

We all know that there are 6 110 planes and in each 110 plane there are 2 111 type burgers vector, where the, which is the closed pack direction for this case. And so, there are 12 slip systems for you know for the BCC material to deform.

Depending upon the strain rate and the temperature of the deformation, body centered cubic materials, such as steels, and irons, can also deform at 112 and 1 or 123 slip planes in the same 111 slip directions. So, there are multiple slip planes and slip directions present in the body centered cubic meter. So, the deformation of the body centered cubic material mostly depends upon this slip dislocation related activity or mechanisms which are related to slip dislocations.

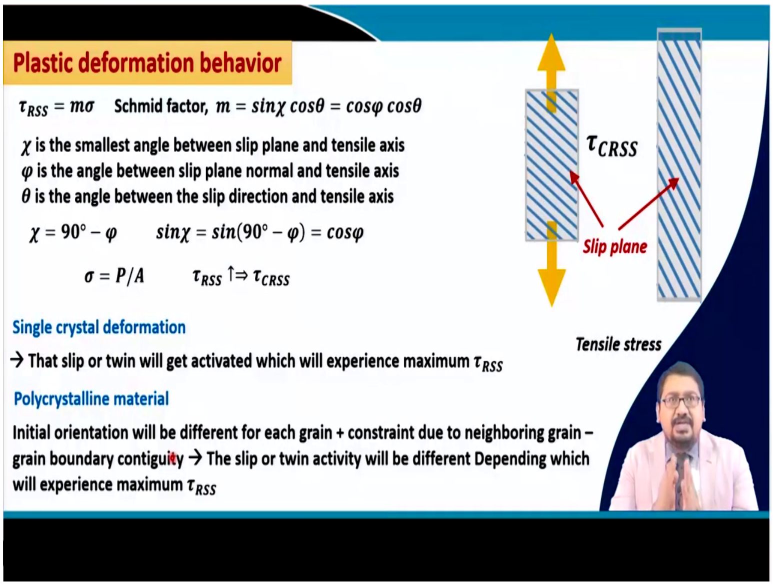
Now, then also there are possibility in certain cases where 112, 111 type slip systems starts to devolve develop or evolve during the process, and thereby it may influence the texture evolution. Now, the point, now the hexagonal close packed materials also have multiple slip systems like the basal slip, the prismatic slip, the pyramidal slip system, but it has various c by a ratios, right.

So, depending upon the c by a ratio, the deformation behavior, that is the activities of various slip systems will vary. And under certain conditions contraction type twinnings or extension type twinnings which I will explain in the later lectures, but to let you know that when there is a contraction along the c axis it is known as the contraction twinning and when there is an extension near along the c axis is called the extension twinning. And this occur, and all this factor will definitely going to affect the texture evolution in the material.

So, in some cases, when there is an increased activity of a certain slip plane and slip direction that activity is going to influence the texture evolution. In other place, if that activity is lesser and there is another slip activity or another twin activity that will influence the texture evolution.

We can say that the deformation behavior in a polycrystalline material require multiple slip systems, and in order to activate all the slip systems, cross slipping of screw dislocation and climb of s dislocation leading to recovery is simultaneously needed in order for the deformation to sustain. And thus, the deformation includes most of the time at least a little bit of recovery leading to this. So, we will talk about this later. But this is the whole thing and the most basic fundamental of you know deformation or plastic deformation.

(Refer Slide Time: 14:06)



Plastic deformation behavior

$\tau_{RSS} = m\sigma$ Schmid factor, $m = sin\chi \, cos\theta = cos\varphi \, cos\theta$

χ is the smallest angle between slip plane and tensile axis
φ is the angle between slip plane normal and tensile axis
θ is the angle between the slip direction and tensile axis

$\chi = 90° - \varphi$ $sin\chi = sin(90° - \varphi) = cos\varphi$

$\sigma = P/A$ $\tau_{RSS} \uparrow \Rightarrow \tau_{CRSS}$

Single crystal deformation

→ That slip or twin will get activated which will experience maximum τ_{RSS}

Polycrystalline material

Initial orientation will be different for each grain + constraint due to neighboring grain – grain boundary contiguity → The slip or twin activity will be different Depending which will experience maximum τ_{RSS}

So, if we look into the plastic deformation behavior for a single crystal say for example. And if we say that yes this is the sample that we had, and this is a single crystal, and we tried to pull it by a tensile loading, and say that these are the certain slip plane which starts to get activated, there could be various slip planes.

