

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

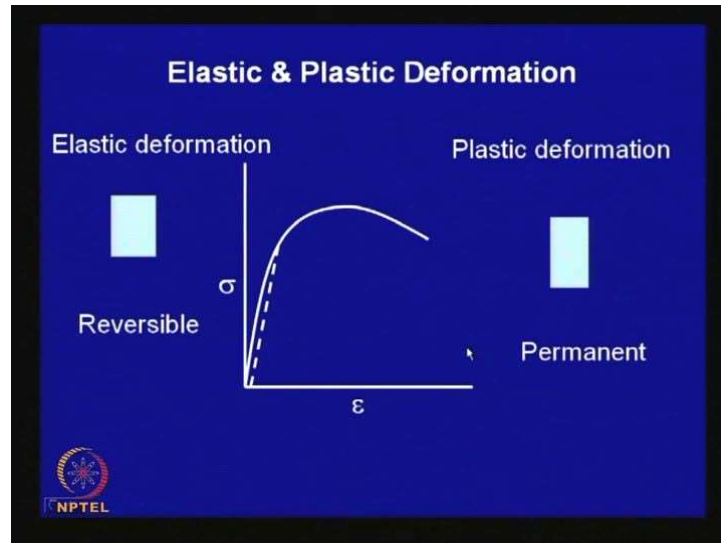
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Good morning. Today, we begin a new chapter. This is on plastic deformation of pure metal. Last class, we looked at evolution of microstructure of pure metal. The metals that we use, they are made up of several crystals. They are oriented at random 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 metals. And we will try to 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 an 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.

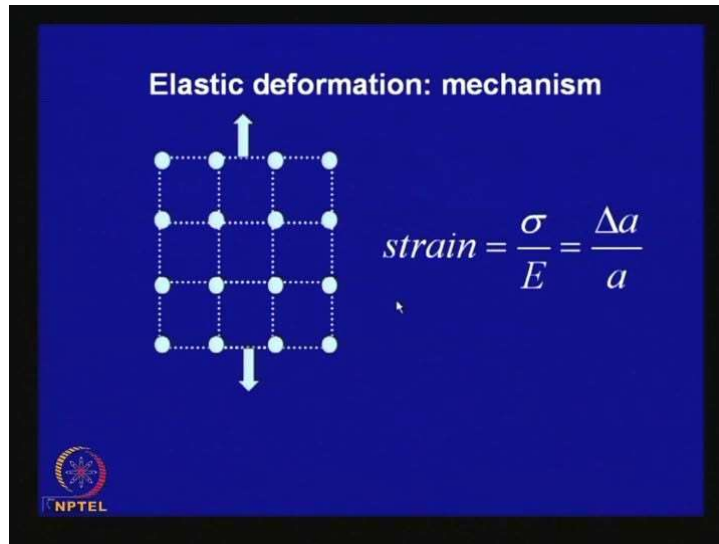
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Now, to recapitulate the difference between elastic and plastic deformation: you are already familiar with this type of stress strain plot, which we normally perform to find out strength of material. We looked at it in detail and the type of information 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, 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 stress, there is 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's 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 Hooke's law under uniaxial tension. So, in terms of crystal structure, you have, I have just shown a 2D crystal structure. 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, even though stress is uniaxial, you have strain in this direction as well as perpendicular to the plane. So, you will have three components of strain. If you have a system, if you can measure, we have seen how x-ray diffraction can be used to measure the lattice spacing (a). If lattice spacing is measured, then the change in lattice parameter (Δa) can be converted into strain. That is change in lattice parameter $\left(\frac{\Delta a}{a}\right)$: this is strain.

So, that means, x-ray 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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three normal components; that means all principal stresses: these normal components, these diagonal components are also known as principal stress. If these 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 $-p, -p, -p$ that means, you are trying to compress a particular solid from all directions. Now, this kind of stress, state of stress is hydrostatic state of stress. It cannot cause any plastic deformation because under this condition, if you convert, if you try that reference axis, try to find out what kind of shear stress you will have; you will find all the shear stress components 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 in a simple tensile test, you subject a material to uniaxial stress; but for deformation often you will have multiple stresses applied along different directions. And you should be conversant; one should be conversant with the state of stress, which can result in plastic deformation. Now, using this kind of representation, as I said, that σ_{ij} and ϵ_{kl} : 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 an inverse of this: a strain is related to stress by this. So, this is the strain tensor. This is the stress tensor and you also need another tensor, which will convert one into the other. This matrix S_{ijkl} : this is called compliance matrix (tensor). This is called C_{ijkl} it's called stiffness matrix. This kind of a representation also signifies that, this is not just one term; see i, j, k, l (subscripts); they 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 as it indicates. Now, as you can see, if these numbers; you know; each you change from 1 to 3. If you start writing this full expression, it will be a very long equation. So, one way, a convenient way of reducing it is to see that, how many components of state of stresses are important or present.

