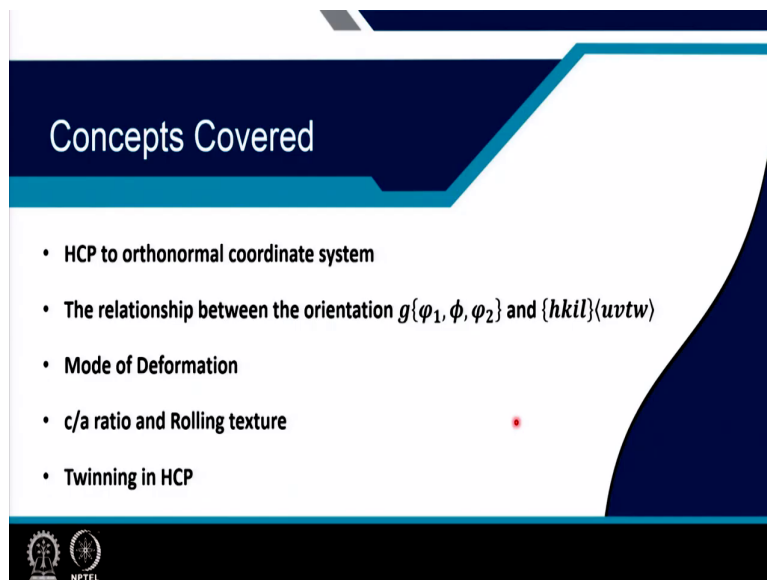


Texture in Materials
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Module - 10
Texture in FCC, BCC and HCP materials
Lecture - 51
Texture in HCP Polycrystals - I

Good afternoon everyone. We are continuing with module 10, which is Texture in FCC, BCC and HCP materials and today is lecture number 51. We will start with understanding Texture in hexagonal close packed system hexagonal close packed Polycrystals.

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The concepts that I will cover today are. How hexagonal close packed system or hexagonal close packed structure is converted to orthonormal coordinate system in order to you know relate it with the sample orthonormal coordinate system? Secondly, what is the relationship between the orientation, which is φ_1 ϕ φ_2 , or g φ_1 ϕ φ_2 and the $hkil$ $uvtw$ that is the Bravais Miller indices?

Third, what are the mode of deformation in hexagonal close packed structure material? How the c by a ratio is affecting the deformation texture evolution in terms of rolling texture development in the material? And finally the twinning in hexagonal close packed structure.

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Transformation between Coordinate Systems: The Rotation (Orientation) Matrix

Coordinate System

The axes of the sample or specimen coordinate system $C_s = \{s_1, s_2, s_3\}$

$s_1 =$ Rolling Direction = RD
 $s_2 =$ Transverse Direction = TD
 $s_3 =$ Normal Direction = ND

The crystal coordinate system $C_c = \{c_1, c_2, c_3\}$

For cubic: $c_1 = [100], c_2 = [010], c_3 = [001]$

For Hexagonal and Trigonal symmetry
 $X_1 = 10\bar{1}0, Y_1 = \bar{1}2\bar{1}0, Z = 0002$ or $X_2 = 2\bar{1}\bar{1}0, Y_1 = 01\bar{1}0, Z = 0002$

Relationship between crystal coordinate system and sample coordinate system

$$C_c = g \cdot C_s$$

So, this particular slide I have already explained a certain time ago in a in this course in a certain lecture. So, it is just a repetition, but it is important to show it here. We know that the sample coordinate systems and we have already taken all the time the example of a rolled material because most of the exercise most of the research that has been done in case of deformation texture are mostly in rolling.

So, RD ND TD are if the sample you know important reference directions. We can consider it as s_1, s_2, s_3 as the important 1 because it could be for casting it could be for you know extrusion it could be for a process like equal channel angular pressing or any other thing like forging or multi axial forging multi directional forging or any other processes like high pressure torsion. S

o, it is it has been taken s_1, s_2, s_3 and s_1, s_2 and s_3 are at 90 degrees to each other. So, this is the sample coordinate system that we usually use. On the other hand the crystal coordinate systems c_1, c_2, c_3 usually in case of you know an orthonormal coordinate system like a cubic crystal or bct are usually at 90 degrees. So, c_1, c_2, c_3 which are you know 100 010 001 for a cubic crystals are at 90 degrees to each other, but if we look into hexagonal or trigonal symmetry systems then the X Y and Z of these systems are not at 90 degrees.