Like for example, if it is an face centered cubic single crystal, then there will be 12 111, 110 type slip systems which can get activated. So, there are 4 slip planes which can get activated. Now, which slip plane will get activated first? Right. The activation of the slip system or slip plane depends upon its Schmid factor.

Now, why Schmid factor? Because you see that when we are trying to pull this material the material is being pulled, the one slip system which will you know go to its critical resolved shear stress most faster; that means, the what is the critical resolved shear stress? The critical resolved shear stress is the shear stress where the slip system will start to slip in order to start the minimum amount of plastic deformation.

Now, when this situation occurs, then the load which leads to produce a resolved shear stress for that slip system should reach the critical resolved shear stress faster as possible, right. So, the factor which will allow, which will you know what you call the relate the load loading direction or the loading you know force to the resolved shear stress is known as the Schmid factor.

Now, Schmid factor is basically related by 2 angles. The first angle is the zeta angle which is the smallest angle between the slip plane and the tensile axis. So, the zeta angle is basically equal to you see 90 degrees minus an angle which is you know phi.

Now, what is phi? Phi is the angle between the normal to the slip plane and this loading direction. So, Schmid factor is related to sin of zeta which becomes equal to sine of 90 minus phi, the phi is the angle between the normal of the slip plane to the loading direction and the loading direction. So, it becomes cos of phi.

On the other hand, the slip direction and the loading direction if between them has an angle of theta, then it is related by cos of theta. So, m which is basically the Schmid factor is equal to sine of zeta cos of theta which becomes equal to cos of phi cos of theta. This is known as Schmid factor.

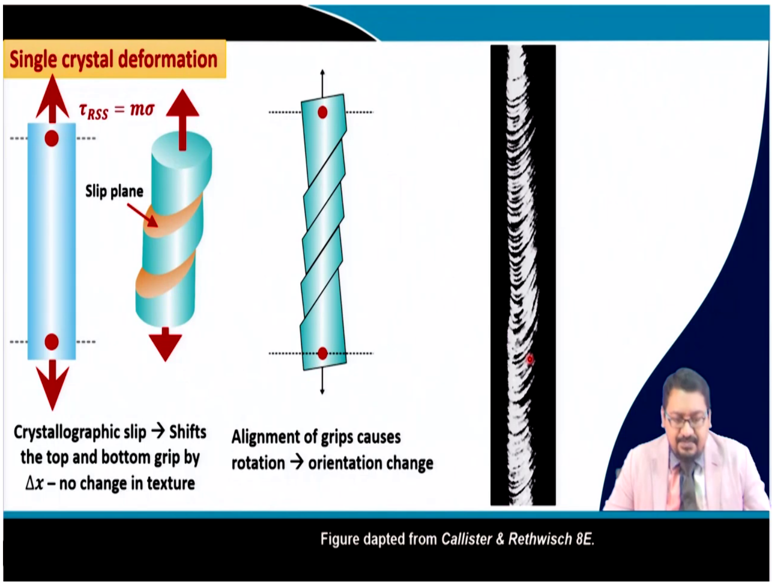
Whereas sigma which is the stress, along the loading direction is given by the loading force p divided by the cross-sectional area of the material. So, the resolved shear stress for a certain slip plane out of this 4 111 plane, the one which has the highest Schmid factor will reach the critical resolved shear stress faster and that will be the one which is going to do the slipping or where the dislocation slip will occur in case of a single crystal.

And you will see that while this dislocation slip is going to occur, the particular slip plane and the slip direction, the slip direction will try to align itself towards the loading or the tensile direction, right. Now, so if we say single crystal deformation, that slip or twinning, may get activated and will experience which the one which will experience the maximum tau RSS that is the resolved shear stress, right.

