Mechanical Behaviour of Materials - 1
Prof. Shashank Shekhar
Department of Materials Science and Engineering
Indian Institute of Technology - Kanpur

Lecture – 25
Slip Systems

Welcome back students. So, we have looked at motion of the dislocations. The next thing that we will be discussing is the resistance that comes to this motion. So, we remember when we talked about theoretical strength, so all the atoms have to break and then because of that we see that sinusoidal energy valleys, although the whole plane is not getting sheared.

And even if the row is getting sheared and even if only steps it is moving in steps, but still there are resistance in that sinusoidal wave and this resistance arises primarily from two sources, one is the size of the core and other is the density of the planes, meaning lattice resistance. So, depending on what is the density of the planes, different planes have different resistance and that is why we have certain preferred planes for glide of the dislocations, and which leads us to what we say as the slip system.

So, certain planes would be preferred, but we already know that for certain directions are what become the Burgers vector, so together the direction and the plane define the dislocation and hence together we call what is called as now the slip system. So, for different crystal system, you will see that we have different slip systems. So, with this introduction, let us move on to understand what kind of resistance does dislocation face in motion.

(Refer Slide Time: 01:59)

So, like I said there are two-fold resistance to dislocation motion, and one is from the core that is from the dislocation structure itself and the other is coming from lattice and as we would look into it we will understand that these two are actually interrelated. So, on the face of it we can say they are two different factors, but they are one and the same thing. So, let us look at what do we mean by resistance to dislocation motion from core.

So, what it means is that the size of the core defines are the total amount of resistance that would be faced by the dislocation would be dependent upon the size of the core. So, for that first let us try to understand what we mean by size of the core. So, I will draw any dislocation

with two different core sizes. So, once we understand the size of the core, we will move on to understand how it affects the dislocation motion.

So over here let us say this is the extra half plane and so it goes only up to this point. So, this is our dislocation and what we see is that it should be symmetric it is just that when I am drawing by hand it is not so accurate, but it should be symmetric. So this is one extreme where I am trying to show that the core is larger in size and I will show the other extreme where I will try to show that the core is very small.

So, this is the plane of the atom and here is our edge dislocation. So, what do we see? What we see is that in this one these atoms are also displaced from its position, and they have moved away from their equilibrium position, and therefore we can say that the displacements are large even for this atom and even for this atom. On the other hand, when we look at this example, here we see that these two atoms are almost not displaced.

There may be a very minor change in their position while there is a good amount of displacement for these two atoms, the one just next to the extra half plane and again these two are almost not moved. Now, if we were to look at displacement with respect to b, so let us we draw with respect to the central line delta u by b, so on the y axis what we have the quantity is delta u displacement, but of course it must be with respect to b and similarly I draw it over here and the x axis is usual distance.

So, what we know is that here the displacements are large up to a very good extent. So, the curve would look something like this. So, the displacement is signs are different on the left hand right hand side, which is represented like this. On the other hand, the atom the displacement goes almost to 0 which would be represented something like this There may be small amount of displacement.

And if we define that the region up to which delta u by b is point one or basically the point at which the displacement is 10% of the Burgers vector is defined as the core. So, we will draw a line here like this. So, let us say this is plus minus 10% and here also we draw a plus or minus 10% of point one strain. So, if we say that the core is up to 10%, then what it means that the core for this particular dislocation is all the way up to here.

So, this would be the size of the core for left side example, while here we see that it is only, so here we are trying up to this point, this is where it intersects and here, we see that 10% line intersect somewhere here. It is not drawn very accurately, but somewhere around this even from this schematic size of the core is very different. So here size of core is large and here size of core is small. Now, this size of the core has a very strong effect on how the dislocation moves.

When the size of the core is very large, then it is easier for it to move. When the size of the core is small, it faces much larger resistance, so we will give some rough estimate on how large or how much difference can it become, and you would be surprised at the amount of difference the size of core can make. But first let me just summarize what I have just mentioned.

(Refer Slide Time: 09:47)

When distortion, I am writing distortion which are dislocation core is large, the dislocation is easy to move. So, clearly this one has a large dislocation core, so it is easier to move. On the other hand, this will be this like just I mentioned the size of the core is small so this dislocation would be difficult to move. So, at first it may look a little counterintuitive, but yes that is the case, larger the core easier to move, smaller the core more difficult to move.