So, hexagonal close packed system for example, X 1 if I take X 1 as $10\bar{1}0$ then X 2 has to be $11\bar{2}0$ type direction, because $10\bar{1}0$ and $11\bar{2}0$ are 90 degrees to each other and now 0002 are 90 degrees to both of them. So, in order to convert an hexagonal close packed

system to an orthonormal system we have to decide that whether we have to take X as $10\bar{1}0$, then Y has to be $11\bar{2}0$, Z always remains 0002 . Otherwise we have to take X equal to $11\bar{2}0$ Y as $10\bar{1}0$ and Z as 002 .

So, in order to determine the positions of the texture component in Euler space, it does not depend it does not depend this thing does not depend on the position of the components in pole figure or the inverse pole figure. But it depends on the Euler space because you see if we are taking X at as you know $c\ 1$. Then the Euler space starts from this $c\ 1$ as ϕ_1 equal to 0 ϕ_2 equal to 0 when ϕ_3 equal to 0 .

Then after a rotation of 30 degrees a $11\bar{2}0$ directions evolve because you see that if $10\bar{1}0$ is this and $1\bar{1}01$ direction is this then there is another $1\bar{1}01$ direction at this angle which is at 30 degrees to $10\bar{1}0$. So, in this case if the an important sample direction is at $11\bar{2}0$ it will form at 30 degrees of say for example, ϕ_1 if it is the.

Now, in case of X if we take $11\bar{2}0$ then it will be the position of the components will be 30 degree different in the ϕ_1 section. So, it is very important to decide upon the coordinate system when we are dealing with the hexagonal or trigonal coordinate system so defining X Y and Z is very important.

After we define the X Y and Z either it is this one or this one we have converted the hexagonal or trigonal system into an orthonormal coordinate system the crystal system is now orthonormal coordinate system. So, now, we can relate the crystal coordinate system to the sample coordinate system with respect to g matrix which is the orientation matrix. And that is how we determine the texture of the hexagonal close packed material.

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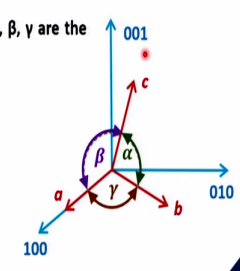
Subsequently the crystal axes are made orthonormal → normalized to be all the same length

Triclinic case where a, b, c are the lattice parameters and α, β, γ are the inter-zonal angles

$$l_{11} = a \quad l_{12} = b \cos \gamma \quad l_{13} = c \cos \beta$$

$$l_{21} = 0 \quad l_{22} = b \sin \gamma \quad l_{23} = \frac{c(\cos \alpha - \cos \beta \cos \gamma)}{\sin \gamma}$$

$$l_{31} = 0 \quad l_{32} = 0$$

$$l_{33} = \frac{c(1 + 2\cos \alpha \cos \beta \cos \gamma - \cos^2 \alpha - \cos^2 \beta - \cos^2 \gamma)^{1/2}}{\sin \gamma}$$


For orthorhombic crystals

$$L = \begin{pmatrix} a & 0 & 0 \\ 0 & b & 0 \\ 0 & 0 & c \end{pmatrix}$$

For hexagonal crystals

$$L = \begin{pmatrix} a & -a/2 & 0 \\ 0 & a\sqrt{3}/2 & 0 \\ 0 & 0 & c \end{pmatrix}$$

Young and Lytton, 1972

So, we have shown in the previous lecture that, Young and Lytton in 1972 have shown that how the you know the hexagonal close packed system is basically converted into orthonormal system and then it is normalized to the same length. So, it is related by a matrix which is containing nine variables which are $l_{11} \ l_{12} \ l_{13} \ l_{21} \ l_{22} \ l_{23}$, sorry $l_{23} \ l_{31} \ l_{32}$ and l_{33} by these equations. So, these are geometric relationship between the hexagonal coordinate system Bravais Lattices with respect to the orthonormal coordinate system as we have decided in the previous slide Now, for the you know orthorhombic crystals. The L is equal to $a \ 0 \ 0 \ 0 \ b \ 0 \ 0 \ 0 \ c$.

