Basics of Materials Engineering
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Lecture - 18
Defects in Crystalline Materials - 4 (Slip System, Burgers Vector and Dislocation Motion)

Okay, let us get started. In the last class, we looked at the stress state around an edge dislocation.

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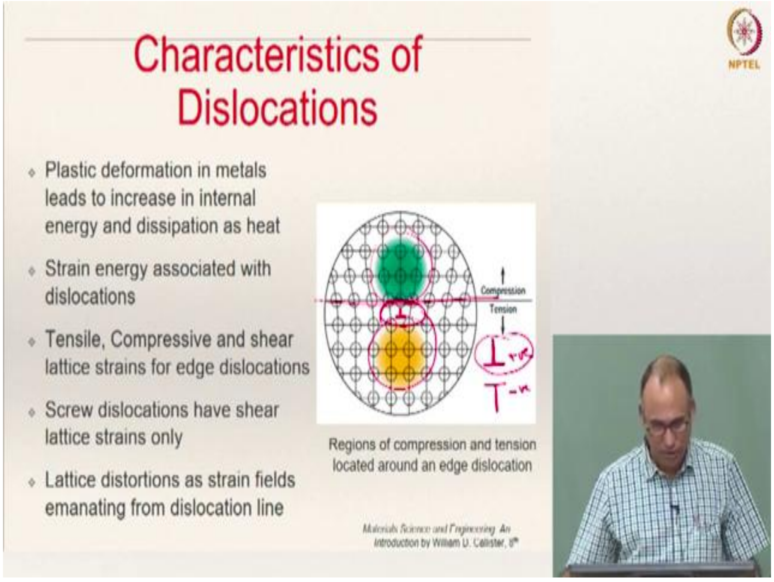

Characteristics of Dislocations

- Plastic deformation in metals leads to increase in internal energy and dissipation as heat
- Strain energy associated with dislocations
- Tensile, Compressive and shear lattice strains for edge dislocations
- Screw dislocations have shear lattice strains only
- Lattice distortions as strain fields emanating from dislocation line

Regions of compression and tension located around an edge dislocation

Materials Science and Engineering: An Introduction by William D. Callister, 8th

We have seen that when you have an extra half plane in the region, you will have a state of compression above this plane, and a state of tension below the dislocation. Typically, this is represented as shown (+ve) and it is called a positive edge dislocation.

Similarly, a negative edge dislocation is represented as shown (-ve). The positive edge dislocation representation basically tells you that you have an extra half plane above and do not have one below. It is the other way around for the negative edge dislocation. This will be the representation used in Material Science textbooks to represent edge dislocations.

So, typically, if you have an edge dislocation and a screw dislocation in a material, they will create a stressed state around the dislocation core. Stresses are induced because of the presence of this foreign half plane. It would have been a perfect crystal otherwise.

The state of the stress will be compressive in the region where you have an extra half plane and tensile in the region where you do not. Typically, the presence of edge dislocations will result in tensile, compressive and shear strains.

Whereas, in screw dislocations, only shear strains occur. These shear strains are what cause lattice distortions. In other words, lattice distortions in the presence of a dislocation are caused by the shear strains.

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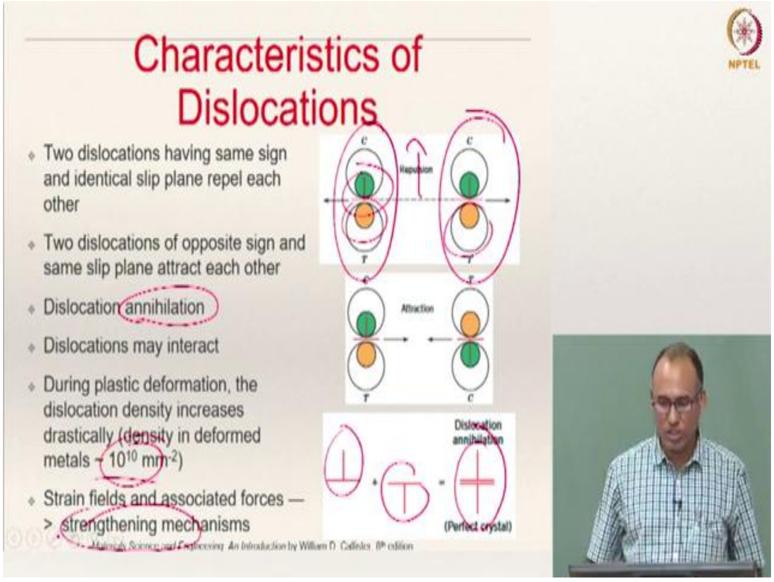