In case of polycrystal material, however, initial orientation of each grain present in the polycrystalline material may be different and there will be constraint due to the neighboring grain. So, the grain boundary has to be intact. So, the grain boundary contiguity has to be maintained.

So, slip and twinning activities, and multiple slip and twinning activities, or multiple slips or the combination of multiple slip and twinning, in different grains will be different in order to sustain that applied load P and in order to maintain the grain boundary contiguity. So, that those slip systems which will reach whose tau RSS, whose Resolved Shear Stress, will reach the critical resolved shear stress of that slip system will start to deform plastically in order to make the plastic deformation possible.

(Refer Slide Time: 20:16)



Single crystal deformation

Crystallographic slip → Shifts the top and bottom grip by Δx – no change in texture

Alignment of grips causes rotation → orientation change

Figure dapted from *Callister & Rethwisch 8E.*

In case of single crystal deformation, as I said, how we can say that the texture is basically evolving? When we are pulling a sample or a tensile specimen like this, and we will see that the as I said in the last slide that the one slip system which will have the highest tau RSS with the combination of the Schmid factor m, and the loading stress sigma will start to deform plastically fast. Because it will reach the critical resolved shear stress much earlier than any other slip systems, right.

So, in case, if the grips which are pulling this specimen are not pivoted and they are free to move in any of this x and y direction. Say z is the pulling direction, and while it is pulling it can it is free to move in any of this x and y direction. So, it is not pivoted. Then, under such situation you will see that after a certain point the you know the loading directions you know has shifted in x and y, and the slip plane will look something like this, right.

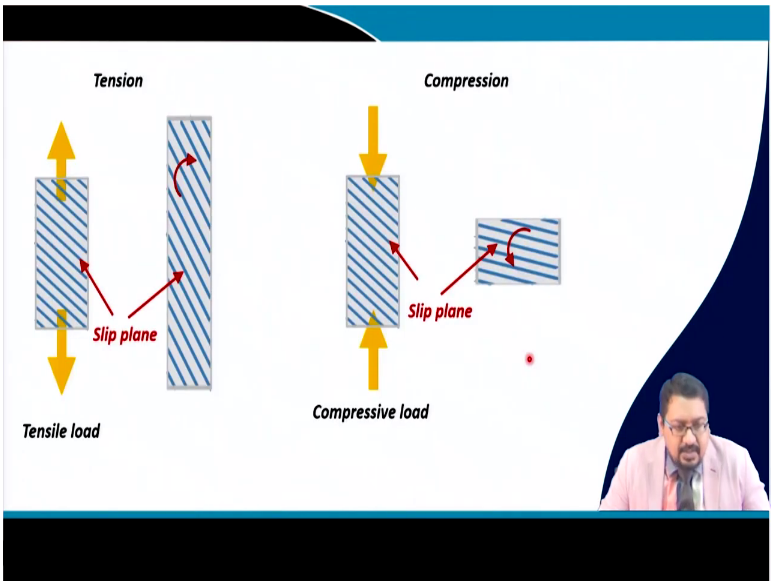
And, but you see the shifting of the top and the bottom grip will produce no change in the inclination of the slip plane and the inclination of the slip direction with respect to the loading axis, right. So, there is no evolution of the texture. So, texture evolved in the material because when we are pulling or we are doing a certain deformation in the material, the for example, in case of the tensile is the most simplest example. The grips are basically pivoted and they are restricted to move or shift in the x and y direction.

So, the grips remains at this position, and when it is being pulled, the slip plane basically tries to rotate in such a way that the slip direction tries to go along the loading direction. So, the theta that is the angle between the slip direction and the loading direction decreases.

Whereas, the angle zeta of the orientation, the smallest angle of the you know slip plane with respect to the loading direction also starts to decrease. And therefore, the angle phi which is normal to the slip plane the angle between, the normal to the slip plane and the you know the loading direction starts to increase.

These you see leads to the to the rotation of the slip plane with respect to the loading direction. Say, it was initially like this and then slowly it becomes like this and then it goes like this, right. So, this formation of you know striations and the rotation of the slip plane because of the pivotion of the you know grips the non alloying of the movement of the grip in the x and y direction leads to the change in the orientation of the material, and such kind of specimen could be observed in the material. This figure has been adapted by Callister and Rethwisch book which you all might know.

