

Principles of Physical Metallurgy
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Lecture No. #08
Plastic Deformation of Pure Metal

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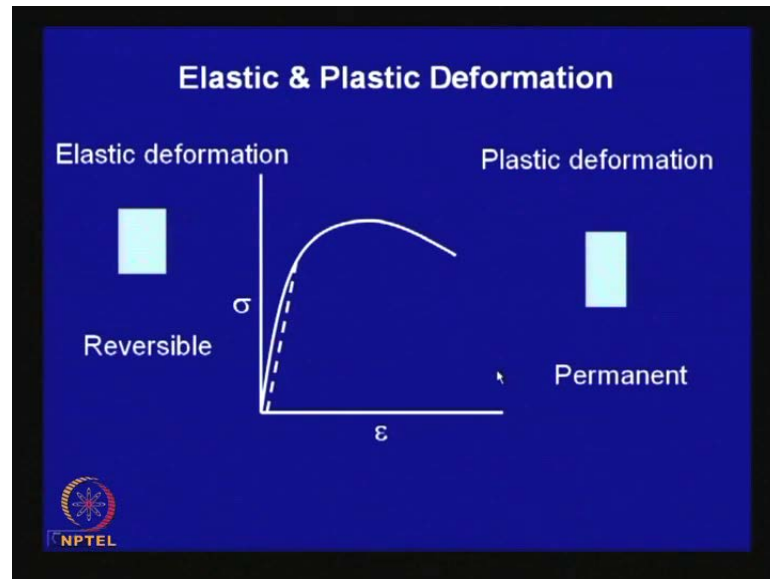


Good morning. Today, we begin a new chapter. This is on plastic deformation of pure metal. Last class, we looked at evolution of micro structure of pure metal, and normal the metal that we use, they are made up of several crystals. They are oriented at random and its properties will depend on the type of crystal of which it is made up of, and it will also depend on the way; these crystals are arranged in the metal. And today, we will look at what happens if we try to deform the metal. Now, we will look at the types of deformation broadly. The deformation can be classified into elastic, and plastic deformation. The elastic deformation is reversible. It remains as long as there is a state of stress present. Once you remove the stress, the material comes back to its original shape, and position or shape and size. Now, plastic deformation on the other hand is permanent, even if you remove the stress applied.

It is only the elastic part of the stress which disappears, but the permanent deformation remains. Now, we will look at critically the mechanisms of plastic deformation of pure metal. And we will try and find out at what stress actually the deformation permanent

deformation takes place. What is the nature of the stress? What type of stresses can cause plastic deformation. We will also look at the stress strain behavior of typical crystals, say particularly face centered cubic crystal. We will also try to find out and estimate of the theoretical strength of an ideal crystal. So, basically, these are the four topics that we are going to consider in this chapter.

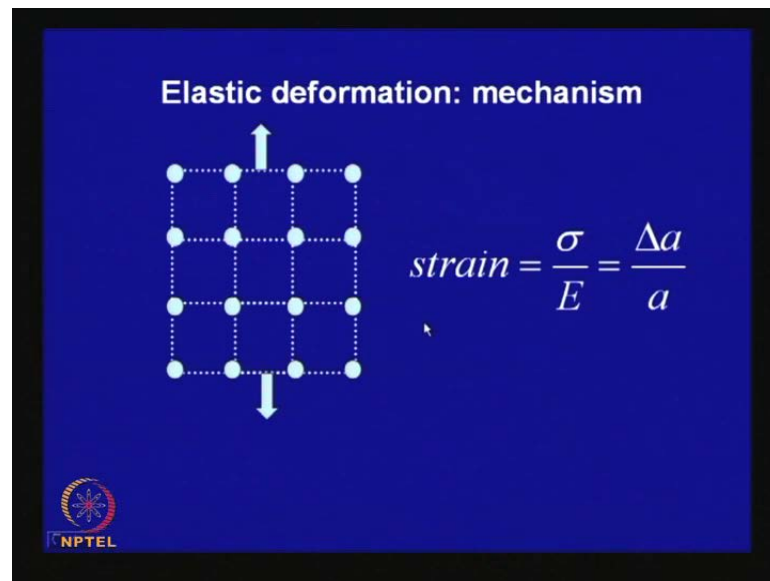
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Now, to recapitulate the difference between elastic and plastic deformation; you have already familiar with this type of stress strain plot, which we normally perform to find out strength of material. We looked at it in detail and the type of information that, you get from this kind of test. Now, this part of the stress strain diagram represents elastic deformation. If you deform a material here unload, it will trace back its path and come back to its original shape and size. But if you load it beyond this point called proof stress, then if you unload, it will only the elastic part will get recovered, but there will be a permanent strain left behind.

This is schematically shown here; elastic this is the nature. If you apply, there is a deformation; but once the stress is removed, it comes back to its original position. So, this is reversible. On the other hand, plastic deformation if you apply the stress, you go somewhere here; you remove the stress; it that permanent the deformation remains, only a small part which is elastic, is recovered. So, this is permanent.

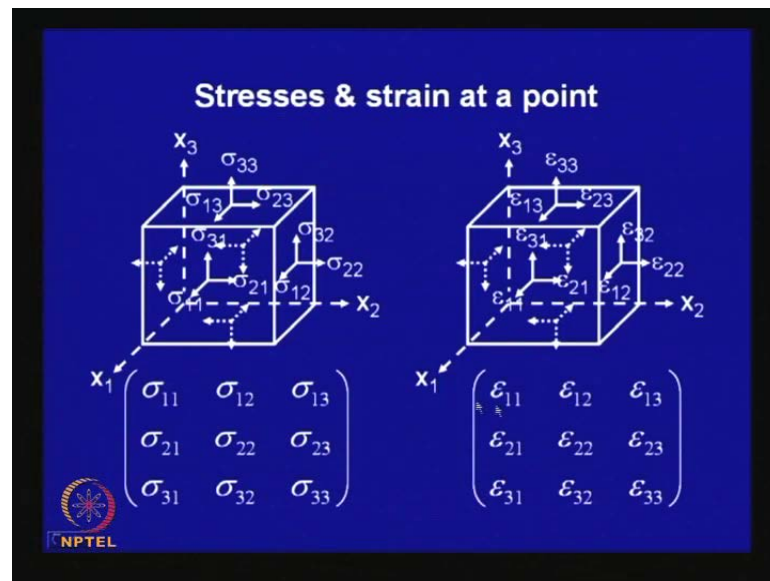
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Now obviously, if you look at the mechanism of deformation, what happens with respect to the crystal structure? We have seen that, strain is defined as stress over young's modulus; this is the hooks law under uniaxial attention. So, in terms of crystal structure so you have, I just shown a 2 D crystal structures. If you apply stress, what happens in one direction? This direction it elongates, but in this direction there is a contraction. So basically, you have strain in two directions. In one direction, in the direction of tensile load, there is an expansion; whereas perpendicular to that, there is a little contraction.