We have just seen that; this stress matrix is symmetric. So that means, these off diagonal elements, they are equal. So, actually you will have the 6 components of stress at a point, $\sigma_1 \sigma_2 \sigma_3$. And this is a shear stress component, which is represented as I said, that is 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, this kind, 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

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{bmatrix}$$

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




So, this component; the strain component, this should be $\frac{\varepsilon_6}{2}$; it's represented like this. In that case, you have 6 stresses; 6 components of stresses; there will be 6 components 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's as I said that's, σ_{ij} is same as σ_{ji} . So, these indices, they are interchangeable. With this, it is very easy to show that, in this kind of stiffness matrix; this component C_{12} will be same as C_{21} . So, what it means is: this 6 by 6 matrix is actually a symmetric matrix.

So, how many elastic constants do you have here? So, you can count this. So, first row is 6; second row 5; this row 4; so, basically, it is a sum of $1 + 2 + 3 + 4 + 5 + 6$. So, it will be 21. 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

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} \\ S_{21} & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} \\ S_{31} & S_{32} & S_{33} & S_{34} & S_{35} & S_{36} \\ S_{41} & S_{42} & S_{43} & S_{44} & S_{45} & S_{46} \\ S_{51} & S_{52} & S_{53} & S_{54} & S_{55} & S_{56} \\ S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & S_{66} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix}$$


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 constants to describe the elastic state of stress in a material. This number of elastic constants, that you need for material which does not have any symmetry element, that is triclinic crystal, you need 21 elastic constants. But we are fortunate, we often handle, the number or types of metals that we use; they are mostly cubic and cubic crystals have high symmetry.

It is possible to show using this tensor representation that, if you impose these symmetry conditions; the number of these elastic constants; that you need; independent elastic constants; that you need to describe the state of stress is reduced drastically. So, for example, what does it mean? A cubic crystal has 4-fold symmetry, three 4-fold symmetry; that means, if you try to rotate it about one crystal axis, say, let us say, crystal axis is usually represented as a , b , c as has been mentioned. So, about ' a ' if you rotate it by 90° , it comes to occupy exactly similar position.

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Cubic symmetry & isotropy


$$S_{11} = \frac{C_{11} + C_{12}}{(C_{11} - C_{12})(C_{11} + 2C_{12})} \quad C_{44} = \frac{1}{2}(C_{11} - C_{12})$$

$$S_{44} = \frac{1}{C_{44}} \quad S_{44} = 2(S_{11} - S_{12})$$

$$S_{11} = \frac{-C_{12}}{(C_{11} - C_{12})(C_{11} + 2C_{12})} \quad E = \frac{1}{S_{11}} \quad \nu = -\frac{S_{12}}{S_{11}}$$

$$\mu = \frac{1}{S_{44}} = C_{44} = \frac{E}{2(1 + \nu)}$$

Single crystal W is isotropic. Polycrystalline solids with random orientation are isotropic wrt elastic constants.