Whereas, for the hexagonal system L becomes equal to $a \ -a/2 \ 0 \ 0 \ a\sqrt{3}/2 \ 0 \ 0 \ 0 \ c$. So, one can calculate these and once we get the variation of a b and c which is at an angle of α β and γ to you know an orthonormal normalized orthonormal as $100 \ 010 \ 001$. Then, we can relate this orthonormal crystal you know reference system to the sample reference system and find out the value of g which is the orientation matrix.


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The relationship between the orientation $g\{\varphi_1, \phi, \varphi_2\}$ and $\{hkil\}\langle uvw \rangle$

$$\begin{bmatrix} h \\ k \\ i \\ l \end{bmatrix} = \begin{bmatrix} \sqrt{3}/2 & -1/2 & 0 \\ 0 & 1 & 0 \\ -\sqrt{3}/2 & -1/2 & 0 \\ 0 & 0 & c/a \end{bmatrix} \begin{bmatrix} \sin\varphi_2 \sin\phi \\ \cos\varphi_2 \sin\phi \\ \cos\phi \end{bmatrix}$$

$$\begin{bmatrix} u \\ v \\ t \\ w \end{bmatrix} = \begin{bmatrix} 2/3 & -1/3 & 0 \\ 0 & 2/3 & 0 \\ -2/3 & -1/3 & 0 \\ 0 & 0 & c/a \end{bmatrix} \times \begin{bmatrix} \cos\varphi_1 \cos\varphi_2 - \sin\varphi_1 \sin\varphi_2 \cos\phi \\ -\cos\varphi_1 \cos\varphi_2 - \sin\varphi_1 \sin\varphi_2 \cos\phi \\ \sin\varphi_1 \sin\phi \end{bmatrix}$$

Young and Lytton, 1972



Now, the calculation can even revert back to you know the what is the you know Bravais Lattices sorry, the Bravais Miller indices of this you know texture component that is the hkil and uvw. So, what I am saying is that we can relate the g matrix that is the phi 1 phi phi 2 with respect to the hkil and uvw by the relationship that hkil is equal to a matrix like this into the you know the trigonometric functions of phi 1 phi and phi 2.

And that's how I am not giving the calculations here, but you can see the Young and Lytton and you can see that how hkil and uvw is related to the phi 1 phi phi 2 components. So, the relationship of the Miller Bravais indexes of the hexagonal close packed system with respect to phi 1 phi phi 2 of the Euler space is well defined.

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Mode of Deformation **Dislocation glide**

Slip System	b	Slip Plane & Direction	Slip System	
			Total	Independent
Basal	$\langle a \rangle$	$(0002)(11\bar{2}0)$	3	2
Prismatic	$\langle a \rangle$	$\{10\bar{1}0\}(11\bar{2}0)$	3	2
Pyramidal	$\langle a \rangle$	$\{10\bar{1}1\}(11\bar{2}0)$	6	4
I st Pyramidal	$\langle c + a \rangle$	$\{10\bar{1}1\}(11\bar{2}3)$	12	12
II nd Pyramidal	$\langle c + a \rangle$	$\{11\bar{2}2\}(11\bar{2}3)$	6	5

Yoo: MMTA, 1981, 12, 409; Reed Hill Physical metallurgy;
Balasubramanian & Anand: Acta Mater., 2002, 50 133;
Salem, Kalidindi, & Doherty: Acta Mater., 2003, 51, 4225.

If we look into the deformation modes of the hexagonal close packed system. We will be able to see that an hexagonal close packed system will contain many slip systems. And these are you see the prismatic slip system that is the slip system which contains which occurs in the 101 bar 0 type slip plane in the 112 bar 0 direction. So, there could be total 3 out of which 2 independent prismatic slip system.

On the other hand one can observe the basal slip system. The basal slip system the occurs in the basal plane that is the 0002 plane and it occurs in the 112 bar 0 direction. You see depending upon the c by a ratio when the c by a ratio of the hexagonal close packed material is high then the basal plane is the closest pack plane. And thereby the slip occurs mostly in the closest pack plane which will have the lower critical resolved shear stress.

On the other hand when the c by a ratio is lowered down and in a range of say c by a ratio equal to 105 then the prismatic slip systems that the prismatic planes are slightly closer to each other and thereby their activities increases. For example, in titanium the prismatic slip system is found to be a little more active than the basal slip system. So, you see that c by a ratio has an important consequence on the deformation behavior of the material.

