Basics of Materials Engineering
Prof. Ratna Kumar Annabattula
Department of Mechanical Engineering
Indian Institute of Technology, Madras

Lecture – 21
Defects in Crystalline Material – 5
(Geometry & Slip, Stress Field Around a Dislocation and Deformation Twinning)

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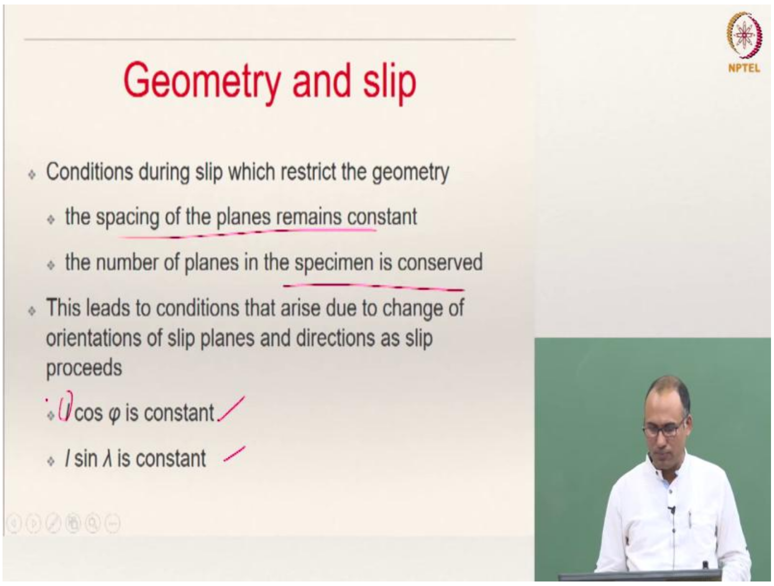

So, when dislocation motion happens in a single crystal, then slip occurs, but while the slip is happening, it has to follow certain geometric conditions. The spacing of the planes remains constant and the number of planes in the specimen is conserved.

So, that leads to these two conditions: $l\cos\phi$ and $l\sin\lambda$ being constant , where l is the length of the crystal.

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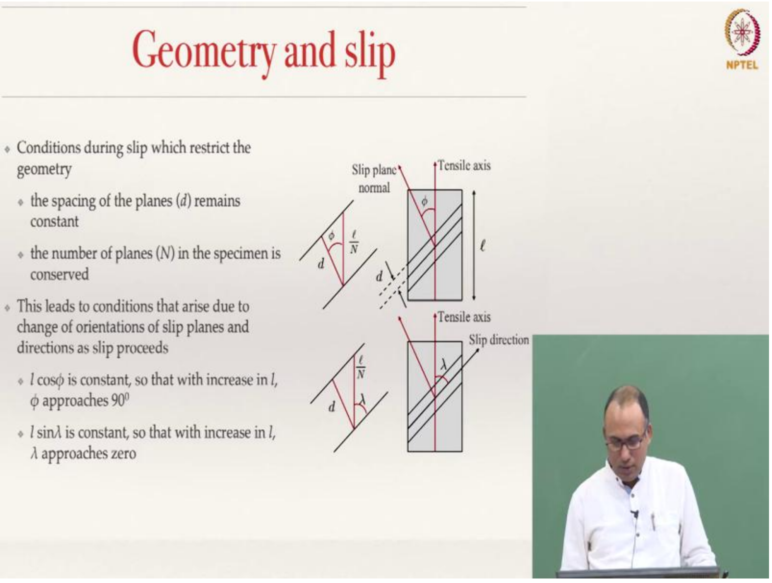

In the picture shown, l is your length and d is your inter planar spacing. The tensile axis is shown, and λ is the angle between the loading direction and the slip direction.

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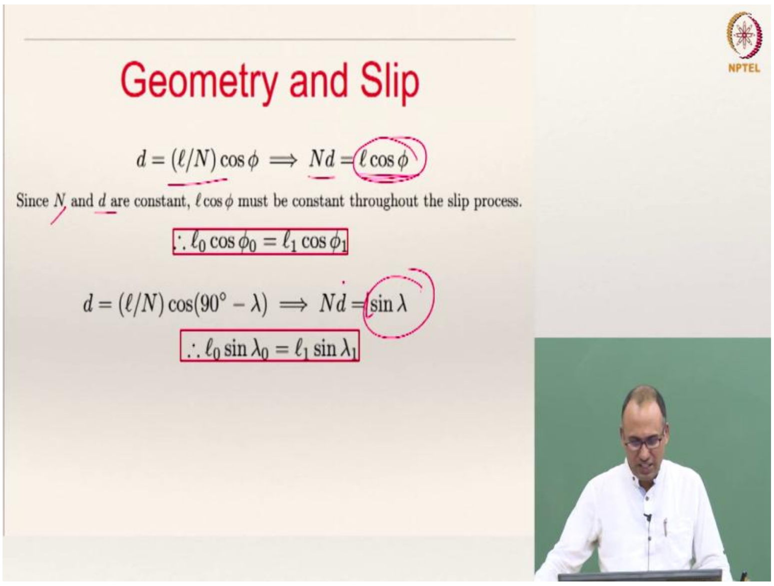