Characteristics of Dislocations

- Two dislocations having same sign and identical slip plane repel each other
- Two dislocations of opposite sign and same slip plane attract each other
- Dislocation annihilation
- Dislocations may interact
- During plastic deformation, the dislocation density increases drastically (density in deformed metals ~ 10^{10} mm^{-2})
- Strain fields and associated forces —> strengthening mechanisms

Materials Science and Engineering: An Introduction by William D. Callister, 8th edition

Let us now look at the different characteristics of dislocations. Suppose, you have two dislocations of the same sign; this means that both dislocations, present in the same crystal lattice, are either positive (meaning that you have an extra half plane above as per the terminology we are adopting) or both are negative.

Then, when these dislocations move within the crystal lattice during the application of shear strain or shear stress, as we have seen, if these two dislocations of the same sign encounter each other, they repel. If they were of opposite signs, they would attract.

Dislocations of the same sign repel and dislocations of opposite signs attract. When you have two dislocations of opposite signs, they come together and they annihilate the dislocation. The extra half plane of one and the extra half plane of the other come together and you will have a perfect crystal lattice.

Typically, in a crystal lattice, there will be several dislocations. When the crystal lattice is subjected to external stress, these dislocations tend to move. Given the fact that they are moving, depending upon their signs, it is possible that sometimes the dislocations annihilate. They may also interact without annihilating each other -- that is, the dislocations may repel each other or perhaps even do something else. In general, we can expect interaction of the dislocations.

When you are subjecting the material to an external stress, if you are imparting plastic deformation to the material, then the dislocation density keeps on increasing. That means, you are generating more and more line defects.

So, the dislocation density of a deformed metal is typically$10^{10}\ mm^{-2}$. The units are actually mm/mm^3. Sometimes, this is thought of as 10^{10} dislocations per unit mm^2.of area. However, the right way to define this is that the total length of the dislocation is 10^{10} mm in a volume of $1\ mm^3$.

The presence of the dislocation alters the strain field around the dislocation core locally. This might lead to something called strengthening mechanisms, which we shall see in the coming lecture.

The most important point here is that, in a crystal lattice, you are going to see several dislocations, and these dislocations are bound to interact with each other when you are applying external load on the material.

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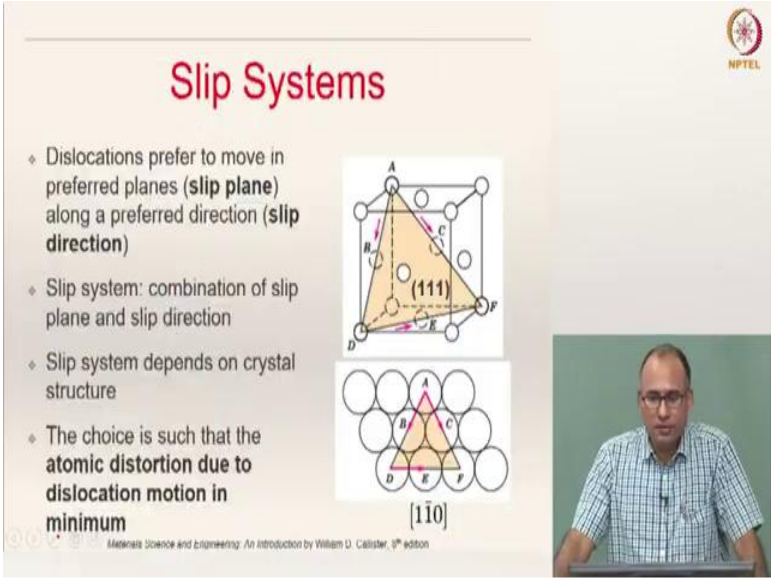

Slip Systems

- Dislocations prefer to move in preferred planes (**slip plane**) along a preferred direction (**slip direction**)
- Slip system: combination of slip plane and slip direction
- Slip system depends on crystal structure
- The choice is such that the **atomic distortion due to dislocation motion in minimum**

Materials Science and Engineering: An Introduction by William D. Callister, 9th edition

We now introduce the concept called slip systems. In the previous lectures, we have discussed something called close packed planes and close packed directions and these concepts have an implication on the deformation in materials.