(Refer Slide Time: 24:12)

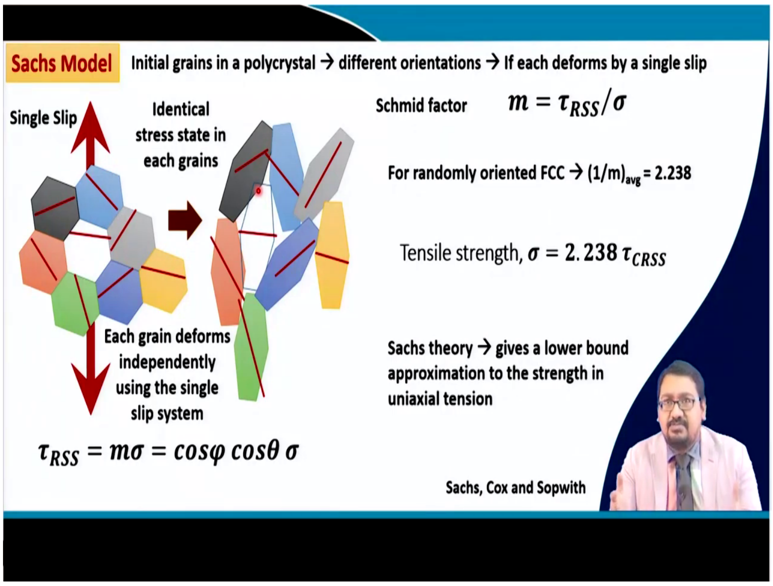


So, texture evolution during any kind of deformation, these two example are of the tension and the compression test, occurs due to restriction in the movement or restriction in the change in the shape of the material because of the boundary conditions. And say for example, as I said, while we are giving tensile test the slip plane starts to rotate in this direction, right.

So, that the slip direction becomes goes towards the you know tensile direction. On the other hand, in case of compression what happens that, if these are the slip planes which produces the highest amount of tau RSS with the combination of Schmid factor and the you know the loading stress.

Then, if this is the slip system which is the primary slip system, then the plane will start to rotate away from the compression direction, and the plane normal will start to go towards the compression direction. And the direction in which the slip is taking place is also is going away from the compression direction, and this leads to the you know evolution of texture during deformation, right. So, this is quite simple, right.

(Refer Slide Time: 25:48)



Sachs Model Initial grains in a polycrystal → different orientations → If each deforms by a single slip

Single Slip

Identical stress state in each grains

Each grain deforms independently using the single slip system

$\tau_{RSS} = m\sigma = cos\varphi\ cos\theta\ \sigma$

Schmid factor $m = \tau_{RSS}/\sigma$

For randomly oriented FCC → $(1/m)_{avg} = 2.238$

Tensile strength, $\sigma = 2.238\ \tau_{CRSS}$

Sachs theory → gives a lower bound approximation to the strength in uniaxial tension

Sachs, Cox and Sopwith

So, if we look into the Sachs model. The Sachs model considered that initial you know grains of the polycrystalline material. Say for example, these grains are having different textures. So, they all have different orientation. And each deformed by a single slip as single crystals present in this polycrystal.

So, each deform independently by a single slip, following the rule of Schmid factor which relates to tau RSS and sigma by this equation. So, m is equal to tau RSS by sigma. So, tau RSS is equal to Schmid factor times sigma which is the loading stress along the tensile direction. So, the based upon this arrow.

So, thus, it is assumed here in the Sachs model that in a polycrystalline material, if the material follows the Schmid law, then in each material it will deform by a single slip and say these are the slip planes which has the highest Schmid factor.

And thereby, produces the largest resolved shear stress tau RSS and thereby these are the slip systems which will reach the critical resolved shear stress most earlier and they thereby they are the primary slip systems. And so, in each grain it is assumed that for each grain identical stress state is given. So, each grain deforms independently using the single slip systems, right.