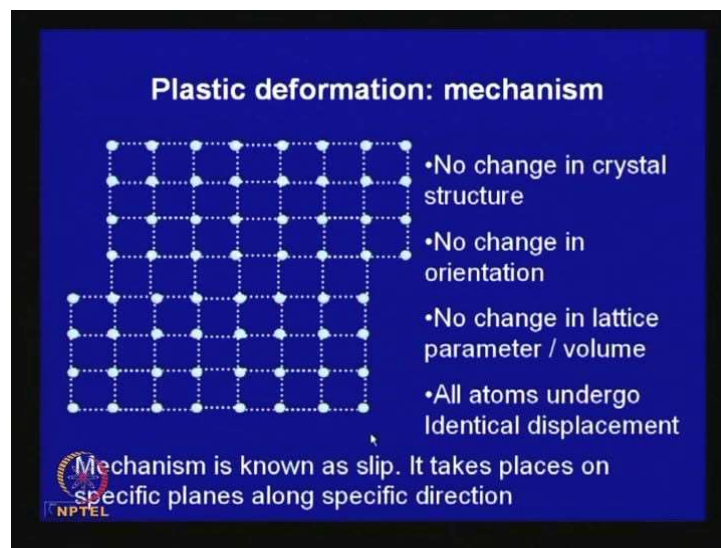


So, in that case, also you can convert, this matrix to that, and each of these elements; they will be equal. By imposing this condition; it is possible to show that, in case of a cubic crystal you need only three elastic constants S_{11} S_{44} and this is I think, S_{12} . There is a mistake here; this 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, you are more familiar with this, this is called shear modulus.

Basically, if you look at these elastic constants of different crystals, 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 , in that direction, you measure modulus; it should be same. So, if you impose this condition; you will find, there is a further relationship between these three elastic constants; that means S_{11} S_{12} and S_{44} which is listed here. So that means, similar relationship exists between the stiffness coefficients.

We are more familiar with Young's modulus. And how is this Young's modulus (E) is related to these compliances with respect to a single crystal? Like E is $1 / S_{11}$. Poison ratio; this is the ratio of $- S_{12} / S_{11}$ and shear modulus? 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 Poison ratio. If one looks at the list from hand book, that elastic constants of different crystals which have been measured. If you look at that, you will find in case of tungsten; although it is crystalline BCC; tungsten, has BCC (structure) its elastic constants are such that, the material 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. (Refer Slide Time: 24:55)

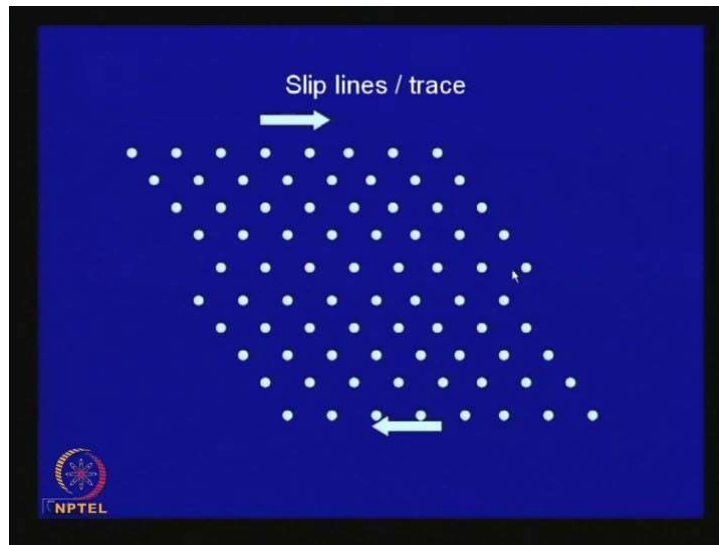


You have a 2 D crystal, which is shown here. You can also visualize, as if, these are different layers of atoms; it is like a pack of cards, say if you put a pack of card try to slide. So, that is the case of a state of shear stress. Now, what happens if you apply shear stress? If you apply shear stress, 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 in which in the plane, there will be a specific direction along which this displacement takes place; that direction is call slip direction.

And here, after this deformation, if you remove the stress since it has 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 crystal structures: 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 its distance from this plane, the bottom plane on which slip has taken place. Their displacement is identical. It's one atomic distance for each one of these. So, this mechanism is known as slip. As has been mentioned, it takes place on specific planes along specific direction.