It can be shown that .

$$d = \frac{l}{N}\cos\phi => Nd = l\ \cos\phi$$

Therefore, $l\ \cos\phi$ must be constant throughout the slip. Also,

$$d = \frac{l}{N}\cos(90-\lambda) => Nd = l\ \sin\lambda$$

Therefore, $l \sin\lambda$ must be constant

This is the geometric requirement while we are doing dislocation when the plastic deformation is taking place in these single crystal materials.

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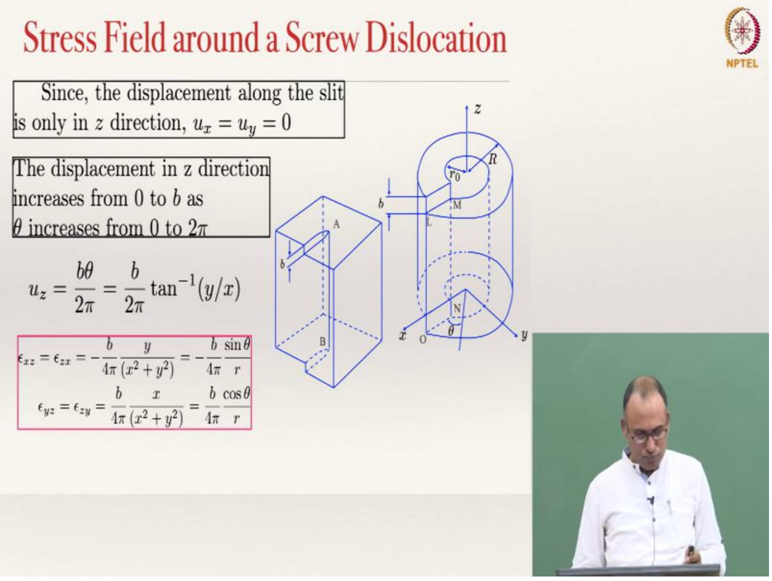

We know that if you have a perfect crystal and you introduce a half plane, then, above the slip plane, all the atoms around the dislocation will experience a state of compression and all the atoms below the slip plane experiences a state of tension. A local stress field right is created around a dislocation. We now discuss how the stress state evolves or changes as a function of space, around the dislocation core. So, for a stress field around a screw dislocation the Burgers vector and the z direction is shown. There will not be displacements in x and y direction since it is a screw dislocation. So, $ux = 0 = uy$ and

$$uz = b\frac{\theta}{2\pi} = b/2\pi \tan^{-1}\frac{y}{x}$$

The strain components will be only $\epsilon_{yz} and\ \epsilon_{xz}$.

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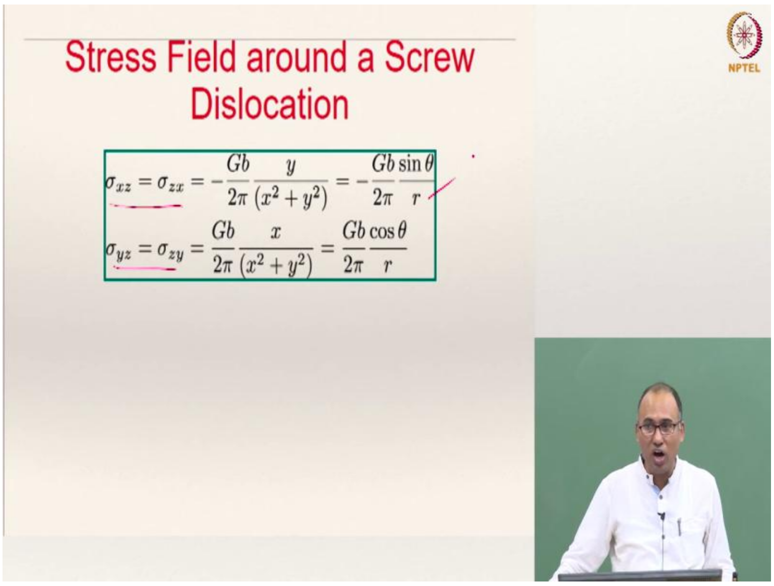