So therefore, eventhough stresses uniaxial, you have strain in this direction, this direction as well as perpendicular to the plane. So, you will have three component of strain. If you have a system, if you can measure we have seen the how extra diffraction can be used to measure the lattice spacing. If lattice spacing is measured, then the change in lattice parameter can be converted into strain; that is change in lattice parameter delta a over that initial lattice parameter a. So, this is strain. So, that means, extra diffraction can be used to find out the extent of elastic deformation or the presence of stresses in metals, residual stresses in metal.

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Now, it may be worthwhile to understand deformation, we have to know what kind of stresses will actually be responsible for deformation? So, for that it is just to recapitulate, people having background of applied mechanics will know, how stresses and strains at a point is represented? This is shown here as a unit cube. And with respect to this X 1, X 2 X 3, this is a set of orthogonal axis. This represents the state of stress. This represents state of strain. Strain is a represented as epsilon i j, let us say and I can have any value from 1 to 3. Similarly, j can also have 1 to 3. For example, this epsilon 3 3 represents normal strain on plane, this intersects X 3 axis at right angle.

So, this is the plane which intersects, which is normal to X 3 axis. So, this is the normal strain. You also have strain in this direction, which is called shear strain. This is represent, these acts on plane three in direction two along this direction. And the same way, sigma 3 3 represents the normal stress on the plane which intersects, X 3 axis at right angle. sigma 2 3 is shear stress, along X 2 direction acting on plane, which intersects which is normal to X 3 axis. So, therefore the state of stress can be represented in the form of a matrix. Like this, sigma 1 1, sigma 1 2 is a 3 by 3 matrix and also you must remember that, state of stress should be such that there should be a state of equilibrium.


So that means, if there is a sigma 3 3 stress acting here on this plane, there should be a stress equal and opposite to the other side, this. Similarly, the torque which is generated by sigma 1 3 and this is also 3 1, 1 3 and this is 1 3; this is also 1 3; this is the torque generated by this should be balanced by the torque generated by the sigma 3 1. So,

basically, so that means, σ_{12} or σ_{13} should be equal to σ_{31} . So, in reality, it is good enough to define stress. So that means, the stress matrix is symmetric. σ_{21} is equal to σ_{12} ; σ_{13} is equal to σ_{31} ; σ_{32} is equal to σ_{23} and same thing happens, in case of strain as well. So, you have 6 component of stress 6 component of elastic stress, 6 component of elastic strain.

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Stress strain relation

$$\begin{bmatrix} \sigma_{11} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad \begin{bmatrix} s & 0 & 0 \\ 0 & -s & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad \begin{bmatrix} p & 0 & 0 \\ 0 & p & 0 \\ 0 & 0 & p \end{bmatrix}$$

$$\begin{bmatrix} \sigma_1 & \sigma_6 & \sigma_5 \\ \sigma_6 & \sigma_2 & \sigma_4 \\ \sigma_5 & \sigma_4 & \sigma_3 \end{bmatrix} \quad \begin{bmatrix} \epsilon_1 & \frac{1}{2}\epsilon_6 & \frac{1}{2}\epsilon_5 \\ \frac{1}{2}\epsilon_6 & \epsilon_2 & \frac{1}{2}\epsilon_4 \\ \frac{1}{2}\epsilon_5 & \frac{1}{2}\epsilon_4 & \epsilon_3 \end{bmatrix} \quad \begin{aligned} \epsilon_{ij} &= S_{ijkl} \sigma_{kl} \\ \sigma_{ij} &= C_{ijkl} \epsilon_{kl} \end{aligned}$$


Now, advantage of this kind of matrix representation is helps you to transfer the state of stress from one reference axis to another reference axis. Very often, those who are familiar with stress analysis; they will know that stress at a point. You know can be defined with respect to a reference axis. If it is defined with respect to one reference axis, and often you have to determine stress with respect to another reference axis. And what you need to know is the direction cosine between this old reference system and the new reference system.

Is this direction cosines are known, it using $(())$ representation very easily, state of stress can be converted from one reference axis to another. Now, let us look at few very common state of stress. Like, when you do a tensile test, you subject the specimen to uniaxial loading. You have stress only in one direction, that is σ_{11} and rest of the components, they are 0. You can also have a situation, where the stress says this is s and this component is minus s . This type of stress actually represents a case of pure shear. What does this mean? It means there is no tensile component.

It is shear and later on, we will see, it is this shear stress component which is primarily responsible to cause plastic deformation in pure metals of crystal. If the state of stress is like this, you have only these three normal components; that mean all principal stresses, this normal component, this diagonal component are also known as... If this diagonal components only exist, rest of these are 0 then, one can call them as principal stress. This reference axis is described with respect to the three principal stresses. Now, if all the three principal stresses, they are equal; say in this case, this is p p p . So, this means, this is a case which is something like, you can say a state of hydrostatic stress.

So, if it is minus p , minus p , minus p that means, you are trying to compress a particular solid from all direction. Now, this kind of stress, state of stress that hydrostatic state of stress cannot cause any plastic deformation; Because under this condition, if you convert, if you try that reference axis, try to find out what is the state of what kind of shear stress you will have? You will find all the shear stress component will be 0. If there is no shear stress, the material cannot undergo any plastic deformation. So, it is important to know the state of stress, because very often, although a simple tensile test you subject material to uniaxial stress.

But for deformation often you will have at multiple stresses applied along different direction. And you should be conversion; one should be conversion with the state of stress, which can give plastic result in plastic deformation. Now, using this kind of representation, as I said that σ_{ij} and ϵ_{kl} . So, suppose this is the state of stress; ϵ_{kl} is the state of strain at a particular point. These two are related by a relationship like this and in inverse of this, a strain is related to stress by this. So, this is the strain tensile. This is the stress tensile and you also need another tensile, which will we convert one in to the other. This matrix S_{ijkl} , this is called compliance matrix.

This is called C_{ijkl} is called stiffness matrix. This kind of a representation also signifies that, this is not just one term C_{ijkl} ; the change from 1 to 3 and wherever these indices are repeated like k appears here; k appears here. So, this represents summation over k , that k extending from 1 to 3; similarly, l extending from 1 to 3. Similarly, you will have here also exactly same thing it indicates. Now, as you can see, if this number you know each you change from 1 to 3. If you start writing this full expression, it will be a very long equation and as. So, one way a convenient way of reducing it is to see that, how many component of state of stresses important?