And when we are defining the size dislocation core, we have to remember that the width of dislocation core is defined as the distance over which displacements of the atoms are large enough that what do we mean by large enough that we will not be able to apply linear theory of elasticity. So, that is what has been defined as the cut off for dislocation core. So, you remember even when we obtained the stress field and strain field, we applied linear theory of elasticity and therefore this theory was not applicable for dislocation core.

Now, in the same way we will define that the core is that where the displacement is so large that theory of linear elasticity cannot be applied, and it is generally accepted to be of the order of b by 10. So, in magnitude wise when 10% of the Burgers vector value, the displacement is more than 10% of the Burgers vector, then we would say that we will not be applying the theory of linear elasticity and this width is usually denoted by w.

(Refer Slide Time: 13:28)

And just to give you like I said rough estimate of how much difference it can make, so let us say if your tau is the shear stress required to move the dislocation then it would vary like this. So, let us say this is the w, this is the tau and if the width is 0, meaning basically there is no dislocation then shear stress that would be required would be of the order of G. And just when the width increases to b, then the shear stress reduces drastically to g by 400.

So, just by additional one layer of atom thickness of the dislocation core from zero layer, we can see that the shear stress requirement has dropped by two orders of magnitude. And if you were to make the width 5b, it will come down several orders. These are some simulation experiments carried out by Prasanna Subramanyam and it is based on this. So, the actual values may differ from material to material.

So, we can say dislocation glide occurs most easily in wide dislocations. These wide dislocations are found in metals with simple close-packed structure and hence these materials are ductile. On the other hand, ceramics tend to have narrow dislocation and not surprisingly the dislocations there are difficult to move and hence have high strength but brittle. Another factor which is where which gets related to the resistance,

Next factor for instance which is lattice resistance is the fact that large interplanar distance of the planes leads to wider core. So, if the lattice planes are such that it has in larger interplanar distance, then it leads to wider code and hence the dislocation becomes more easier to move and hence the material will be more ductile in nature.

(Refer Slide Time: 18:18)

So, which brings us to our next factor which is resistance to dislocation motion lattice or lattice resistance to the dislocation motion. So, we know that dislocations, then they are trying to move, so basically there will be lattice resistance. So, there will be valley like this, and which is called Peierls-Nabarro valley. So, let us say this is the extra half plane. So, you need to move extra half plane.

This is how it would have the energy variation where we can say that this is the E PN what is called as Peierls-Nabarro energy from where we can calculate the Peierls-Nabarro stress. So, when stress is applied, dislocations move and face additional sinusoidal resistance of lattice, sinusoidal resistance which is depicted here due to lattice.

(Refer Slide Time: 20:11)

$$E_{PN} = \frac{Gb^2}{\pi(1-\mathcal{V})} \exp\left(\frac{-2\pi w}{b}\right)$$

$$\tau_{PN} = \frac{2\pi}{b^2} E_{PN}$$

$$\tau_{PN} = \frac{2G}{(1-\mathcal{V})} \exp\left(\frac{-2\pi w}{b}\right)$$

So, if you were to write down the Peierls-Nabarro energy, which is actually varying, but if we look only at the amplitude, then the amplitude can be given by this equation and if we have the energy, we know that we can calculate the shear stress which will be by differentiating this relation with respect to b. So, tau PN which will be equal to, so when we differentiate with this –2 pi will come out and there will be b square which will again be–1 over b square.

So, this minus gets cancelled into E PN and therefore this tau PN the shear stress. So now, we are in looking at terms of the shear stress that needs to be applied to move the dislocation. So, we have already mentioned that you need to apply a shear stress to get the dislocations moving and that has to be applied parallel to the Burgers vector. So, tau PN that we will get will be equal to 2 G by 1 – nu exp, this is a very important equation from where we will be able to derive what should be the slip system of the material.

Here w width is you can give it in terms of a lattice parameter and the Poisson ratio, so a is the lattice parameter and nu is the Poisson ratio. Therefore, you can replace this by 2 pi a by 1 – nu. And now, if you want to have a slip system or you want to define a slip system, then we know that we want a dislocation, or the dislocations would want to move on a plane where least resistance is present which means the tau PN is the smallest. So, now all we need to find out is what are the condition that leads to the smallest value of tau PN. So, we can list it.

So, one of the parameters that we can for given material that can be selected is a and other is b, not sorry not the a but the particular plane. So, I made a mistake here, this a is not the lattice parameter, let me define it, a is the interplanar spacing and w is the width of the core. So, clearly what we had mentioned earlier that large interplanar distance leads to wider core, which is what we see here.