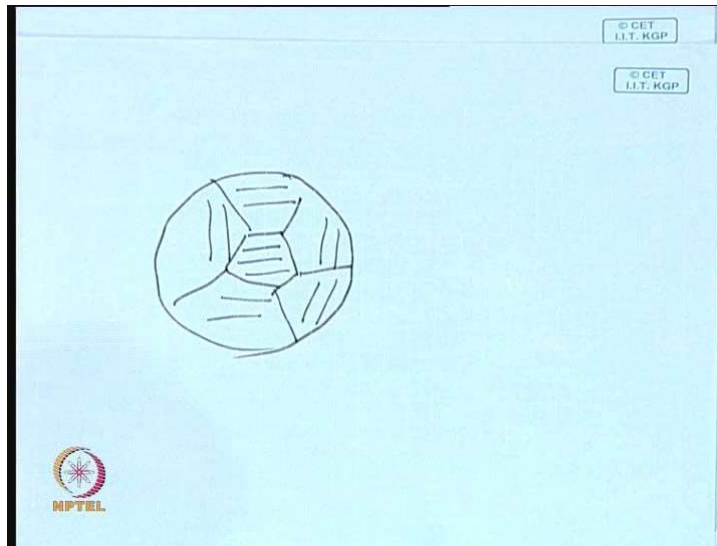
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Now, is it possible to look at the slip lines in a micro structure? See, we are familiar with the microstructure of metals. It is made up of several grains. If you try to visualize, say, suppose slip has taken place. It has deformed like this. Now 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 to look at microstructure, normally what you do; you will polish / grind off the surface; make it smooth then, you etch with chemical agent.

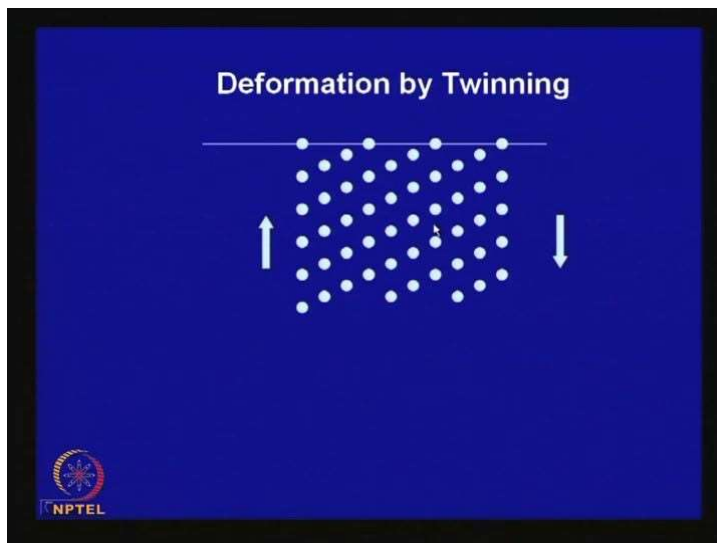
So basically, since the orientations are identical, if you grind off; so, this portion goes; there is no trace left behind. So that means something like this. If you try and look at this face microstructure, it will look both sides of the slip plane, the structure will look identical. You won't be able to distinguish. So, if you want to see slip traces what you have to do? You have to polish the sample, deform it and then look at the microstructure. In that case, you may able to see that, some lines along which permanent deformation has taken place.

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So that means what you do? You polish a sample which you see even before you subjected to deformation, you look at its microstructure; 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; the orientation of these slip traces will be different. So, this is the situation; but if you polish it, they will disappear. You won't see any such lines.

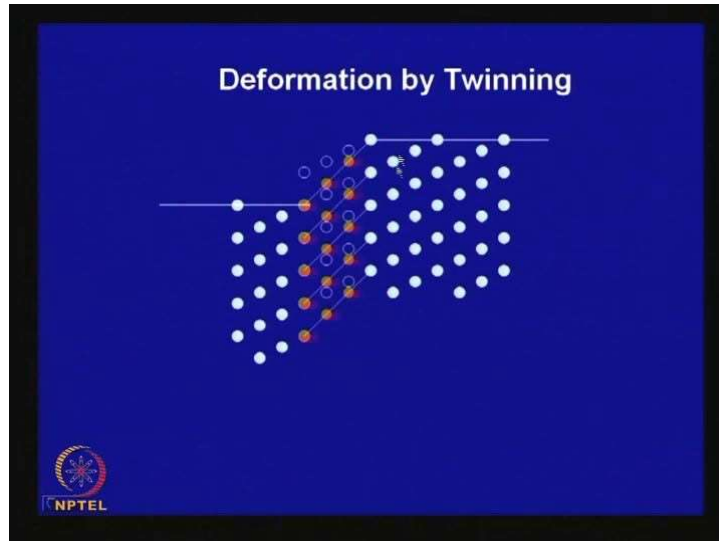
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There is another mode of deformation, which is called twinning. Now, what is twinning? This is shown; illustrated here. Suppose, this is a 2 D crystal; now, here also like slip, the deformation takes place because of shear stresses. A part of the crystal, what happens? It

takes of an orientation, which is related to the parent matrix in a definite way. That is, the twinned portion is just a mirror reflection of the parent crystal.