We have just seen that, this stress matrix is symmetric. So that means, these (σ_{ij}) diagonal elements, they are equal. So, actually you will have the 6 component of stress at a point, $\sigma_1, \sigma_2, \sigma_3$. And this is a shear stress component, which is represented said that σ_{23} is represented as σ_4 ; σ_{13} is represented as σ_5 ; σ_{12} is represented as σ_6 and same thing is done with respect to strain. But to maintain that similarity, it is possible to show when you convert you know these kinds of two indices to represent strain and two indices to represent stress. When you do and you convert it into just 6 indices 1, 2, 3, 4, 5, 6 in that case, there will be some conversion factor and which is listed here.

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Stress strain relation: Stiffness

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix} \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \epsilon_4 \\ \epsilon_5 \\ \epsilon_6 \end{bmatrix}$$

No of elastic constant = 21: Triclinic crystal: no symmetry




So, this ϵ_6 component that strain component, this should be $\epsilon_6/2$ is represented like this. In that case, you have 6 state of stress; 6 component of stresses. There will be 6 component of strain and they will be related by a 6 by 6 matrix. This matrix is called stiffness matrix. C matrix is the stiffness matrix. And from this, you can find out it is possible to show that, that symmetry that is I said that, σ_{ij} is same as σ_{ji} . So, these indices, they are interchangeable. With this, it is very easy to show that, this kind of and this stiffness matrix; this component C_{12} will be same C_{21} . So, what it means is, this 6 by 6 matrix is actually symmetric matrix.

So, how many then elastic constants do you have here? So, you can count this. So, first row is 6; second row 5; this row 4. Basically, it is a sum of 1 plus 2 plus 3 plus 4 plus 5 plus 6. So, it will be 21. So, in... So, you can have actually 21 numbers of elastic constants, stiffness constants. And this is true I mean this is what, you need to describe

elastic stress strain behavior of crystals, where you do not have any symmetry. For example, it is the triclinic crystal, where there is no symmetry and similar relationship also exists with respect to you can say, this is an inverse relationship strain is expressed as a function of stress.

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Stress strain relation: Compliance

$$\begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \epsilon_4 \\ \epsilon_5 \\ \epsilon_6 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} \\ S_{21} & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} \\ S_{31} & S_{32} & S_{33} & S_{34} & S_{35} & S_{36} \\ S_{41} & S_{42} & S_{43} & S_{44} & S_{45} & S_{46} \\ S_{51} & S_{52} & S_{53} & S_{54} & S_{55} & S_{56} \\ S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & S_{66} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix}$$


In that case, the matrix is like this; S_{11} , S_{12} and this is called compliance matrix. Now, this elastic constant; that means, you need a large number of elastic constant to describe the elastic state of stress in a material. This number of elastic constant, that you need for material which is which does not have any symmetry element, that is triclinic crystal. You need 21 elastic constant, but we are fortunate. We often handle with the number of type of metals that we use.

They are mostly cubic and cubic crystals have high symmetry. It is possible to show using this (()) representation that, if you impose this symmetry conditions; this number of this elastic constants; that you need independent elastic constants; that you need to describe this state of stress is reduced drastically. So, for example, what does it mean? A cubic crystal has a 4 fold symmetry, 3 4 fold symmetry; that means, if you try to rotate it about one crystal axis, say let us crystal axis is usually represented as a b c as has been mentioned. So, about a if you rotate it by 90 degree, it comes to occupy exactly similar position.

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Cubic symmetry & isotropy

$S_{11} = \frac{C_{11} + C_{12}}{(C_{11} - C_{12})(C_{11} + 2C_{12})}$ $S_{44} = \frac{1}{C_{44}}$ $S_{12} = \frac{-C_{12}}{(C_{11} - C_{12})(C_{11} + 2C_{12})}$	$C_{44} = \frac{1}{2}(C_{11} - C_{12})$ $S_{44} = 2(S_{11} - S_{12})$ $E = \frac{1}{S_{11}} \quad \nu = -\frac{S_{12}}{S_{11}}$ $\mu = \frac{1}{S_{44}} = C_{44} = \frac{E}{2(1 + \nu)}$
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Single crystal W is isotropic. Polycrystalline solids with random orientation are isotropic wrt elastic constants.

So, in that case, also you can convert this matrix to that and each of this element; they will be equal by imposing this condition. It is possible to show that, in case of a cubic crystal you need only three elastic constants S_{11} , S_{44} , and this is I think is S_{12} . This is a mistake here; this should be S_{12} . So, you need these three elastic constants and there is a relationship between stiffness and compliance and which is written here. In terms of stiffness, you will have C_{11} , C_{12} and C_{44} . In fact, more familiar with this, this is called shear modulus.

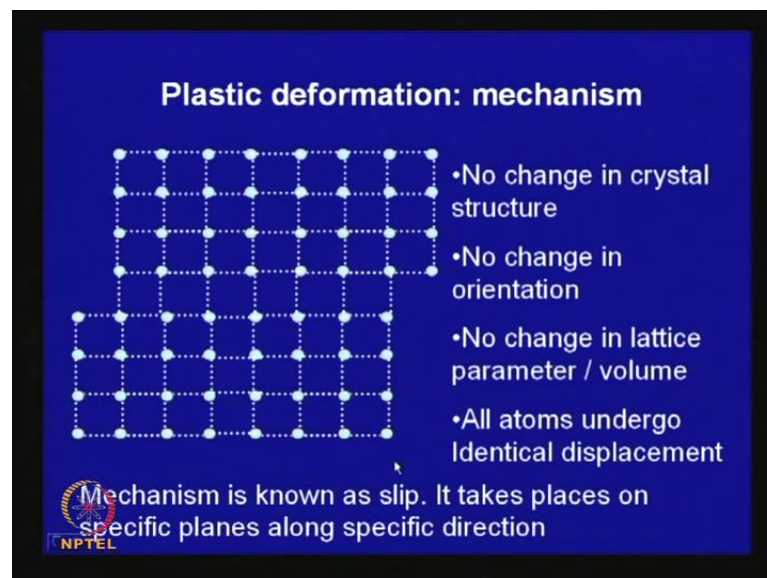
Basically, this is and also if you look at this elastic constants of different crystals and you will find, if this relationship is satisfied; if there is a relationship between say suppose material is isotropic; by isotropic means, it has same property in all directions. So, even if you rotate a crystal by any angle θ and that direction, you measure modulus; it should be same. So, to impose this condition also, **if you impose this condition** you will find, there is a further relationship between these three elastic constant; that means S_{11} , S_{12} and S_{44} which is listed here. So that means and similarly, similar relationship exists between the stiffness coefficients.