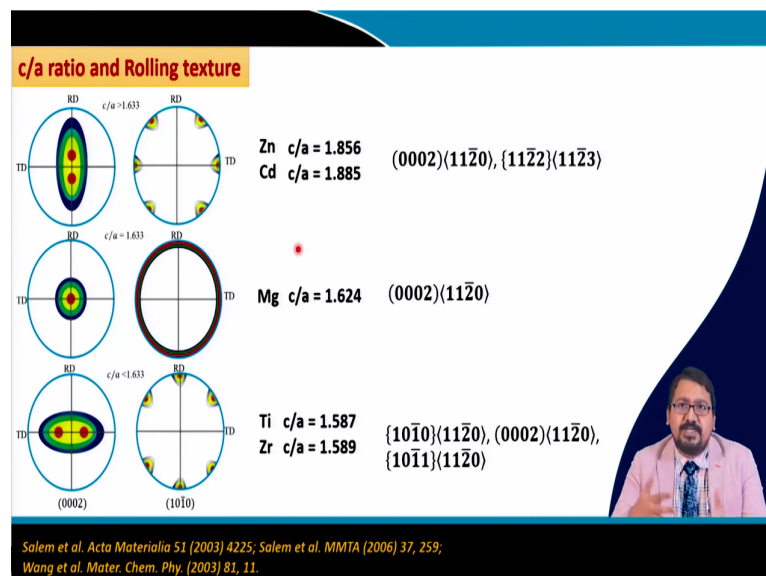
Now, apart from these two slip systems which contains 2 2 independent slip systems are, we have a pyramidal a which usually occurs in the 101 bar 1 type slip plane and in the 112 bar 0 direction which is same the closest pack direction. Apart from this there is pyramidal c plus a 1 type of slip system and c plus a 2 type of slip system which is shown here.

So, the c plus a 1 type of slip system occurs in the $10\bar{1}1$ type plane is shown here and in the c plus a direction which is $11\bar{2}0$ type. So, there are a total of 12 independent pyramidal slip system. Whereas the pyramidal c plus a type basically is occurs on $11\bar{2}0$ type slip plane in the same c plus a direction, which is the second closest packed direction in the hexagonal close packed system.

However, if you see that this two slip planes slip systems are very important to be operated in during deformation of the hexagonal close packed system because, otherwise the you know the $11\bar{2}0$ is only confined within a certain plane which is mainly the basal plane. So, you see the $11\bar{2}0$ if it occurs it can occur only in these direction these three directions and none of them. So, in order to have a sustained poly crystalline deformation deformation of poly crystalline material hexagonal material conforming to the von Mises criteria having 5 independent slip system.

A slip along $11\bar{2}0$ is also necessary in the absence of weight there could be you know the deformation will sustain only by the formation of twinning. Even the deformation in most of the hexagonal material occurs by the formation of deformation twinning because the absence of or the presence of only less than 5 independent slip systems.

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So, if we look into the you know the evolution of texture during rolling by seeing the 0002 and the $10\bar{1}0$ pole figure, we will see that in case of when the c by a ratio is nearly ideal that is this second 1. What we will see that is for example, in case of magnesium where the c

by a ratio is 1.6324 which is nearly equal to the ideal c by a ratio of hexagonal close packed material 1.633.

The deformation occurs mostly by basal slip of course, followed by prismatic and pyramidal slip without which the slip cannot occur and the material will fracture. Therefore magnesium specifically when it deforms it has to deform at a little higher temperature. So that apart from the basal slip system which is quite active the other slip system like pyramidal and prismatic slip system start to active in order to support the basal slip system in order to have the material more than 5 independent slip system so that it deforms plastically without failure or fracture.

Under such situation it is observed that strong basal texture in the rolling plane that is at ND will form. And under such situation you will see the rolling direction will have a strong 112 bar 0 type you know component. Now, in case the rolling texture may have you know the rolling texture, when the rolling is taking place a fiber is usually obtained.

A fiber usually of 101 bar 0 or 112 bar 0 along the, you know 90 degrees to ND is obtained because the rolling is possible only at a little higher temperature. And at this temperature the deformation occurs at the same time dynamic recovery and recrystallization processes are active in the material, and thereby the there is a rotation of the texture component along 002 axis by 30 degrees.

So, the deformation texture which was initially along 112 bar 0, now rotates to form 101 bar 0 texture component and such a situation leads to the formation of a fibrous type texture along the radial direction sorry, along the you know RD and TD and therefore, a formation of fiber such could be observed right.