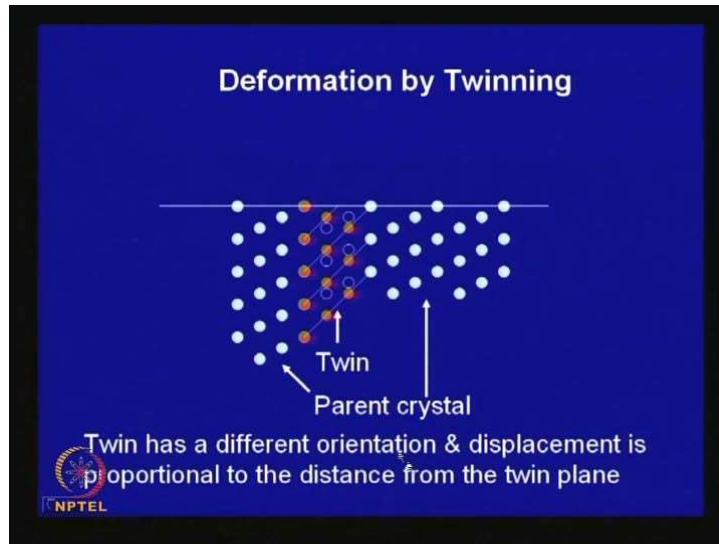
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Now, let us look at this process here. Something like this, you can see, these are say, these are the original positions and on this plane, by deformation, I mean, a part of this crystal takes up a different orientation. This is the original position 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 original lattice point. So, there is one here. So basically, this one moves, you can say, one third of the lattice spacing in this direction, this atom moves two third 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 here also. That means, these points which are marked by red, they are mirror image 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 or polish, you will be 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 in the twinned zone is proportional to the distance from the twin plane. (Refer Slide Time: 32:48)

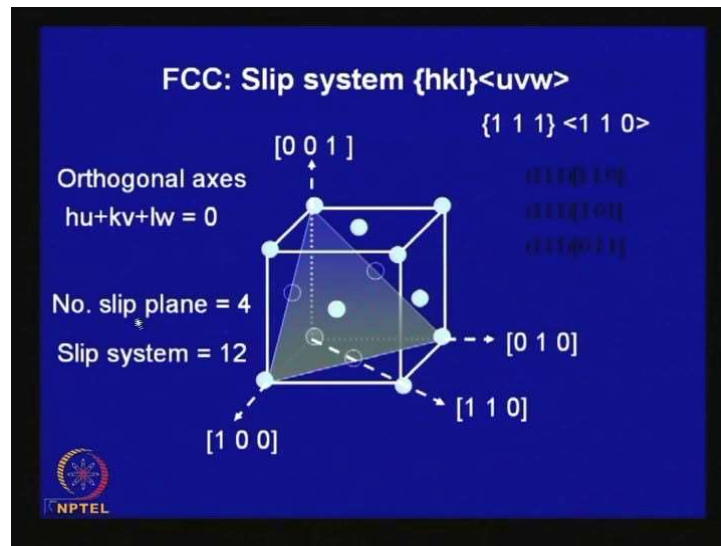
Twin planes & directions

Crystal structure	Twin plane	Twin direction
BCC	$(11\bar{2})$	$[111]$
HCP	$(10\bar{1}2)$	$[10\bar{1}1]$
FCC	(111)	$[\bar{1}12]$

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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 $(11\bar{2})$; direction is $[111]$. For HCP, the twin plane is, it is a prism plane $(10\bar{1}2)$; twin direction is $[10\bar{1}1]$; whereas in face centered cubic, it is the close packed plane, (111) is the twin plane and twin direction is $[\bar{1}12]$.