We are more familiar with young's modulus and what is how is this young's modulus is related to this compliances with respect to a single crystal, like E is S_{11}^{-1} ; $1/S_{11}$ **(C)**. This is the ratio of this is minus ratio of S_{12} over S_{11} and shear modulus, the C_{44} actually represents shear modulus. So, there is a relationship if a material is isotropic, there is a relationship between shear modulus, young's modulus and **(C)**. If one looks at the listed from hand book, that elastic constants of different crystals which are **(C)**

measured. If you look at that, you will find increase of tungsten; although it is crystalline BCC tungsten, as a BCC its elastic constants are such that, it is the material that it is isotropic.

Now, polycrystalline material we have seen, it is made up of several crystals which are oriented at random. Random orientation will even out the effect of the single crystal property. Because of that random orientation, most polycrystalline material will exhibit isotropic property with respect to these elastic constants. In fact, same will be true with respect to other properties which depend on crystal orientation. With this background, I think it will be worthwhile to look at mechanism of plastic deformation, because to cause the deformation you need a given state of stress. It has been mentioned state of stress, which can give plastic deformation is shear stress, which is shown here.

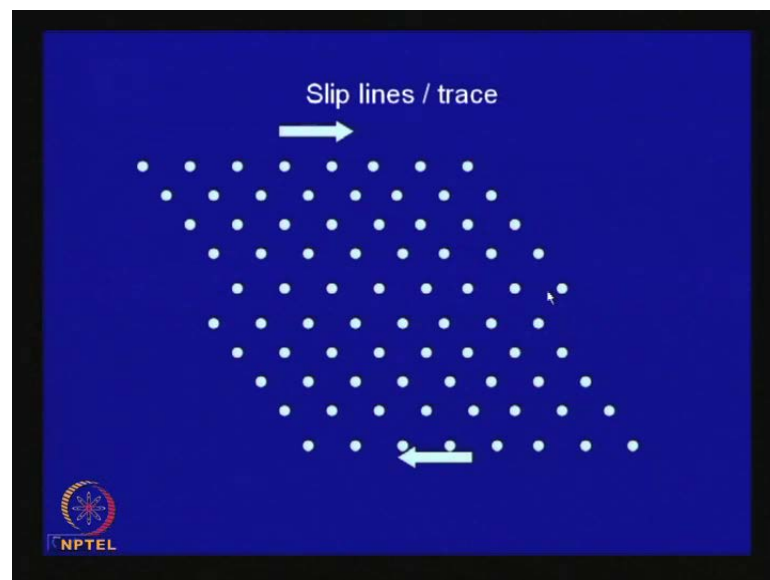
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You have, I have a 2 D crystal, which is shown here. You can also visualize as if these are different layers of atoms; it is like a pack of cards, say if you put a pack of card try and slide. So, that is this case of state of shear stress. Now, what happens if you apply shear stress? If you apply shear stress, if it is large enough to overcome the lattice forces; it can move a part of the crystal will move the top part moves over the bottom along this direction. So, this plane on which this movement takes place, this mechanism is called slip. The plane on which this movement takes place is called slip plane and the direction and which and the plane, there will be a specific direction along with which this displacement takes place. That direction is call slip direction.

And here after this deformation, if you removed the stress since it is comeback a gone to another state of stability minimum energy; it will not come back. The deformation is permanent. And if you look at the crystal structure on both sides, the crystals structure they are identical. There is no change in lattice parameter; there is no change in orientation; there is no change in volume. If there is no change in lattice parameter, there will be no change in volume and all atoms here, the top part which has slipped over the bottom. All atoms irrespective of a distance from this plane, the bottom plane on which slip has taken place. Their distance, the displacement is identical is one atomic distance for each one of this. So, this mechanism is known as slip and has mentioned, it takes place on specific planes along specific direction.

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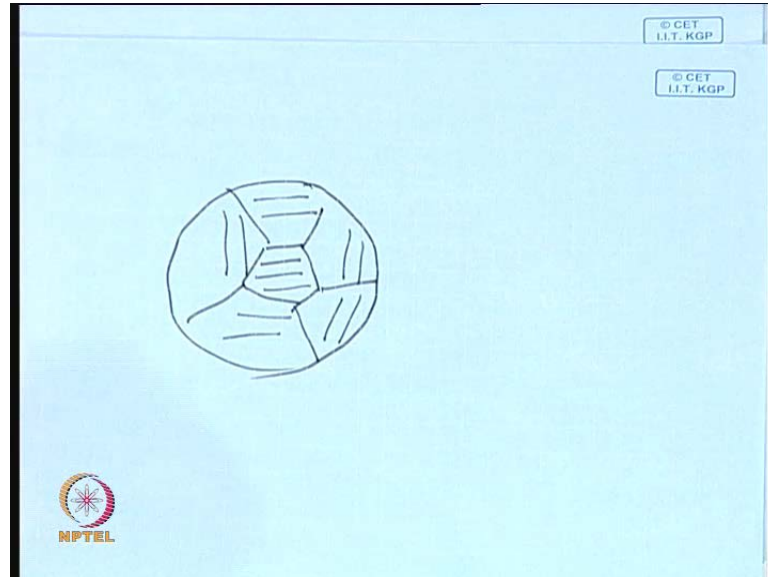


Now, is it possible to look at the slip lines in a micro structure? So, we are familiar with the micro structure of metals. It is made up of several grains. If you try and visualize, say suppose it is slip has taken place. It has deformed like this. Now point is, there is no change in orientation. Now, if you can look at the micro structure just after deformation without polishing, you will see a line here. But you polish it normally, to look at micro structure normally what you do? You will polish grind of the surface; make it smooth then, you (()) with chemical agent.

So basically, since the orientations are identical, if you grind of. So, this portion goes; there is no trace left behind. So that means something like this. If you try and look at this phase micro structure, it will look both sides of the slip plane, the structure will look identical. You would not able to distinguish. So, if you want to slip slip traces what you

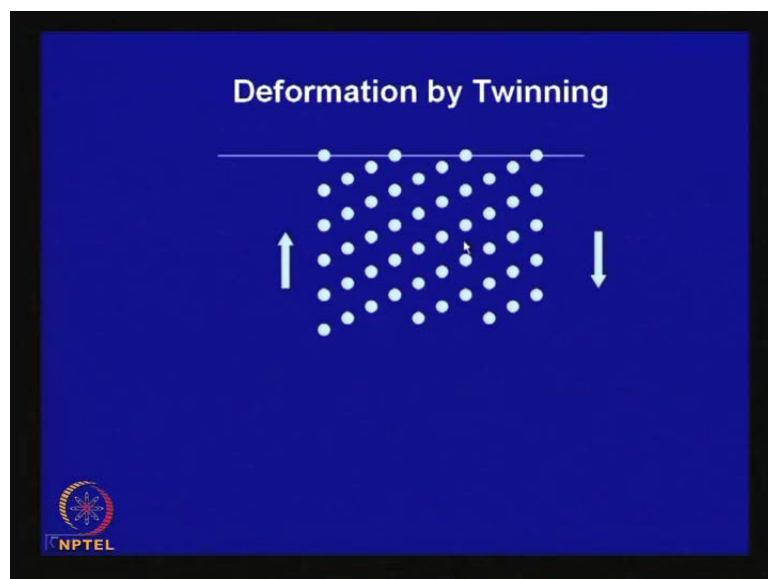
have to do? You have to polish the sample, deform it and then look on the microstructure. In that case, you may be able to see that, some lines along which permanent deformation has taken place.