Now, in case of c by a much higher than the ideal c by a ratio of 1.633 that is 1 point nearly 1.8 or something. Now, under such situation we will observe that more of basal slip is possible, but the prismatic slip is now restricted because the prismatic slip has a much loosely packed plane.

Now, apart from this in order to sustain the deformation pyramidal type slip system starts to activate. Under such situation the pyramidal c plus a 1 and 2 types of slip systems if it gets activated then we it is observed experimentally, that the basal poles actually divides itself into

2 poles and along the RD and it remains along the rolling direction; whereas, 1 observed the formation of 101 bar 0 poles at these positions.

So, this is a typical texture being observed rolling texture for the zinc and cadmium those materials which have the c by a ratio greater than the much greater than the ideal c by a ratio of hexagonal close packed material. Whereas, in case of c by a ratio which are smaller like you see titanium or zirconium which has c by a ratio of around 1.56 1.587 1.589.

Now, under such situation under such situation what happens that the initial slip system becomes prismatic followed by the basal and thereby pyramidal slip systems also start to operate in this. Under such situation what happens that the basal poles basically shifts towards the TD orientation to towards the TD sample direction and it looks something like this.

The 101bar 0 pole figures can also be observed to be slight is rotated by 30 degree as compared to the one with c by a ratio greater than 1.633. So, I would suggest to go and look into the paper by Salem and Wang et al. Salem in Acta Materiali 2003 Wang et al in Materials Chemistry Physics in 2003 again. So, also Salems Metallurgical and Materials Transaction in 2006.

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Twinning in HCP For eg. Titanium

Twin Type	K1	K2	η_1	η_2	Shear Plane	angle	Shear	q
Extension	{1012}	{1012}	{101 1}	{1011}	{1210}	~85°	0.167	4
	{1121}	{0001}	{112 6}	{1120}	{1100}	~34°	0.638	2
Contraction	{1122}	{1124}	{112 3}	{2243}	{1100}	~63°	0.225	6
	{1011}	{1013}	{1012}	{3032}	{1210}	~57°	0.098	8

M.H. Yoo: MMTA, 1981, 12, 409; Reed Hill Physical metallurgy;
 S. Balasubramanian & L. Anand: Acta Mater., 2002, 50 133;
 A. Salem, S.R. Kalidindi, & R.D. Doherty: Acta Mater., 2003, 51, 4225.

So, this is this was all about the slip system and the relative formation of texture components during rolling using these slip system. Apart from this as I said earlier that hexagonal close

packed material plastic deformation cannot happen without formation of certain fraction of twins. Of course, if the temperature of the rolling is increased then the twinning deformation could be reduced and the material can be sustained by slip based deformation. But it is always important to know that what various types of twinings can develop during deformation annealing and other conditions in hexagonal close packed material.

And here is an example of titanium because a lot of different kinds of deformation and other twins are observed in here. So, most importantly before we start we see that if this plane is the K 1 plane and this is the eta 1 direction and the parent grain has the K 2 plane. This is the K 1 plane and eta 1 plane of the parent grain and this is the K 2 plane and the eta 2 plane of the parent grain before the shear. Then twinning is a process where keeping K 1 and eta 1 same the shearing takes place from this K 2 plane to this plane which is at the similar you know angular relationship with the K 1 plane. But you see now the angular relationship which is in this direction is now changed into this direction because of the displacive mechanism and this is not a diffusive mechanism.

So, a displacive transformation twinning occurs and without any phase transformation; however, by the process of shear where the K 2 and eta 2 plane after the shear becomes this one right; so this is a process of twinning. So, in case of hexagonal close packed material mainly two kinds of twins were observed; one is the $10\bar{1}2$ $10\bar{1}1$ type twinning.

In this case what happens that the a sample a crystal structure a hexagonal crystal structure it is shown vertical if, one cannot understand then I would like to know show it with the help of a pen. This crystal structure if you look you know in a three dimensional structure then one second let me take the eraser and let me take the pen. So, if we look it is something like this ok, so this one. Under the situation when a deformation that is a compression is given along this direction or this direction ok or a tension is given along this direction. Extension twins develop so a extension or a tension along the c axis produces a twin; the twin is known as the extension twin. So, there are two types of extension twin one of the important twin as I said is the $10\bar{1}2$ $10\bar{1}1$ which forms by rotation or by shearing by 85 degrees.