So, large interplanar core means larger width and hence easier movement of the dislocation and a is the interplanar spacing. So, again, let me reemphasize a is not the lattice parameter, but the interplanar spacing. So, a is something for a given material we can decide basically whether it should be 111, 100, 110 or any other plane and similarly b which directions should be b 100, 110, 111 and so on.

So, a and b are something that we can select and accordingly we can see which one would give the smallest value of tau PN. Other factors like nu is a material property, G is a material property, so we cannot change that and therefore those remain constant.

(Refer Slide Time: 24:15)

So, now, let us look at what values of a and b would lead to the smallest value of tau PM. So, a the interplanar spacing, over here now if you look for tau PN to be small, this whole quantity should be small which means there is a negative sign, so therefore this quantity should be larger and this quantity should be smaller. So, what it is saying is that a should be as large as possible.

So, what we want is that the glide planes with wider interplanar spacing which at the same time when it has a wider interplanar spacing, it means that on that plane the density of atoms is very large, so densest planes. So, in other words, we can either look at planes with highest interplanar spacing or we can look at planes which have densest atomic density, densest planes. So, this defines the a for a given system.

Now, coming to b, we have said it should be small because the whole quantity has to be small as far as possible and therefore this would be small. If b we will make it large which means minus term would be large and therefore the whole quantity would be small, and therefore b should be small and when we say b should be small it means slip, remember b Burgers vector is also called as slip vector.

So, slip vector or slips should be along direction with shortest lattice formation or in other words slip should be along closest packed direction. So, once we have a given material system and there are only certain type of material systems and when we limit it to metals

where we see the deformation, we are also mostly talking about FCC, BCC and in some cases simple cubic. So, let us look at with the example of BCC and FCC.

What we have understood is that a should be densest and b should also be densest. So, or basically we should select densest planes and the denser directions. Denser planes would become the planes where the glide will take place and b is the slip vector which should be along the densest direction.

(Refer Slide Time: 28:00)

So, let us look at BCC and there are primarily three main points which we will consider so that I can also draw the planes. How would the planes look like in BCC? We know that if you join the corners of the cube, then you have atoms at the corner. So, the atoms would look like somewhere over here, over here and over here. And then the next column I want to have over here is the number of atoms.

Because if you want to find the density of atoms, what we need is number of atoms and the area of the region under consideration and this will give us when we divide number of atoms by A then we will get planar density which will be equal to N over A and then we can also look at value of A. So, over here for the 111 plane clearly what you have is 16 16 16 three of these which brings us to 1 over 2, total number of atoms as 1 over 2 and the area is equilateral triangle.

So, this will be root 3 by 4 and the length here is a 0 root 2 for the square. So, when you put it over here, what you would see that it comes out to 1 over root 3 a 0 square. And I will come to the interplanar spacing in a little later stage, first let me compare the other planes. So, the other important planes for the cubic system are 110, so in a BCC you have atoms only at the centre. So, 110 also has one atom at the centre and four atoms at the corner which are quarter of the atoms. So overall it makes up 2 atoms.

So, the number of atoms is 2 and the area here is a 0 root 2 times a 0 and here I am using the term a 0, which is lattice parameter. So, this is not interplanar spacing, interplanar spacing is given by a. So, this becomes a 0 square root 2 and therefore your planer density would come out to root 2 by a 0 square. Now, moving on to the third plane, which is 100, which is simplest of all these three, it is a 0 by a 0 area and there are four atoms at the corners.

So, what we get here is number of atoms 1 by 4 into 4 = 1, area is 1 0 square and planar density will turn out to be 1 over a 0 square. So, clearly what we see that the planar density is highest for this particular case which is the 110, and not surprisingly for BCC 110 is the preferred slip or glide plane and the last thing that I was about to write here is the distance between the planes.

And you can find out that for 111 planes, the distance between them is a 0 by 2 root 3, for 110 it will come out to a 0 by root 2 and for the 100 it will come out to a 0 by 2. So, again what we see is that this is the largest value, and these are much smaller than this. So, this has the largest interplanar spacing in the case of BCC atoms and therefore this is the glide plane.

(Refer Slide Time: 32:45)

So, we have looked at the light plane and when it comes to the densest direction, then it is again not very difficult to imagine. So, BCC we have atom at the centre, then we have atoms at the corner and the atoms are actually touching only along the body diagonal which is along this one, which is a long 111 direction and the basic translation vector from one atom to another atom would be half of this and therefore this will come out to Burgers vector equal to a by 2 111 and the glide plane we saw was of the family 110. So, together these forms the slip system for the BCC material.