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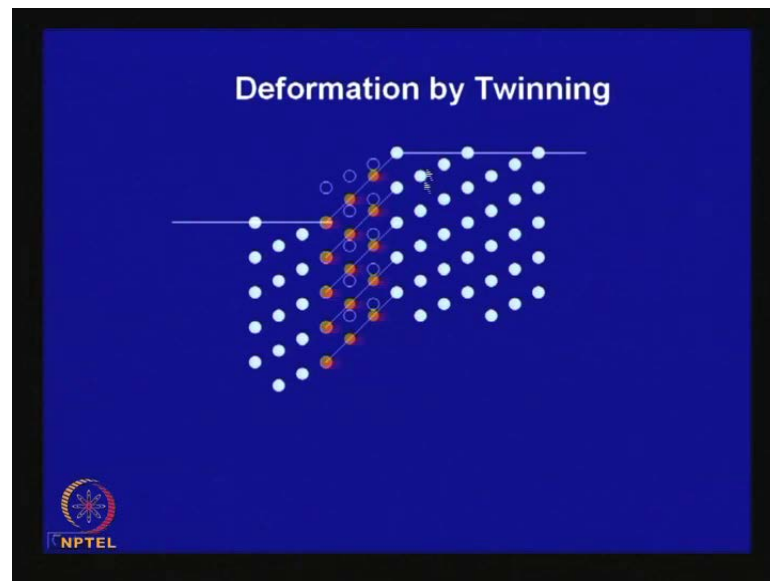
So that means what you do? You will **you** polish a sample. So, which **(())** see even if you before you subjected to deformation, you look at its micro structure something like this. And you deform it and then, if you look you will find that, some lines marks like this appear after deformation. Different planes, they are differently oriented; this orientation of these slip traces will be different. So, this is a situation; but if you polish it, they will disappear. You would not see any such lines.

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There is another mode of deformation, which is called twinning. Now, what is twinning? This is zone illustrated here. Suppose, this is a 2 D crystal; now, here also like slip, the deformation takes place because of shear stresses. A part of the crystal, what happens? It takes of an orientation, which is related to the parent matrix in a definite way. That is, the twin portion is just a mirror reflection of the parent crystal.

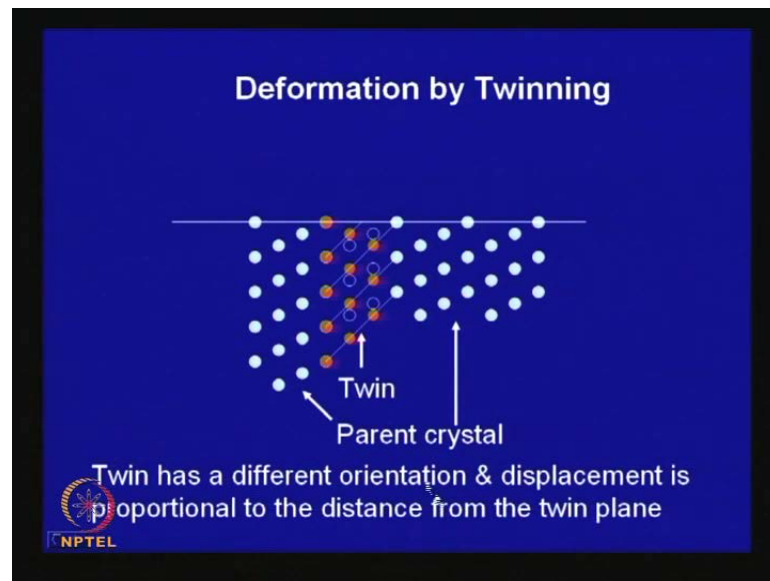
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Now, let us look at this process here. Something like this, you can see these are the ... So, these are the original positions, and on this plane or on this plane is a deformation I mean a part of this crystal takes up a different orientation. This is the original position of the atom. Now, here this atom moves here; this moves a little more distance; this moves still more distance and this distance is the same as its original lattice point. So, there is one here. So basically, this one moves you can say, one third of the lattice spacing and this direction, this atom moves two thirds and this moves one lattice distance.

Now, look at the atomic arrangement across the plane. Look at this. If you join these, this is normal and this distance and this distance; they are equal. So, this is a mirror image or reflection of this. This is a mirror exactly the similar relationship every part. So, this atom which is further down here. So, this is the distance and this distance, they are same. So, this part is actually a mirror image of this part, same also here also. That means, this point which are marked by red, they are mirror image of with respect to those, which are marked as blue light blue here.

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Now, this part of that deformed portion, now look at it; the orientations are little different. So, even if you polish grind of the top, the atomic arrangements are distinctly different. So therefore, here even if you grind of polish, you will able to see the twins here. This part is the twin; this is the parent crystal and there is a definite relationship, crystallographic relationship between this and that. So, twin has a different orientation and displacement here. The twin zone is proportional to the distance from the twin plane.

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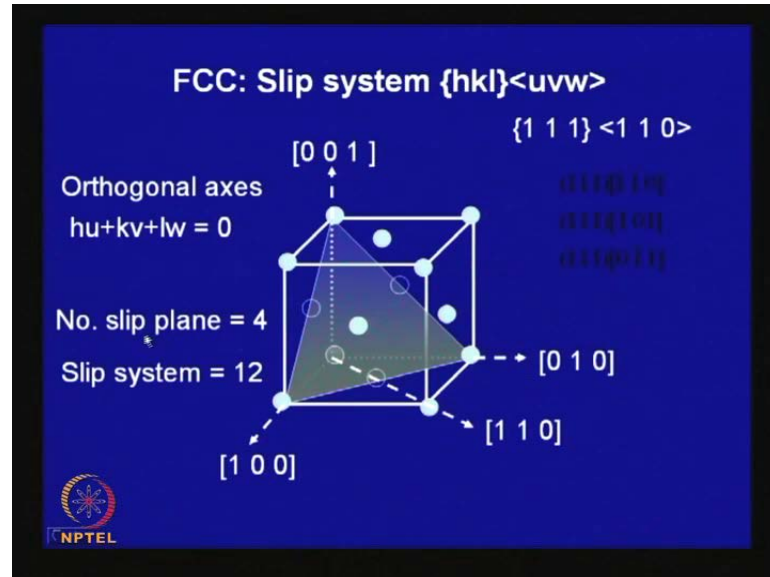
Crystal structure	Twin plane	Twin direction
BCC	(112)	[111]
HCP	(1012)	[1011]
FCC	(111)	[112]

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A twin also, like slip, it takes place on specific crystal planes along specific direction, which are listed here. For BCC, twin plane is 1 1 2; direction is 1 1 1. For HCP, the twin plane is, it is a prism plane 1 0 1 bar 2; twin direction is 1 0 1 bar 1; where as in face

entered cubic, it is the close packed plane, 1 1 1 is the twin plane and twin direction is 1 1 2.