So, the twin material has the unit cell which is rotated by you know 85 degree to the parent so if this is the twin right. On the other hand it is always it is also observed let me take the highlighter that there is $11\bar{2}1$ 001 $11\bar{2}1$ $11\bar{2}6$ type extension twin 2 and the angle

of shear is 34 degree or the angle by which the shearing takes place that is the relationship between K_2 . And this undeformed and this deformed after the shear is 34 degree right.

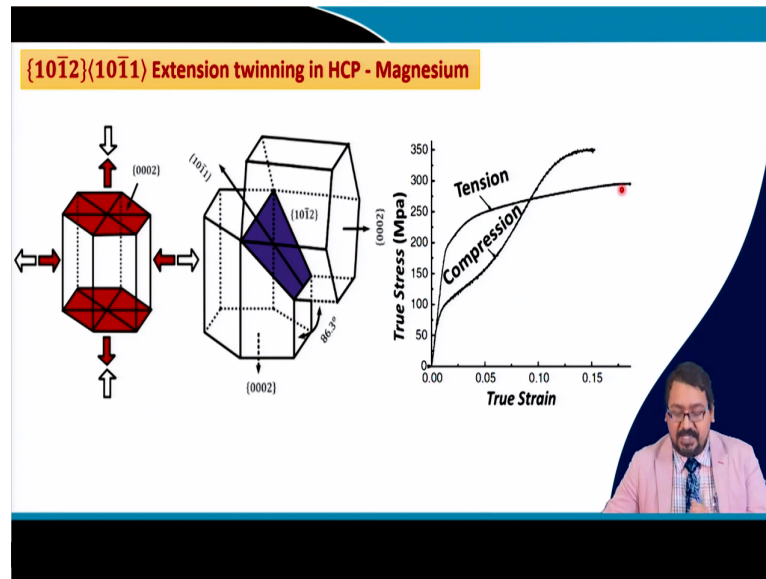
So, you can see that the shear strain associated with $10\bar{1}1$ type extension twinning is 0.167 and it is less. Therefore, large number of you know extension twins are observed. On the other hand and of course, it will only be observed when the deformation is extension along the c axis. Whereas, another important twin or twins are contraction twinings and one of the important contraction twin is $11\bar{2}2$ type and this is shown here, and then it happens by the contraction along the c axis.

So, if I show you that in this case I will take another color let us say let us take blue, and if I draw the crystal structure for the parent grain it will look something like this you see. So, in case of the first case this line is this line and it is looking like this and in case of the second case we can see there are the orientation is like this so, we can see two lines right.

And if I extend it will look something like this so this is the unit cell that we are talking about right. So, this is the parent one and while the contraction twinning takes place the contraction twinning takes place stack by you know the compression along the c axis. So, it is involved in compression along the c axis that is why it is called the contraction twinning. So, one can give either compression or extension along the you know other directions.

So, the formation of the contraction twinning $11\bar{2}2$ type contraction twinning this is the twin orientation of the twin that will form right. So, this crystal unit cell is basically you know 60 degree rotated from the parent crystal orientation. And one can see that a shear strain of 0.225 is required to do this you know contraction twinning. Another type of contraction twinning is $10\bar{1}1$ type contraction twinning which occurs at 57 degrees angle to the parent orientation. These contraction twinning and the extension twinning which is $11\bar{2}1$ are observed in hexagonal close packed material but rarely.

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So, if we look into the $10\bar{1}2$ $10\bar{1}1$ type extension twinning, in case of titanium and in case of magnesium their influence on the deformation behavior is highly. And you can see that these $10\bar{1}2$ $10\bar{1}1$ type extension twins as I said develops when the material is compressed along you know the you know this direction perpendicular to the c axis. So, the material is basically extended along the c axis.

Now, why it is always called a compression because you see that whenever we take a material the material is rolled and when the material is rolled the basal plane basically develops in the rolling plane. So, if we are producing samples either we are producing samples along the rolling directions or the transfers direction.

And if we are giving compression to that sample the compression is taking place at the direction which is perpendicular to the c axis most of the time and thereby the formation of tensile twinning is evident. And thereby when compression is done tensile twinning takes place and the compressive curve looks something like this and so a sigmoidal curve could be observed.

So, this sigmoidal type curve occurs due to the formation of extension twinning during compression along RD right rolling direction; that means, compression perpendicular to the c axis. Now, the increase in the strain hardening that is the increase in the strain hardening rate is observed during this compression process.