You have

$$\sigma_{xz} = -\frac{Gb}{2\pi}\frac{\sin\theta}{r} = -\frac{Gb}{2\pi}\frac{y}{x^2+y^2}$$

$$\sigma_{yz} = \frac{Gb}{2\pi}\frac{\cos\theta}{r} = -\frac{Gb}{2\pi}\frac{x}{x^2+y^2}$$

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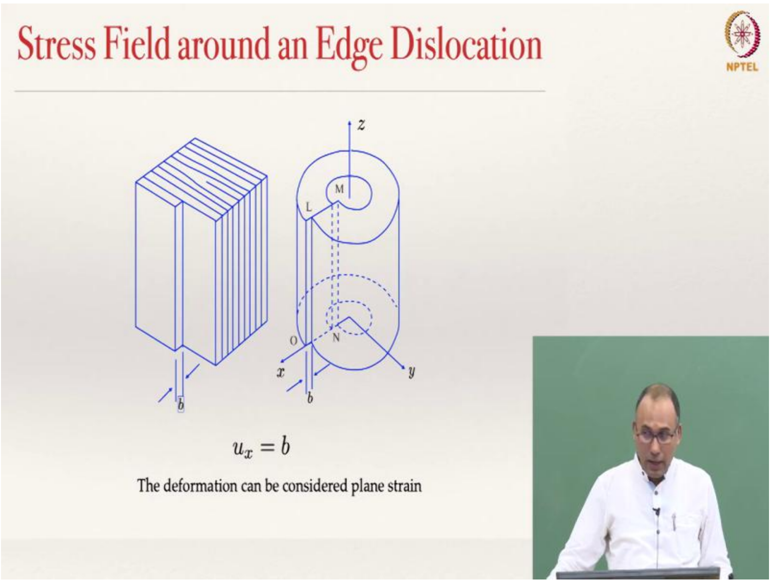

The derivation for edge dislocation is not presented here. The deformation can be considered to be plane strain and $u_x = b$

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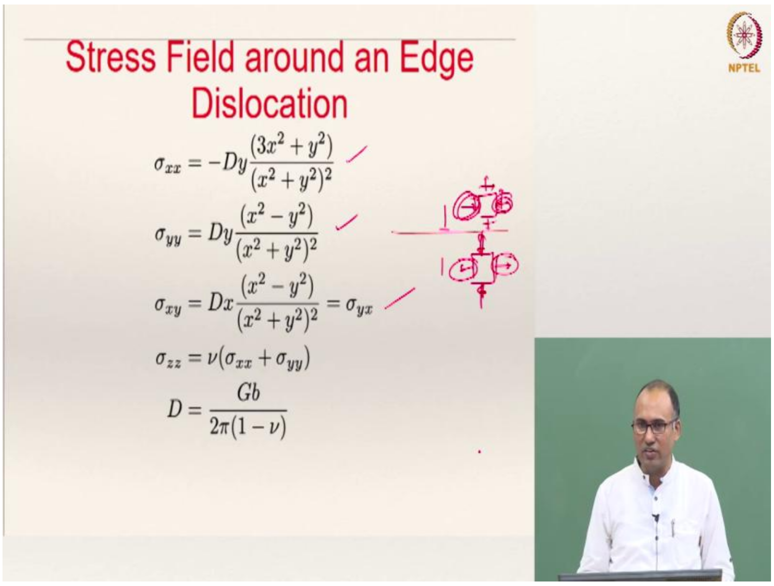

Thus you can derive equations for $\sigma_{xx} and\ \sigma_{yy}$. The equations are given by

$$\sigma_{xx} = -Dy\frac{3x^2+y^2}{(x^2+y^2)^2}$$

$$\sigma_{yy} = Dy\frac{x^2-y^2}{(x^2+y^2)^2}$$

$$\sigma_{xy} = Dx\frac{x^2-y^2}{(x^2+y^2)^2}$$

$$\sigma_{zz} = \nu(\sigma_{xx} + \sigma_{yy})$$

Where,

$$D = \frac{Gb}{2\pi(1-\nu)}$$

If you have an edge dislocation, the kind of stress state that you would observe is such that below you will have compression; and above, tension. You will also have some shear. So, a edge dislocation can actually cause both normal as well as shear stress; whereas, screw dislocation will only cause shear stresses. You can actually go and plot the variation of stress around the dislocation core and you will see how the stress variation is going to take place