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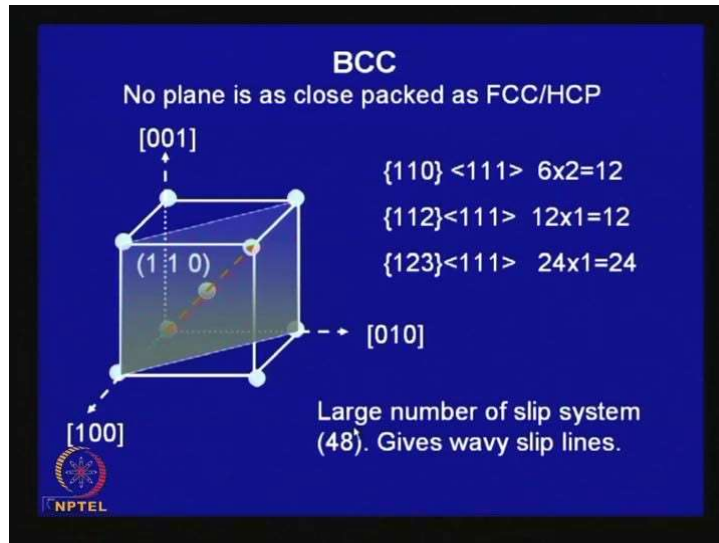


Now, let us look at slip, in little detail. So, slip as has been mentioned, can take place in crystals on specific plane along specific direction. Now, we are familiar with the representation of crystal planes and direction; that means Miller indices. So, slip planes, slip system will actually be represented by a set of crystal plane say, $\{h\ k\ l\}$ along a crystal direction $\langle u\ v\ w \rangle$. This direction must lie, it's is a direction lying on the crystal plane. Now, cubic axes; they are orthogonal and in orthogonal crystal, there is a definite relationship, a very simple relationship, between the Miller indices of the plane, and the Miller indices representing the direction, which is shown here, $(hu + kv + lw) = 0$. Now, the number of slip planes is? Here the (111) , this is octahedral plane. So, this is shown over here in this crystal, this is (111) . So, (111) plane there will be not one; there will be several of these (111) planes. And it is possible, using this relationship, it is possible to write down the indices of the slip directions quite easily. As has been mentioned here, there are four such slip planes, (111) and if you try and look at this here, (111) is a plane. Now, you try and find out which $[110]$ directions will lie on this.

So, one direction which is written over here, this is $[\bar{1}10]$. Now, substitute here, you multiply & add: $(1 \times 1 + 1 \times (-1) + 1 \times 0) = 0$. So, that means this satisfies this condition. Also, if you try this permutation and combination, you will find there are three directions, which will satisfy this. In fact, we are ignoring the direction like $[\bar{1}10]$, 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 4 number of slip planes and each slip plane has 3 such directions. So, the number of slip system in FCC is $3 \times 4 = 12$.

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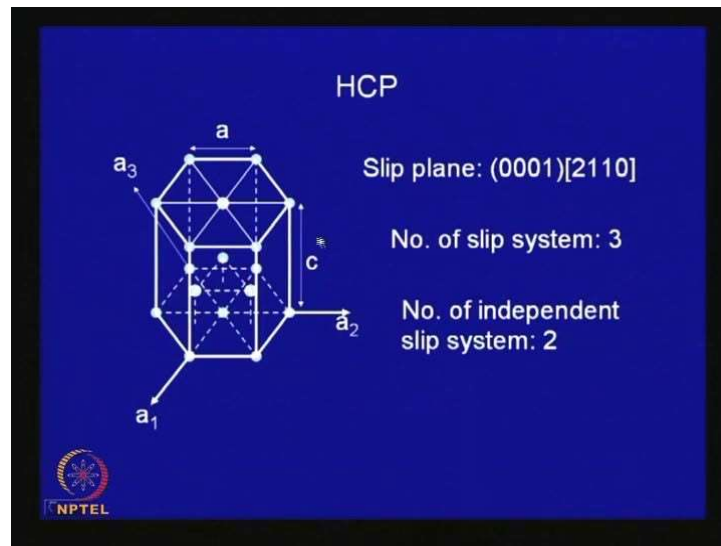


So, same thing you can do it for BCC crystal, but BCC crystal if you calculate this atomic density, here the close packed plane is (110), which is shown here. This is (110), it's the close packed direction and I'm sorry, it's close packed plane and close packed direction is this diagonal of the cube. So, in FCC, the 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} planes and <111> directions can; how many such combinations are there? You will be able to show easily, there are 6 {110} planes.