So, now, then if the deformation takes place, then the shape change in the grains will be such that it will not allow the polycrystalline material to have grain boundary contiguity. So, the grains may deform, but their boundaries may not be intact. So, this is how we basically started to simulate in earlier times, we started to understand the deformation behavior mathematically.

And so, we saw that under such process when the stress state is identical in each of the grains and there is a single slip system present in each of the , the shape change in each of the grain will be such that that it will not allow the grain boundary contiguity to keep intact.

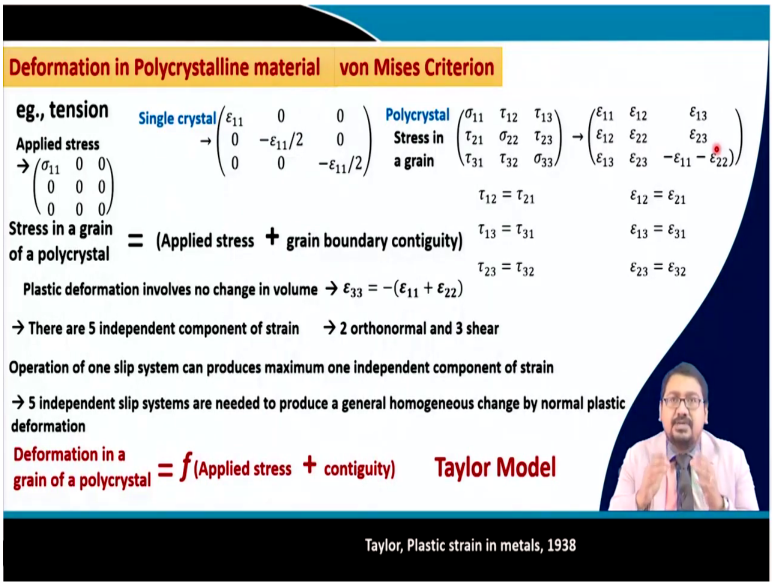
So,. So, you see such a situation is where we consider that for each grain the stress state is same is known as the Sachs model. The strain incorporated in each grain will be different because the orientation of each grains are different. So, the resolved shear stress for that for the primary slip system for each grain will be different. And therefore, each grain will deform differently and thus the grain boundary contiguity will not be maintained.

In case of a randomly oriented face centered cubic material, it was observed that 1 by m average. that is the inverse of the average of the Schmid factor comes out to be 2.238. And thereby, if we calculate the tensile strength of the material, using relating the tau RSS of the slip systems which are considered same for all the slip systems, and it is of course, that assumption is true tau RSS will be same because tau RSS for each 111, 110 slip systems should be same because it is the same slip system, but for of a family, of the same family.

So, the tensile strength which is basically the sigma can be calculated from m and tau RSS if it is known, so it will be equal to tau c RSS, sorry. So, if you want to calculate you know the tensile strength, then tensile strength is related to the Schmid factor m and the tau CRSS that is the critical resolved shear stress when the minimum amount of plastic deformation just started.

So, tensile strength becomes equal to sigma times a sigma tensile strength which is sigma becomes equal to 2.238 times tau c RSS. And this is for the randomly oriented face centered cubic material. And this Sachs model or Sachs theory, predicts or gives the lower bound approximation of the strength of the material for this kind of uniaxial tensile condition. And if you look for this, you will look into the papers by Sachs, Cox and Sopwith.

(Refer Slide Time: 31:47)



Deformation in Polycrystalline material **von Mises Criterion**

eg., tension

Applied stress $\rightarrow \begin{pmatrix} \sigma_{11} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$

Single crystal $\rightarrow \begin{pmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & -\varepsilon_{11}/2 & 0 \\ 0 & 0 & -\varepsilon_{11}/2 \end{pmatrix}$

Polycrystal Stress in a grain $\begin{pmatrix} \sigma_{11} & \tau_{12} & \tau_{13} \\ \tau_{21} & \sigma_{22} & \tau_{23} \\ \tau_{31} & \tau_{32} & \sigma_{33} \end{pmatrix} \rightarrow \begin{pmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{12} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{13} & \varepsilon_{23} & -\varepsilon_{11} - \varepsilon_{22} \end{pmatrix}$