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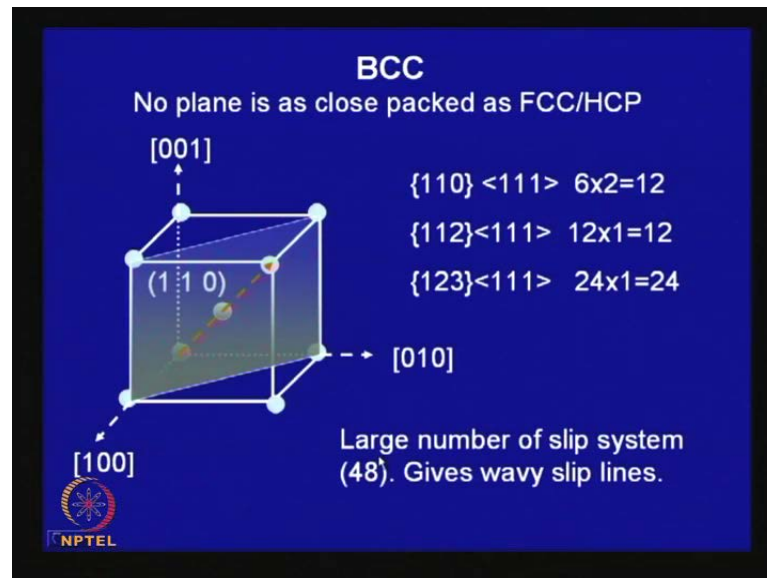
Now, let us look at slip, a little detail. So, slip as has been mentioned, can take place in crystal on specific plane along specific direction. Now, we are familiar with the representation of **representation of** crystal planes and direction; that means miller indices. So, slip plane slip system will actually be represented by a set of crystal plane say, h k l and a crystal direction u v w. This direction must like, it will be a direction line on the crystal plane. Now, cubic axis; they are orthogonal and in orthogonal crystal, there is a definite relationship as very simple relationships between the miller indices of the plane.

And the **and the** miller indices of representing the direction, which is shown here, h u k v l w. Now, the number of slip plane is here. The 1 1 1, this is octahedral plane. So, this is shown over here and this crystal, this is 1 1 1. So, 1 1 plane there will be not one; there will be several of these 1 1 1 plane. And it is possible, using this relationship it is possible to write down the indices of the crystal or the slip direction quite easily as has been mentioned here. There are four such slip planes 1 1 1 and if you try and look at this here, 1 1 1 is a plane. Now, you try and find out which 1 1 0 direction will lie on this.

So, one direction which is written over here, this is 1 1 bar 0. Now, to substitute here, you multiply this is 1 times 1 is plus 1 this is minus 1 times plus 1 minus 1 and this is 1 time 0 0. So, that means this satisfies this condition. So, also if you try this permutation and combination, you will find there are three directions, which will satisfy this. Infact,

they are ignoring the direction like $1\bar{1}0$, which is actually the same direction but the sense is opposite. So that means, each 111 plane has 3 close packed directions. So therefore, you can have you will have 4 number of slip plane and each slip plane has 3 such direction. So, the number of slip system in FCC is 12.

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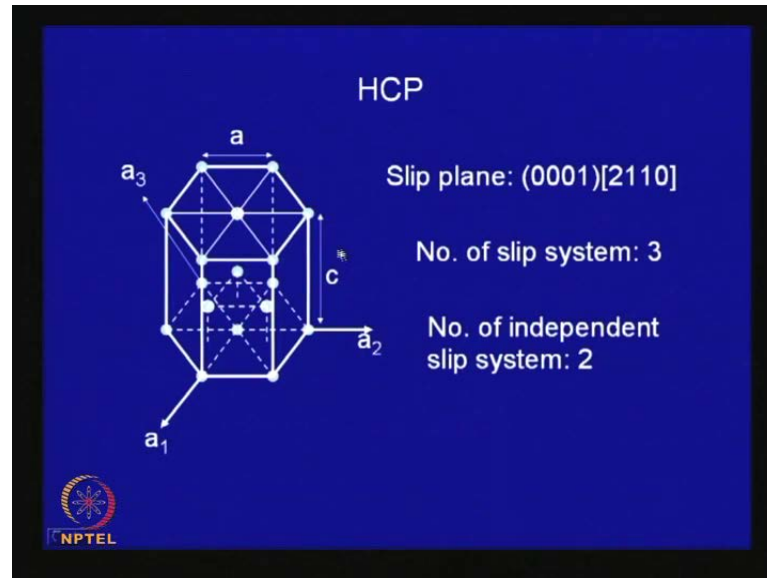
So, same thing you can do it for BCC crystal, but BCC crystal if you calculate this atomic density, here the close packed plane is 110 . So, which is shown here; this is 110 is the close packed direction and sorry close packed plane and close packed direction is this diagonal of the cube. So, in FCC, face diagonal was the close packed direction. In BCC, the cube diagonal is the close packed direction this is 111 . Now, you have to find out, what combination of this 110 plane and 111 direction can how many such combinations are there? You will be able to show easily, there are 6 110 plane.

So, there are 6 and each like in this case, there is one diagonal is this; if you join this, another diagonal is there are 2 111 directions. So, you have 12 slip system of this type but if you let do a little calculation you know; unlike FCC and HCP crystal, the atomic packing density in 110 plane and few other plane like 112 and 123 , they are not very much different. So therefore, very often **this can also** this plane can also act as slip plane. And it is also possible and leave it as an exercise to show that, on 111 plane there is only one 111 direction; there are 12 such planes.

So, you will have 12 slip system of this type and if the plane slip plane is 123 and slip direction is still 111 . You have 24 planes of 123 type and therefore, you will have 24

slip system of this type. So, who have every large number of slip systems, in case of BCC structure. So, that is why if you look at if you do at, you **you** polish the sample, develop the micro structure then, give it a deformation. And look at the slip line, you will find this slip line here is wavy; unlike FCC, the slip lines are straight. Here, the slip lines are wavy; this is primarily because of a large of slip system being available.