So, there are 6 planes. In each like in this case, there is one diagonal is this; if you join this, another diagonal is this. There are two [111] directions. So, you have 12 slip systems of this type. But if you do a little calculation, you know; unlike FCC and HCP crystal, the atomic packing density in (110) plane and a few other planes like (112) and (123), they are not very much different. So therefore, very often these planes can also act as slip plane. And it is also possible and I leave it as an exercise to show that, on one (112) 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 slip plane is (123) and slip direction is still [111]. You have 24 planes of (123) type and therefore, you will have 24 slip systems of this type. So, who have a very large number of slip systems, in case of BCC structure. So, that is why if you look at; if you do

polish a sample, develop the microstructure, then, give it a deformation and look at the slip lines, 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 systems being available. (Refer Slide Time: 39:41)



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 these. This is a close packed 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 add this and this, you get this direction. That means, all these three systems, they are not independent. Actually, there are only 2 independent slip systems.

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

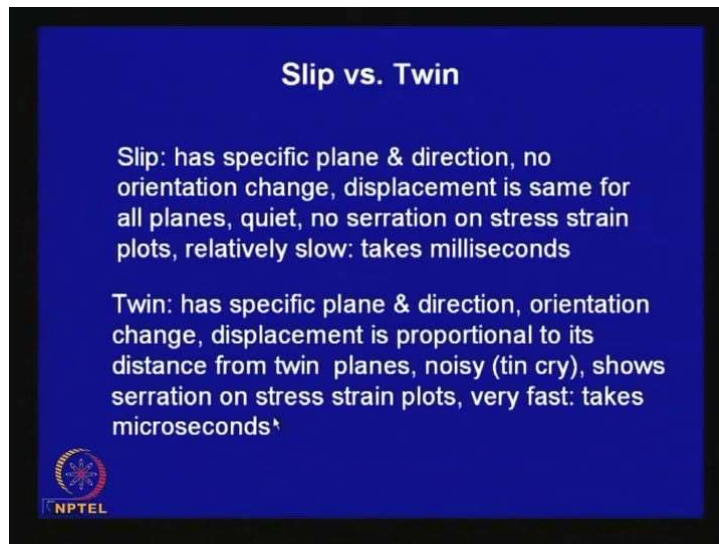


Now a quick look at the state of stress, because we have just looked at stresses and strains. They are represented much more conveniently in the form of this matrix, like ϵ_{11} , ϵ_{12} , ϵ_{13} . So, this represents the state of strain at a particular point. Now, this strain can have two components; 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 ϵ_{ij}^p : plastic strain. Now, if you subtract that elastic component from here, you get the plastic strain tensor or strain matrix. And here if you add these diagonal elements, the sum of this diagonal element gives a measure of volume strain.

We have repeatedly said, as has been mentioned that, during plastic deformation, lattice parameter does not change; crystal structure remains same. There is no lattice strain. So, basically that means, there is no volume change; so that means, sum of this diagonal element is 0. So that means, in the strain matrix, therefore, one of these gets fixed; if you know two, you know the third one. So that means what you have? You really have 5 components of strains. So, five-independent strains; for each of these, 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, at least 5 independent slip systems. We have just seen that, in case of a hexagonal closed packed structure, you don't have 5 independent slip systems. If you consider only the basal plane, you will have 2. So, that is why more; other modes of deformation become important. Either, some other slip planes become operative or a twin deformation is a must to deform a hexagonal closed packed structure.

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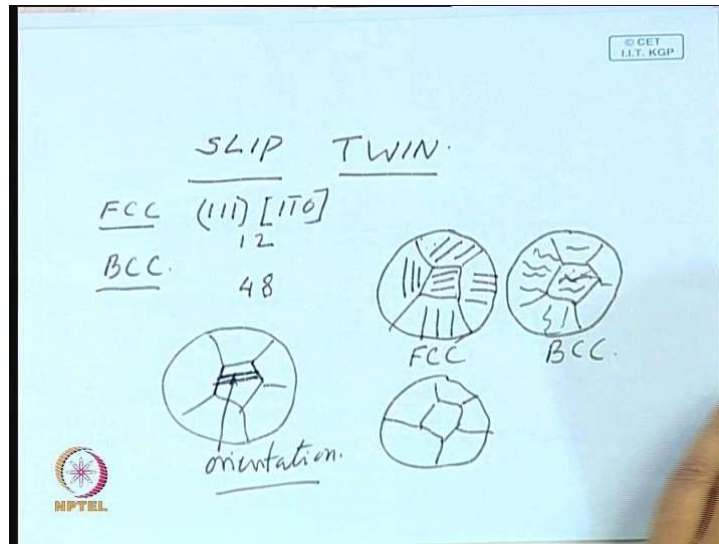


Now, a quick look at the similarity and the difference between these two modes of deformation, slip and twin. Slip is a relatively gradual process and it takes place on specific planes and directions. Twin also takes place on specific plane along specific direction. Here, there is no change; in slip 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 a 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 a quiet process whereas, twinning is a noisy process and a very common phenomenon, we know, is tin cry, say when tin is deformed; tin has body centered tetragonal structure and when it deforms, you know, it twins and it generates sound. So, it is noisy.