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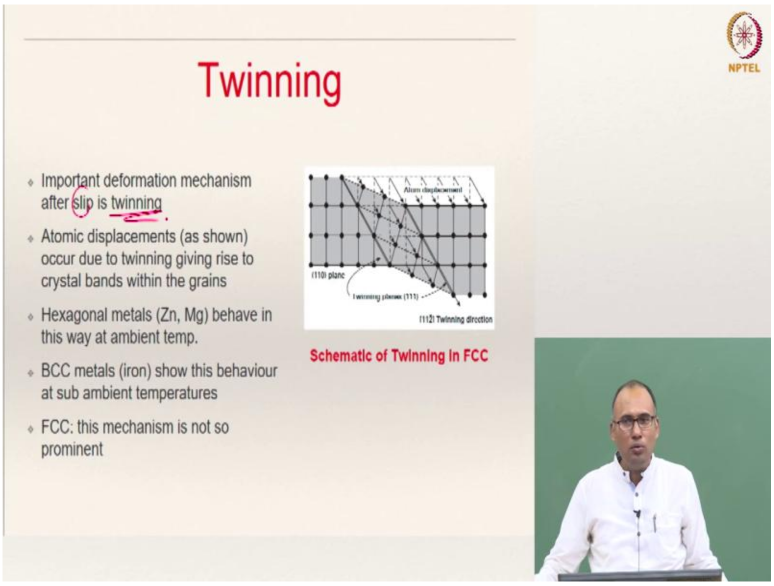

So far, we have discussed the onset of plastic deformation through slip. There is also another important deformation mechanism after slip called twinning. Twinning is a special kind of a deformation mechanism, wherein the atoms should move in a special way such that you should have a coordinated atom motion across the slip plane in such a way that after you have crossed the slip through twinning, you will see that the atoms have taken a mirror image position

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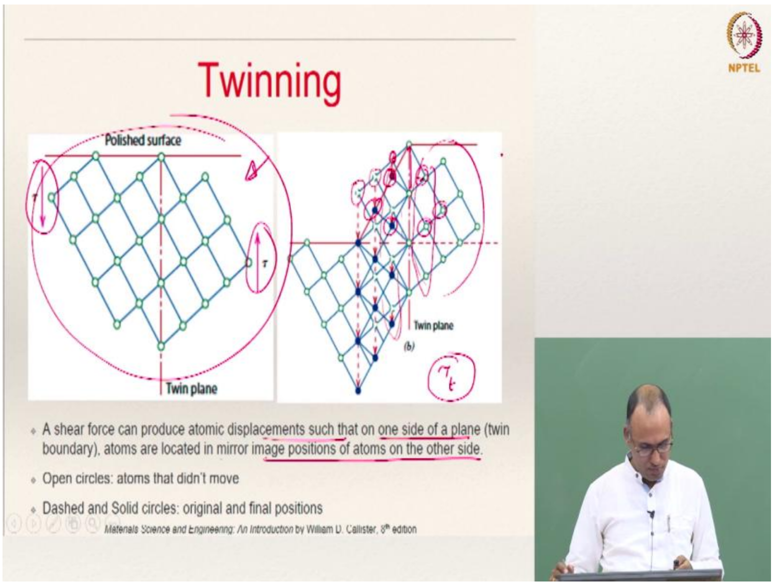

For instance, if this is your initial crystal lattice and now these are your original positions of atoms. What happens is that, with respect to the atoms on this side, these other atoms have moved in such a way that, these atoms become mirror images of the others.

So, your atom motion is such that you will always find, across the twin plane, mirror images of atom from one side to the other. If you motion is of that kind, such a deformation mechanism is called twinning. Again, here, we have not used dislocation we have just said that the atoms have to move that way.

Like in the case of shear by glide of plane of atoms, here also you can have a plane of atoms moving in such a way that they become mirror images of atoms on the other side of the twin plane. Hence, if you were to calculate the shear stress required to cause twinning; it is going to be much larger than when you cause such a deformation through dislocation motion. That means, you really do not have to move all the atoms at once, but you can actually move one atom after the other. Similarly, you can also cause twinning through dislocation motion and then, the amount of stress required to cause twin deformation is going to be much less compared to the theoretical shear strength required for causing twinning.