The plastic deformation in a crystalline material is actually due to dislocation motion, as discussed in the above sections. Slip of crystal planes is basically due to its dislocation motion. Dislocations prefer to move in certain planes in certain directions. This means, they have certain preferences. They try to choose some preferential planes and, in those preferential planes, some preferential directions.

If these are not available, then you might have to do additional work in order to make them move, but if at all there is a preferential plane and a preferential direction that is available, then the dislocations tend to move in those planes in those directions. So, the slip system is actually a combination of the planes in which slip can take place (that means the preferential plane) and the directions in which they can take place.

In other words, the slip plane and slip direction together is called slip system of the crystal structure of a crystalline material. Therefore, the slip system depends on the crystal structure because there are preferred planes and preferred directions. In other words, the slip plane and slip direction are not necessarily the same for different crystal structures. For FCC materials, it is going to be different to that of BCC materials. This is because the dislocations choose to move in certain planes and certain directions such that they cause minimal atomic distortion to the crystal lattice.

They choose their planes such that the motion of the dislocation happens without actually causing too much of a distortion to the crystal lattice. That is the principle. For the dislocation to move without causing too much of a distortion to the crystal lattice, what should it do?

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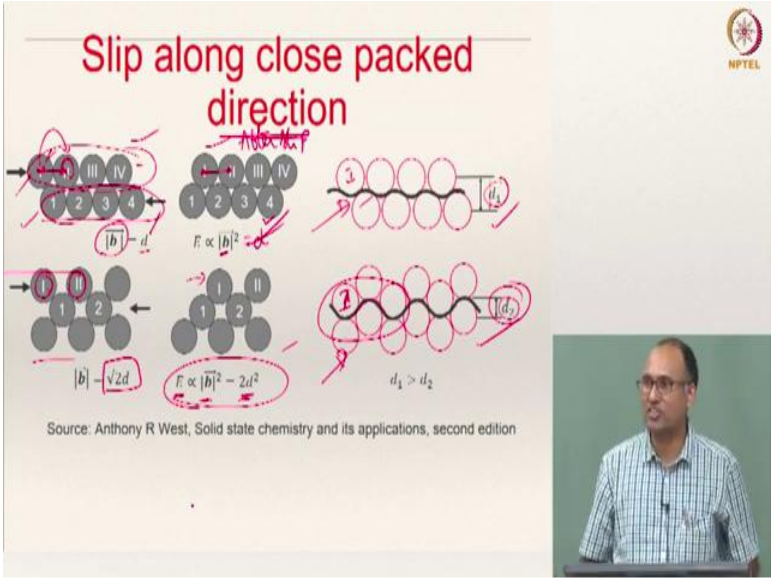

Slip along close packed direction

Source: Anthony R West, Solid state chemistry and its applications, second edition

It has to move in close packed planes, and in those close packed planes, it must move in the close packed directions. Here, you have a close packed plane (above) compared to the other one (below). Suppose 1, 2, 3, and 4 are one plane of atoms and I, II, III, and IV are another plane of atoms, and they are subjected to shear stress on this lattice.

After slipping by one inter-atomic distance, this atom at I has occupied the position of the adjacent atom in the structure (II). The distance it has moved is equal to the diameter of the atom since the inter-atomic distance is equal to the diameter of the atom.

The Burgers vector represents the direction and magnitude of the slip. The Burgers vector in this case is d, where d is the diameter of the atom. The energy associated with the movement of this dislocation is proportional to $|\boldsymbol{b}|^2$. That is,

$$E \propto |\boldsymbol{b}|^2$$

In the other system, the atom at I has occupied here the position of II atom. The distance, that is, the magnitude of the Burgers vector, $|\boldsymbol{b}| = \sqrt{(2\,d)}$. That is the total distance moved.

The energy associated with the movement of this dislocation is given by

$$E \propto |\boldsymbol{b}|^2 = 2\,d^2$$

Thus, we see that more energy is spent here as compared to close packed directions. In other words, by moving in closed pack direction, less energy is spent. Hence, dislocations prefer to move in that direction if they are available.

Now, let us look at why they prefer close packed planes. Here, we have a close packed (above) plane and one which is not (below).

The inter-planar spacing between the close packed planes is largest compared to all other planes. When the atom moves from its position to the adjacent position, it causes much less distortion in the close packed plane than it does for a plane which is not close packed. In a plane which is not close packed, it has to overcome a larger hill in terms of energetic as compared to the close packed plane. Therefore, if you are moving in close packed planes, because of the fact that the inter planar spacing is larger, you are going to cause much less distortion to your crystal structure. This is the reason why dislocations prefer to move in close packed planes and in close packed directions.