Secondly, the process of slip is very slow; it takes time. It is 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 of yield point phenomenon; kind of thing. So, these are in short, the basic difference between the two.

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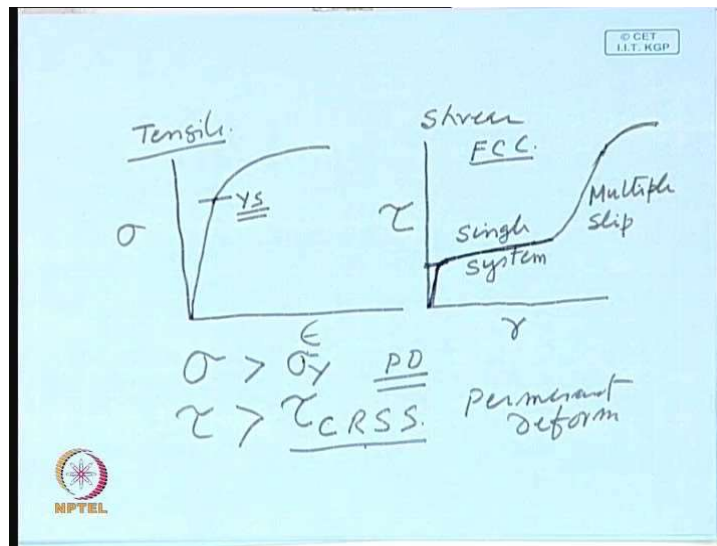
So, today whatever we have looked at to sum up; primarily some of the common modes of plastic deformation. Two common modes of plastic deformation as we have seen are slip and twin. Slip, it takes place on specific crystals along specific directions in each crystal, like FCC: it takes place along plane on plane (111) along direction $[1\bar{1}0]$. 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 (FCC) 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 face centered cubic structure, we have seen that slip lines in a polished sample; if you deform and look under the microscope, you will find such slip traces 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, wavy; 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 wavy slip lines in case of this. This is FCC; this is bcc. Another important thing, we learned that, in 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, 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. In fact, the twinned region is quite small with respect to the whole grain. Another thing is, net strain here is much higher than the strain that takes place with a single slip. Here, even if you polish, this will remain, because this has different orientation. We also

looked at the need for having larger number of slip systems 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 closed packed structures; they are difficult to deform. Actually, they are not so amenable to any deformation process and you need extra mode of deformation that is twinning. In the next class, we will look at how 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. (Refer Slide Time: 51:10)



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 normally in a polycrystalline material, you have a tensile stress strain diagram. So, here (single crystal) the diagram that, we will draw is a shear stress versus shear strain. So, shear stress τ , shear strain (γ):

So, here also you will have similar plot, 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 a face centered cubic crystal will have these distinct stages, now this period is called easy glide: you need the stress to exceed this point

and this stress is called critical resolved shear stress. So, when stress exceeds critical resolved shear stress, you have permanent deformation. That means, with respect to polycrystalline material, when $\sigma > \sigma_y$, you have permanent deformation; plastic deformation.

So, here this you can say has a similarity, has a relationship between σ_y and critical resolved shear stress. Now, you may wonder so, why this slope changes? 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 a case of a linear hardening region; here you have multiple slips and there is again some amount of softening, which says some additional slip planes become operative. So, we will look at this in little more detail and this is where, you need to recapitulate the stereographic projection. Because, this kind of a stress versus 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 in 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 straining device, does the orientation remain same or does it change. And what is the relationship? In what crystal, say, depending on its orientation whether the slip will take place on a single slip system or on multiple slip system? And in the end, we will also try to find out, what is the magnitude of; if the crystal is ideal, ideal crystal that means there is no defect, then what is the level of stress. And why? We will also have a cursory look, why in real crystal you do not have that level of strength. Thank you very much.