$\tau_{12} = \tau_{21}$ $\varepsilon_{12} = \varepsilon_{21}$

$\tau_{13} = \tau_{31}$ $\varepsilon_{13} = \varepsilon_{31}$

$\tau_{23} = \tau_{32}$ $\varepsilon_{23} = \varepsilon_{32}$

Stress in a grain of a polycrystal = (Applied stress + grain boundary contiguity)

Plastic deformation involves no change in volume → $\varepsilon_{33} = -(\varepsilon_{11} + \varepsilon_{22})$

→ There are 5 independent component of strain → 2 orthonormal and 3 shear

Operation of one slip system can produces maximum one independent component of strain

→ 5 independent slip systems are needed to produce a general homogeneous change by normal plastic deformation

Deformation in a grain of a polycrystal = f(Applied stress + contiguity) **Taylor Model**

Taylor, Plastic strain in metals, 1938

So, in case of polycrystalline material, the deformation of a polycrystalline material will be relatively different than what Sachs model has predicted, right. As we have said, we have given always the example of a tensile.

The example of a tensile is given, so that because it is the most easiest way to show how the material deforms during the process and that is the tensile stress, because you see the applied stress is equal to sigma 11 and then the other vectors of the Cauchy stress tensor are 0, right. So, sigma 11, 0, 0, 0, 0, 0, 0, 0, 0. So, this is the Cauchy stress tensor for the tensile stress along 11, which is basically the z direction as I said earlier.

Now, in case of the single crystal what happens? That when such a situation exist, then the strain along the 111, direction should comprise epsilon 11, right and the strain along the you know other directions that is sigma 22 which is 0 and sigma 33 which is 0 comes out to be you know may be addition of this two for an isotropic material or if it is different, then epsilon 22 plus epsilon 33 and plus epsilon 11 should be equal to 0.

And so, epsilon 11 basically governs epsilon 22 and epsilon 33 most of the cases when the material is isotropic. Epsilon 11 is equally shared, so when it is pulled the x and y direction is compressed, almost equally and it is equal to half.

So, this situation is very simple and a single slip system can sustain this strain state. However, in case of a polycrystalline material, the stress which is incorporated in a grain due to a simple tensile loading is equal to the applied stress which is the simple tensile loading plus the grain boundary contiguity.

So, while deformation of a polycrystalline material, as I said in the previous slide the grain boundary contiguity has to be always maintained. So, if the applied stress is simple as this one, in a grain, the stress which is incorporated would be a complex stress state which will have sigma 11, sigma 22, sigma 3 3, tau 12, tau 13, tau 23, tau 21, tau 31, tau 32. So, all the 9 you know stress tensor variables will be present because in order to maintain the grain boundary continuity.

So, the strain with respect to each of the stress variants will be a stress strain state which will have all the 9 components, right. So, epsilon 11, epsilon 22, epsilon 33, whereas, epsilon 12, epsilon 13, epsilon 23, epsilon 21, epsilon 31, epsilon 32, right.

Now, we know that the shear stresses tau 12 is equal to tau 21, tau 13 is equal to tau 31, tau 23 is equal to tau 32. This shows that the shear strains tau 12 is equal to tau 21. So, both of them are same. Epsilon 12 is equal to epsilon 21, and epsilon 13 is equal to epsilon 31, and epsilon 23 is equal to epsilon 32. So, the 6 shear strain tensors gets converted into 3 shear strain tensors, right.