And this happens because the formation of 101 bar 2 101 bar type extension twinning leads to the change in the orientation by about 85 degrees to the parent orientation. Thus the compression, which was initially occurring along the means perpendicular to the pyramidal plane now occurs, perpendicular to the basal plane.

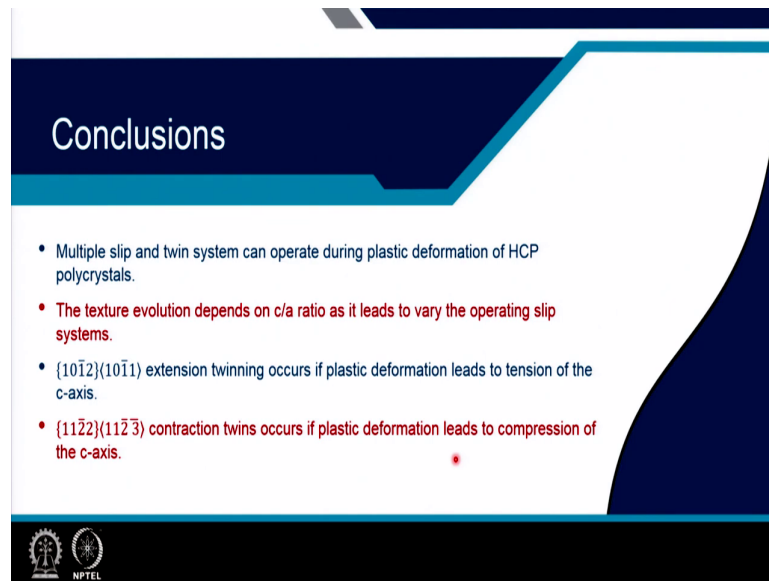
Now, the basal plane compression perpendicular to the basal plane this is a hard texture orientation this is a hard orientation, means its Taylor factor or the orientation factor will be very high. And it has been shown that their Taylor factor or orientation factors are high therefore, they are very strong to deform their strength along this direction is higher.

And therefore, with the volume fraction of formation of the 101 bar 2 101 bar 1 type extension twinning the strain hardening rate increases thereby increasing the strength of the material and thereby forming formation of a sigmoidal type behavior. However in case of tension in case of tension the tension along the RD it does not allow the material that is magnesium to form the you know extension twinning.

And, thereby the material deforms by only slip the amount up to which it can deform before fracture in case of magnesium it has been found that the contraction twinning does not occur under such situation most of the time. So, the as there is no twinning behavior the tension is like a normal tension.

So, this is all this is the first part of the hexagonal close packed materials texture evolution and we will do two more parts of it.

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The slide is titled "Conclusions" and features a dark blue header and footer with a light blue diagonal stripe. The main content area is white with a dark blue curved shape on the right side. It contains a bulleted list of four points. The first point is in black, and the following three are in red. The footer includes two logos: one for NPTEL and another for a university.

- Multiple slip and twin system can operate during plastic deformation of HCP polycrystals.
- The texture evolution depends on c/a ratio as it leads to vary the operating slip systems.
- $\{10\bar{1}2\}\{10\bar{1}1\}$ extension twinning occurs if plastic deformation leads to tension of the c-axis.
- $\{11\bar{2}2\}\{11\bar{2}\bar{3}\}$ contraction twins occurs if plastic deformation leads to compression of the c-axis.

From this part we can give the conclusions that in hexagonal close packed material, multiple slip and twin systems operate at the same time during plastic deformation. And the texture evolution depends upon the c by a ratio because it by varying the c by a ratio that is for different you know hexagonal close packed material, the operating slip systems thereby different and therefore, the texture evolution is different.

Now, $10\bar{1}2$ and $10\bar{1}1$ type extension twinning is most prominently observed in magnesium titanium which are you know technological material are applicable in case of you know Euler space industry, biomedical industry. For example, titanium are very important material as permanent bio implants or in Euler space application magnesium are soon may be coming out as you know temporary bio implant which are bio dissolvable inside the body after its utilization right.

So, extension twinning which is an important plastic deformation phenomena in these two materials occurs during tension along the c axis. Whereas, contraction twinning which is an important phenomena during deformation of titanium and we will show some slides of the latest research in the next lecture. Where contraction twinning in titanium occurs during plastic deformation when it is when the material is compressed along the texture c axis right. So, that's all for today's lecture.

Thank you very much.