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Now, hexagonal crystal is shown over here. Here, the most close packed plane is the basal plane, that is represented as 0001 and close packed directions are this is a close packed direction **this is a close pack direction**. So, the number of slip system here is one plane and three slip directions. But you will actually find that, the third slip direction say, this is one direction; this is another slip direction; this is the third direction; but if you had this and this, you get this direction. That means, all these 3 system, they are not independent. Actually, there are only 2 independent slip systems.

So, this is quite important you know; hexagonal crystal close packed structure, because of its specific arrangement of atom, it has very limited number of slip system. So, that is why as I go down little later, it will be clear; it will be much clearer. That is, hexagonal crystals are difficult to deform because of non availability of slip systems. Often if you other slip system also operate, these are prismatic slip system. So that means, you join this and say this, this, this are similarly are this, this, this. So, this prismatic slip, but the direction is still same. The direction is along this close packed direction, but so that

means, you need additional slip plane; also you need additional mode of the deformation; that is twinning.


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Volume strain during plastic deformation

$$\begin{pmatrix} \epsilon_{11} & \epsilon_{12} & \epsilon_{13} \\ \epsilon_{21} & \epsilon_{22} & \epsilon_{23} \\ \epsilon_{31} & \epsilon_{32} & \epsilon_{33} \end{pmatrix} \quad \epsilon_{ij} = \epsilon_{ij}^e + \epsilon_{ij}^p$$

$$\begin{pmatrix} \epsilon_{11}^p & \epsilon_{12}^p & \epsilon_{13}^p \\ \epsilon_{21}^p & \epsilon_{22}^p & \epsilon_{23}^p \\ \epsilon_{31}^p & \epsilon_{32}^p & \epsilon_{33}^p \end{pmatrix} \quad \epsilon_{11}^p + \epsilon_{22}^p + \epsilon_{33}^p = 0$$

Five independent slip systems are required for any arbitrary deformation / shape change



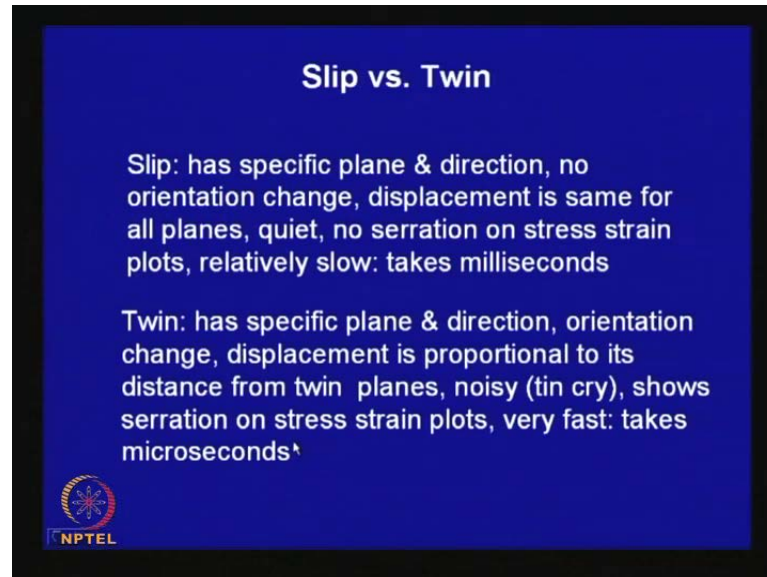
Now a quick look at the state of stress, because we have just look that that is stresses and strains. They are represented much more convenient to represent in the form of this matrix, like epsilon 1 1 1 2 1 3. So, this represents the state of strain at a particular point. Now, this strain can have two components; it is elastic, which is recoverable and plastic. Now, when we are dealing with large plastic deformation, we are primarily concerned with this matrix; that is epsilon i j p, plastic. Now, if you subtract that elastic component from here, you get the plastics strain tensor or strain matrix. And here if you add this diagonal element, the sum of this diagonal element gives a measure of volumes strain.

We have repeatedly as has been mentioned that, during plastic deformation, lattice parameter does not change; crystal structure remain same. There is no lattice strain. So, basically so that means, there is no volume change; so that means, sum of this diagonal element is 0. So that means, in the strain matrix so therefore, you one of this get fixed; if you know two, you know the third one. So that means what you have? You really have 5 components of strains. So, 5 independent and for each of this, you need one slip system.

So, you need for any arbitrary deformation, if you want take a crystal, give any arbitrary deformation. You need a large, atleast 5 independent slip system. We have just in that, incase of a hexagonal close packed structure, you do not have 5 independent slip systems. If you tick consider only the baser plane, you will have 2. So, that is why more

other modes of deformation become important. Some other ideas, some other slip lines become operative or a twin deformation is a must for to deform a hexagonal close packed structure.


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Slip vs. Twin

Slip: has specific plane & direction, no orientation change, displacement is same for all planes, quiet, no serration on stress strain plots, relatively slow: takes milliseconds

Twin: has specific plane & direction, orientation change, displacement is proportional to its distance from twin planes, noisy (tin cry), shows serration on stress strain plots, very fast: takes microseconds^



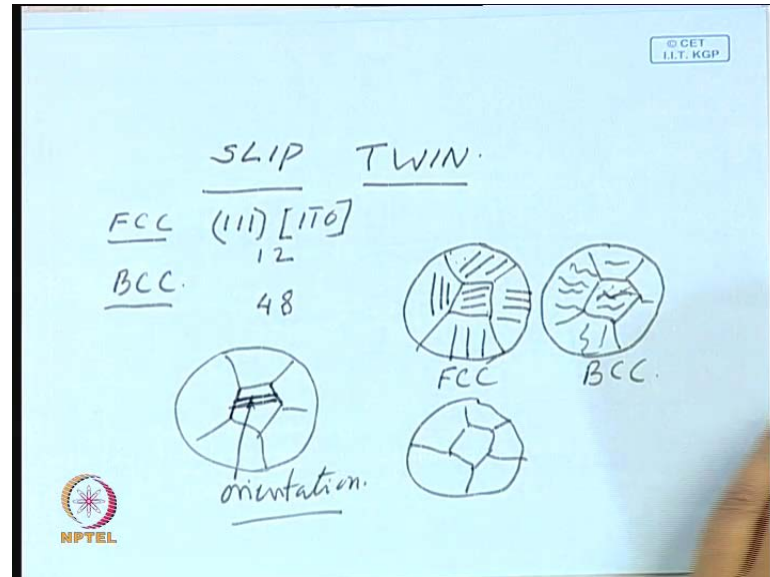
Now, a quick look at little similarity and the difference between these two mode of deformation, slip and twin. Slip is a relatively gradual process and it takes place on specific planes and directions. **it takes place specific planes and direction** Twin also takes place on specific plane along specific direction. Here, there is no change in slip; there is no change in orientation. Orientation of the crystal on either side of the slip plane is exactly same, whereas in case of twin, the orientation on the either side they are different; although they are related, one is the mirror image of the other.