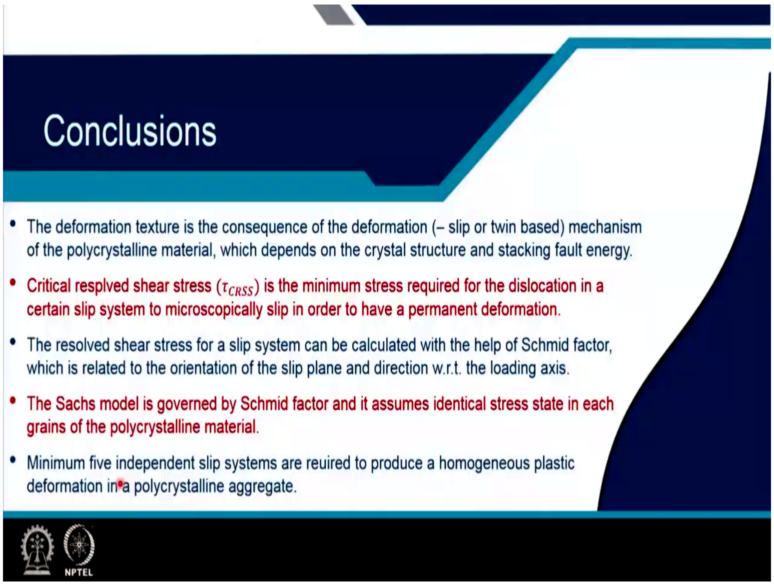
On the other hand, the plastic deformation as I said in the very early classes involves no change in the volume. So, during the plastic deformation the volume of the material remains the same, the shape of the material changes. So, epsilon 11 plus epsilon 22 plus epsilon 33 is equal to 0. So, we can calculate that epsilon 33 is basically equal to minus of epsilon 11 and minus of epsilon 22 combined together. So, epsilon 11, epsilon 22, and epsilon 33 is equal to this value.

Now, this shows that instead of 3 strain tensor you know there are only two strain tensor here. So, total there are 5 independent component of strain variables present in this strain matrix or in the strain tensor. So, out of which 2, epsilon 11 and epsilon 22 are independent orthonormal strains, and 3, epsilon 12, epsilon 13, epsilon 23, are the shear strain variables in that strain tensor which is equal to only 5, right.

So, operation of one slip system as it occurs, in case of a single crystal, will produce only one maximum you know component of strain, right. And therefore, at least 5 independent slip systems will be needed to produce a general homogeneous change by normal plastic deformation. So, at least minimum 5, 1 for each of the strain tensor is needed. So, more than 5 are needed sometime for a homogeneous plastic deformation of the polycrystalline aggregate. So, the thing is that for polycrystalline material, minimum 5 independent slip systems are required to sustain a plastic deformation of that polycrystalline aggregate, ok.

So, the Taylor model that will come in the next lecture comprises of that a deformation of a polycrystalline material is a function of the applied stress which is tensile in this case plus the stress associated with the grain boundary contiguity.

(Refer Slide Time: 39:20)



Conclusions

- The deformation texture is the consequence of the deformation (– slip or twin based) mechanism of the polycrystalline material, which depends on the crystal structure and stacking fault energy.
- Critical resplved shear stress (τ_{CRSS}) is the minimum stress required for the dislocation in a certain slip system to microscopically slip in order to have a permanent deformation.
- The resolved shear stress for a slip system can be calculated with the help of Schmid factor, which is related to the orientation of the slip plane and direction w.r.t. the loading axis.
- The Sachs model is governed by Schmid factor and it assumes identical stress state in each grains of the polycrystalline material.
- Minimum five independent slip systems are reuired to produce a homogeneous plastic deformation in a polycrystalline aggregate.

So, we can conclude here that the deformation texture is a consequence of the deformation mechanism which could be slip type, twin type, combination of this and it depends upon the stacking fault energy of the material and it also depends upon the crystal structure. So, this decides that how, what the texture or the deformation texture will evolve.

The critical resolved shear stress is the minimum stress required for a dislocation in a certain slip system to move microscopically for a slip in order to have a minimum permanent deformation, right.

Third, the resolved shear stress for the slip system can be calculated with the help of the Schmid factor which can be related to the orientation of the slip plane and the orientation of the slip direction, right.

The Sachs model is governed by the Schmid factor, and Sachs model for the polycrystalline material governed by the Schmid factor, and it assumes identical stress in each grains of the polycrystalline material, right. Finally, and most importantly the Von Mises condition for the plastic deformation or the Von Mises criterion is that minimum 5 independent slip systems are required to produce a homogeneous plastic deformation in the polycrystalline aggregate.

Thank you very much.