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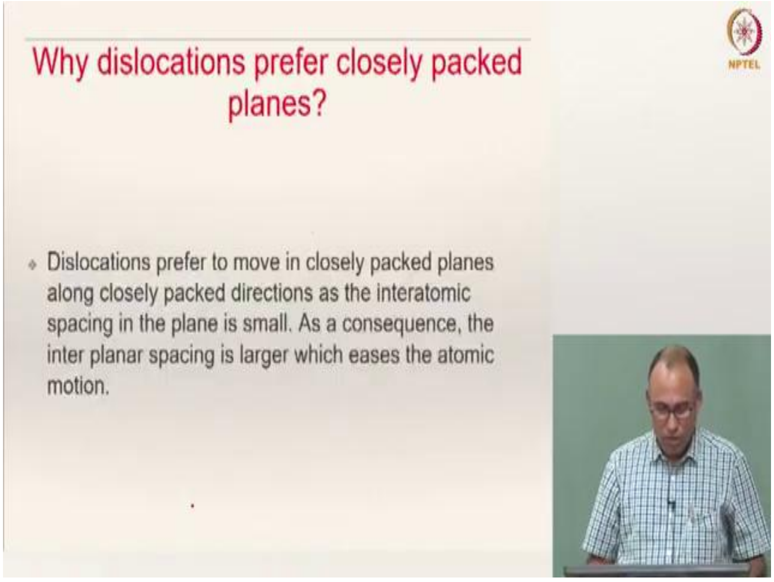

Why dislocations prefer closely packed planes?

- Dislocations prefer to move in closely packed planes along closely packed directions as the interatomic spacing in the plane is small. As a consequence, the inter planar spacing is larger which eases the atomic motion.

The dislocations prefer to move in closely packed planes along closely packed directions as the interatomic spacing in the plane is small. As a consequence, the inter-planar spacing is larger which eases the atomic motion without actually causing lot of distortion to crystal structure.

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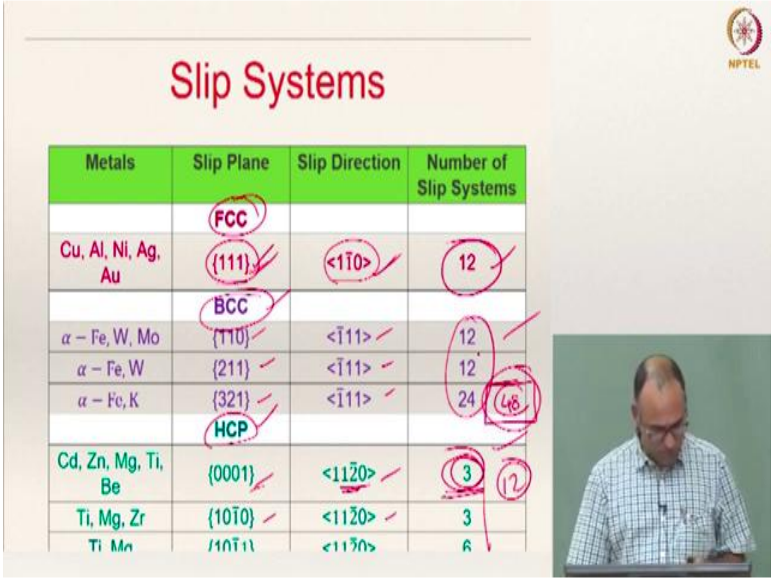

Slip Systems

Metals	Slip Plane	Slip Direction	Number of Slip Systems
	FCC		
Cu, Al, Ni, Ag, Au	{111}	<1$\bar{1}$0>	12
	BCC		
α – Fe, W, Mo	{$\bar{1}$10}	<$\bar{1}$11>	12
α – Fe, W	{211}	<$\bar{1}$11>	12
α – Fe, K	{321}	<$\bar{1}$11>	24 48
	HCP		
Cd, Zn, Mg, Ti, Be	{0001}	<11$\bar{2}$0>	3 12
Ti, Mg, Zr	{10$\bar{1}$0}	<11$\bar{2}$0>	3
Ti, Mg	{10$\bar{1}$1}	<11$\bar{2}$0>	6

Let us now discuss the different kinds of slip systems that we can observe in materials with different crystal structures. In FCC material, we have already discussed in the previous lectures that the (111) plane is the close packed plane. {111} is a family of (111) planes. All the family of (111) planes are the closely packed planes. In the (111) plane, the family of <1$\bar{1}$0> or <110>, is the family of slip directions.