(Refer Slide Time: 34:06)

Now, let's move on to the FCC material. So, again here are the three primary planes which are contenders you can imagine would be the ones with low values of the numbers and those will be 100, 110 and 111. So, again I will start with 111 and here it is FCC. Again, I will have to write the number of atoms area and planar density. So, number of atoms and area of the region being considered, planar density which will be equal to N by A and then lastly what we have is a the interplanar spacing especially.

So, for 111 we have atoms over here one sixth atoms over here. We also have one half atoms over here. So, overall, the number of atoms for this one will turn out to be 2 and the area of the region considered is same as the equilateral triangle that we said earlier for the BCC. So, it is root 3 by 4 a 0 root 2 whole square and when you calculate the planar density it comes out to 4 by root 3 a 0 square. And then let us move on to 110.

So, this will be rectangle in shape, and we have atoms at the corners and also on two of the edge centres which are half, and the total number of atoms again comes out to 2 area is a 0 square root 2, a 0 root two 2 a 0. And therefore, the planar density comes out to root 2 by a 0 square. Now, moving on to the last plane, which is 100 So, here it is square shaped a 0 by a 0 and atoms are located and the corners and one also in the face centre.

The total number of atoms here is 2, areas is a 0 square, therefore 2 by a 0 square. So, clearly the planar density is highest for this one, this is 4 by 1.732, so it is greater than 2 and this is 2 and this is 1.732. So, we are comparing, other factors are constant 2, 1.732 and some number greater than 2. So, this one is clearly highest therefore, this is the preferred glide plane for FCC system and again if you look at the value of the interplanar spacing, you will find that this is a 0 by root 3.

For this one it will come out to a 0 by 2 and this one will come out to a 0 by 2 root 2. So, I leave it to you to find out how we obtain this number, it is not very difficult. You have to just imagine the cube where the planes for example 111 which are carrying these atoms and count the number of planes along the given known length, for example 111 you would count the number along the main body diagonal and therefore you would be able to find the distance between the planes and this also clearly is highest value for the 111.

(Refer Slide Time: 38:59)

So, that is glide plane and for the Burgers vector b value we said it should be the shortest translation vector. So, again it is not very difficult, what we have to look at is the unit cell. And in this particular case, you would be well aware that the atoms touch a long phase diagonal which is 110, hence closest packed direction. So, the total end is 110 and this much is the translation from one atom to another.

Therefore, the Burgers vector would be a by 2 110 and that glide plane would be 111. So, now we have looked at the slip system for the FCC and BCC system. We will not derive for the HCP. You can do that as an exercise as an assignment.

(Refer Slide Time: 40:47)

I will just summarize what are the slip systems for the various cubic materials, so not materials but various crystal systems. Crystal system slip planes and the slip direction. So, we are looking at BCC, FCC and HCP. For BCC we know it is 110 which is the slip plane which was the preferred one and the direction came out to be 111. For FCC 111 is the closest packed plane or densest plane and 110 is the closest packed direction.

And to be precise if I want to, I should actually write not slip direction, I should mention Burgers vector or slip vector and therefore this would be a by 2, a by 2. For HCP the slip plane which is the densest plane you can easily show it is the basal plane and for the slip vector it is a by 6 11 bar 20. For HCP we use the HKIL format to define the directions and planes. So, there are four numbers instead of the three numbers.

So, overall we have looked at the slip system, we were able to derive the slip system based on our understanding of the resistance to dislocation motion that is experienced which is coming out from the lattice the Peierls-Nabarro valley that is present when a dislocation moves and if you know the energy variation, so we can take the amplitude portion and we can differentiate to calculate the minimum shear stress required for the dislocations to move.

And then we can compare and based on that equation we derived that a should be the densest plane and b should be the densest direction and where a defines the glide plane and b is the Burgers vector. For BCC we saw that it is clearly 110 is the closest or the densest plane and a by 2 111 is the translation vector Burgers vector. for FCC 111 is the densest plane and a by 2 110 is the Burgers vector.

We did not derive for HCP. We are mentioning that 0001 is the densest plane and a by 6 111 bar 20 is the slip factor. So, with that we complete the slip system for various materials. We are now in a position to understand which particular planes the dislocations would like to glide. So, we will look at some examples in the next few lectures to be able to appreciate it better. Thank you.