Then, displacement in case of a twin is proportional to the distance of a particular plane from the twin plane, whereas in slip, the displacement is same for all planes. Now, slip is quiet process whereas, twinning is a noisy process and a very common phenomena, we know is tin cry, say when the tin is deformed; tin is body centered, tetragonal structure and when it deforms, you know twins and it generates sound. So, it is noisy and it also...

Secondly, **this process** the process of slip is very slow; it takes times it of the order of milliseconds for the deformation to take place and this process is very smooth. This stress strain diagram if you look at, there is no serration on the stress strain diagram, if the deformation is due to slip. Whereas in case of twin, the process is very fast; it takes place in microseconds and the stress strain diagram shows serrations something like that

(()) point phenomenon kind of that. So, these are in shots, this is the basic difference between the two.

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So, today whatever we have looked at, some of primary some of this common modes of plastic deformation. We, two common mode of plastic deformation as we have seen are slip and twin. Slip, it takes place on specific crystal along specific directions and each crystal, like FCC it takes place along plane on plane 1 1 1 along direction 1 1 bar 0. Similarly, in twin also, it takes place on specific plane along specific direction. BCC also, it has similar type of slip system, but that number is very large. Here it is 12; here it is 48 and this has a marked influence on the nature of the microstructure.

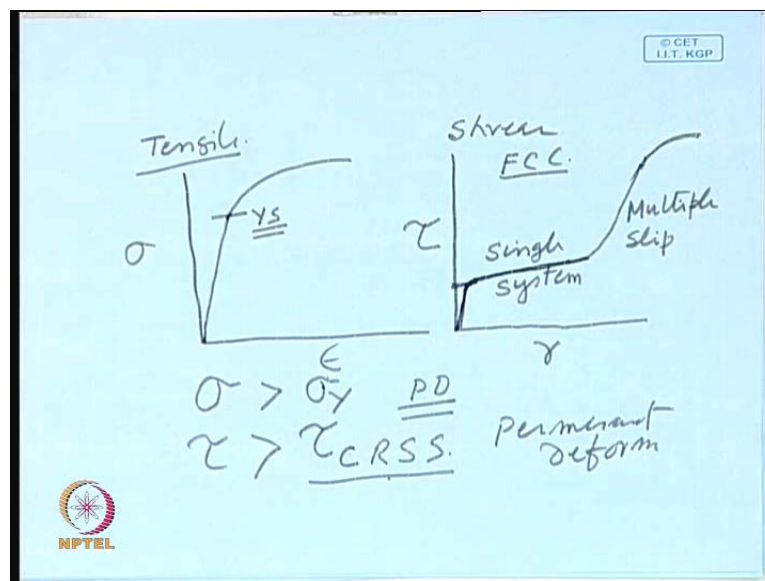
So basically, you see in a **in a** face centered cubic structure, we have seen that slip lines in a polished sample. If you deform and look on the microscope, you will find such slip stresses depending on the crystal orientation. They may be differently oriented, but they are straight. Whereas, same thing if it is a BCC, you will find (no audio from 48:05 to 48:13) say like this. So, where we **so where we** means, this is one plane; this is another plane, another direction; this is another plane; this is another. So, it actually crosses over. So, there will be such a way, we slip lines in case of this is FCC; this is bcc. Another important thing, we learn that, slip on either side the orientation is same.

If you polish it, the lines will disappear. It will look like this; the lines will not be there whereas, in case of twin there is a change in orientation, **whereas in case of a twin there is change in orientation** say something like this. Twin will have two lines, I mean two

planes; this is one plane; this is another plane. So, this is the twin. Infact, the twin region is quite small with respect to the whole grain. Another thing is, next strain here is much higher than the strain that takes place with a single that slip. Here, even if you polish and this will remain, because this has different orientation. We also looked at the need for having larger number of slip system to give any arbitrary deformation.

Because we have seen that, you need around 5 independent slip systems to give any arbitrary deformation. So, FCC and BCC, they have plenty of slip system. So therefore, they are very easy to deform; they can take any shape; they have good ductility in relation to that hexagonal close packed structures. They are difficult to deform an actually. So, they are not show amenable to any deformation process and you need extra mode of deformation that is twinning. In the next class, we will look at how this does this to deform the crystal? What is the level of stress that you need? And we have seen in a polycrystalline material, we have looked at the stress strain diagram.

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We have seen that, if you draw this stress and strain, you have this elastic deformation then, you have that plastic deformation. So, there is a stress called yield stress or proof stress. We say that, if you exceed this, then there is a permanent deformation. So, similar thing is there in case of single crystal as well. In fact, the single crystal like, if you do like this, what will be the nature of stress strain diagram? Now, here this normally a polycrystalline material these are, you have a tensile stress strain diagram. So, here the diagram that, we will draw is shear stress versus shear strain. So, shear stress τ , shear strain.

So, here also you will have semi (σ_y) , you have something like an elastic part and then you will have a region like this; then you will have a region like this and then like this. So that means, a typical stress strain diagram of if let us see, if face centered cubic crystal will have these distinct stages, now this period is called... You need the stress exceed this point and this stress is called critical resolve shear stress. So, when stress exceeds critical resolve shear stress, you have permanent deformation. **permanent deformation**. That means, with respect to polycrystalline material, when σ is greater than σ_y , you have permanent deformation plastic deformation.

So, here so this is you can see has a similarity, has a relationship between σ_y and critical resolve shear stress. Now, you may wonder so, why this slope change is? Now here the slip takes place, this is called stage 1. You can say that, here hardening strain hardening is very little, slip takes place on a single system. Here, this is case of a linear hardening region; here you have a multiple slip and there is again some amount of softening, which says some additional slip planes become operating. So, we will look at this in little more detail and this is where, you need to capitulate this stereographic projection. Because, this kind of this stress verses strain plot will be a strong function of crystal orientation.

We will see, we will look at it in detail the relationship, stress strain relationship little more detail. We will also look at that during this deformation, does the orientation of crystal when you pull a single crystal in a stress strain straining device, does the orientation remain same or does it change. And what is the relationship and what crystal say depending on its orientation whether the slip will takes place on a single slip system or on multiple slip system? And in the end, we will also try and find out, what is the magnitude of if the crystal is the ideal, ideal crystal that means there is no defect, then what is the level of stress. And while, we will also have a look, why in real crystal you do not have that level of strength? **Thank you very much.**