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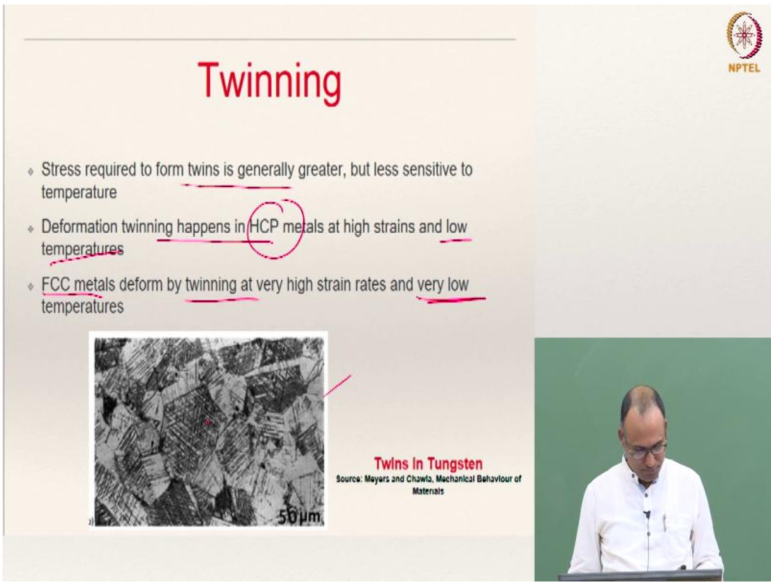

Typically, the stress required to form twins is generally much higher, but it is not really dependent much on temperature. Whereas, for slip, it is the other way around. The amount of stress required to cause slip, compared to twin, is usually much smaller. That is why in FCC materials, particularly, the amount of stress required to cause twinning is usually much higher, at room temperatures and high temperatures, compared to amount of stress required to cause slip through dislocation motion.

So, deformation twinning is usually the mechanism for plastic deformation in HCP metals, at high strain rates and low temperatures. In specific situations, FCC metals also deform by twinning, i.e. when your loading rate is very high and the temperature is very low. When you are operating at very low temperatures, the shear stress required to cause dislocation motion through slip is going to be much higher. Hence, FCC metals also might show twinning.

So, this is the microstructure -- micrograph of Tungsten showing twin deformation, where you see the serration or the twin steps in the material.

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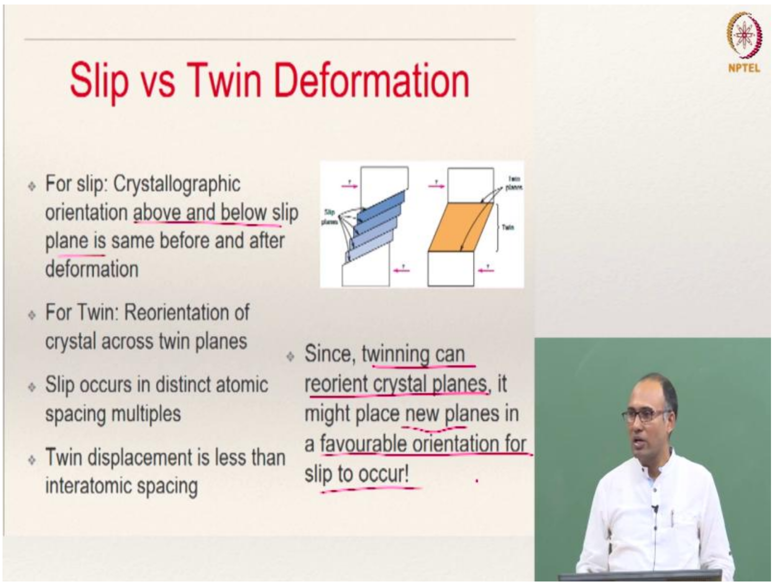


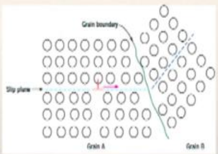
How do we compare the slip versus twin? When you have slip, the crystallographic orientation above and below the slip plane is same before and after the deformation. However, in the case of twinning, that will be altered. In other words, reorientations of crystals occur.

The reorientation of the system might actually trigger slip, because the reoriented systems might now become active slip systems because of the change in orientation. The loading is same, but these crystals are rotating and because of this rotation, the slip factors on these slip system might become higher, initiating the deformation through slip. So, the twinning can sometimes assist in enhancing the slip. Also, slip occurs in discrete atomic spacing multiples; in integer multiples of Burgers vector. Whereas, in twinning, the displacement is usually less than the inter atomic spacing.

Thus, in some materials, you may actually start the deformation with the twinning, but the twinning can reorient the crystal planes such that you might actually trigger slip as a consequence of higher Schmid factor on the reoriented slip system.

Strengthening Mechanisms (Grain boundary)

- Grain boundary acts as barrier to dislocation motion
  - two grains are of different orientations; a dislocation passing into grain B will have to change it's orientation
  - atomic disorder within the grain boundary region will results in discontinuity of slip planes



Stress field around the dislocation

$$\sigma \propto \frac{Gb}{r}$$