How many such planes are there in FCC in one FCC unit cell?

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All other planes parallel, except 4 are parallel and thus are not considered. So, you will have only four non-parallel planes and in each close packed plane, there are 3 close packed directions.

Thus, there are three close packed directions, four close packed planes and hence, you will have total of 12 slip systems. FCC thus has 12 slip systems. So, dislocations can choose to move in any one of these 12 slip systems. Typically, most of the ductile materials that you find are in general FCC in their crystal structure.

BCC, on the other hand, has the close packed planes {110}, {211}, and {321} all of which are a close packed family of planes. The corresponding family of close packed directions for each are <$\bar{1}11$> respectively. In total, you will have 48 slip systems.

In HCP, you have 12 slip systems again. In HCP, the {0001} plane is the basal plane. It is called so because it is the base. In that plane, <$11\bar{2}0$> is the close packed direction. Corresponding to this one plane, you have 3 slip systems. Similarly, you have other planes with their own slip directions and they form a total of 12 slip systems for HCP. However, these 3 are the easy glide planes and thus these 3 are the most prominent slip systems in HCP.

We know that plastic deformation is much easier in FCC as compared to BCC and HCP. However, BCC has 48 slip systems (4 times FCC) and thus one would expect a material with more slip systems to have easier plastic deformation. Thus, we expect them to be more ductile. However, we know that Aluminium is more ductile than steel (mild steel or plain carbon). Steel, at room temperature has BCC crystal structure. Several other materials with BCC and HCP structure tend to be less ductile compared to FCC. Why is this the case although BCC has more slip systems than FCC? This question will be left unanswered currently and for the student to research by himself.

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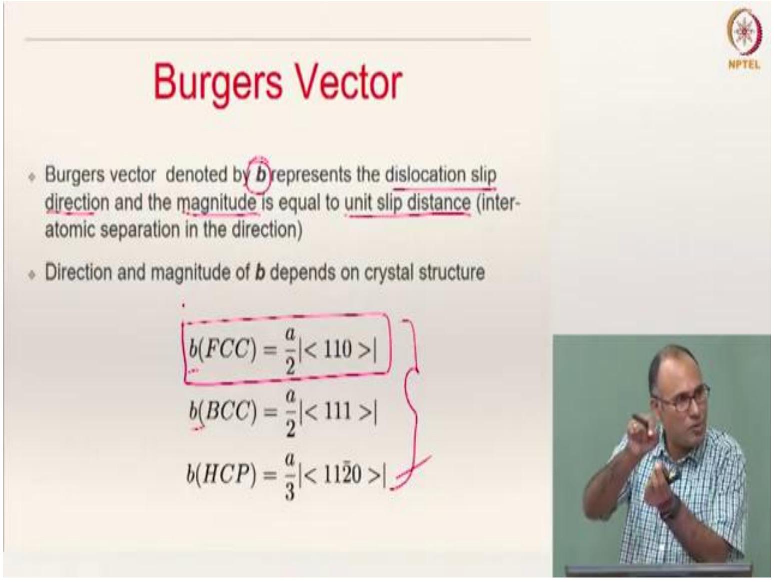

Burgers Vector

- Burgers vector denoted by ***b*** represents the dislocation slip direction and the magnitude is equal to unit slip distance (inter-atomic separation in the direction)
- Direction and magnitude of ***b*** depends on crystal structure

$$b(FCC) = \frac{a}{2}|<110>|$$

$$b(BCC) = \frac{a}{2}|<111>|$$

$$b(HCP) = \frac{a}{3}|<11\bar{2}0>|$$

In each of these materials, the Burgers vector represents the direction and magnitude of the slip. The Burgers vector usually is denoted by **b**. The magnitude is usually equal to the unit slip distance or interatomic separation in the close packed direction.

The direction and magnitude of **b** depends on the crystal structure and is given as follows,

$$b(FCC) = \frac{a}{2}\,|< 110 >|$$

$$b(BCC) = \frac{a}{2}\,|< 111 >|$$

$$b(HCP) = \frac{a}{3}\,| < 11\bar{2}0 > |$$