Defects in Crystalline Solids (Part-II)
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Lecture - 15
Multiplication of Dislocations

Last time we looked at Homogenous Nucleation of Dislocations, and we found that this is not something that will happen spontaneously very often. But one thing we learnt when we looked at homogenous nucleation is that the theoretical strength of the material can also be achieved when we look, when we go through this mechanism. So, now, if homogenous nucleation of dislocation is not the preferred within how do dislocations multiply. So, this is what we are going to look at today. Some of the mechanisms of Multiplication of Dislocations.

The first mechanism that we will look at is what is called as Frank-Read source, ok. So, what is the concept behind this? The concept behind this is that you have a dislocation and you assume that there are the two points on the dislocation any two points on the dislocation is pinned, and I will show you why it can be pinned. Now, if there is a shear stress acting on the plane then the dislocation would want to move, but thus those to pinned points will not move. And therefore, you will need to apply a stress and we know that from the previous part 1 we know that there is a particular shear stress required to maintain a radius R.

So, you will see that there is a that as you keep increasing the shear stress the radius become smaller and smaller, and beyond a point this becomes unstable and then suddenly a large loop forms and it can that large loop becomes independent of the original dislocations. So, now, you have the original dislocation plus and newly created dislocation loop. So, this is dislocation generation mechanism or dislocation multiplication mechanism. So, we will see how it works.

Let us say this is the plane on which we are talking about and let us say this is the dislocation line goes like this. So, this is point A, this is point B. And we have put dislocation like this where we are implying that this part of the dislocation is sessile and this part of the dislocation is sessile. So, only this part A B is; so A B part of dislocation is glissile.

Now, let us say that or resolved shear stress tau is working on this plane and it has to work along the burger vector. So, let us say the burger vector is along this direction. So, resolved shear stress along burger vector is tau. And what is the burger vector?

So, if the dislocation line is like this. Now, we can look at only this portion and we can assume that these two points append, now the force which is equal to tau b that one acts normal to the dislocation line. So, the force would be acting like this. Now, what will that lead to? It will lead to a curvature creation inside it, remember A and B are fixed they cannot move, so it will create something like this. Now, this is a curvature, so it must have a radius. So, the radius would be somewhere very far, so here you can effectively say the radius is infinity over here it has reduced to some finite value. So, let me draw it with the different colors, so that you do not get confused and again the forces are acting normal. So, they are still trying to keep the dislocation moving normal to the dislocation line.

What will happen next? It will move further like this. So, let me call it R 1 because at time t 1 it was R 1, now it has become a smaller radius R 2. Now, if you have to have a dislocation of with a curvature with radius R what is the shear stress required? We know that tau is equal to alpha Gb by R, and so if we look at this and we are keep increasing. So, here what we are happen, what is happening is that you are increasing the stress and curvature is decreasing this time I will make it all the way to the semicircle. So, now, this becomes 2 R.

So, over here we can say and this one will be R 3. So, now, we can say that R 1 is greater than R 2 is greater than R 3, if that is the case then we can also say that the tau 1 equal to alpha Gb by R 1 is less than tau 2 equal to alpha Gb by R 2 is less than tau 3 equal to alpha Gb by R 3. What does this mean? That just what I have been saying that you have to apply larger and larger stress to keep the dislocation becoming curvature of smaller and smaller radius and in the process the dislocation is moving in one particular direction as you can see.

Now, what will be the next step beyond this?

So, here from this particular point it has become this is the smallest radius that you can get. What will happen beyond this let us look at that part now, because here what we have is R 3 is the smallest possible, you cannot have a radius is smaller than this.

Now, let us say that this keeps on going on like this; so this is the. Now, here you wish you should be able to realize that this radius R 4 is actually larger than R 3, similarly if I make it further so in line with what we have a written earlier we can again say that R 3 is less than R 4 is less than R 5. Now, what does that mean? Again, it will mean that tau 3 equal to alpha Gb y R 3 is greater than tau 4 equal to alpha Gb by R 4 is greater than tau 5 equal to alpha Gb by R 5.

So, what do we see? That our tau 3 is the maximum stress required. No matter where you go what will be the radius you started from a straight line you started increasing the curvature then it reaches a semicircle, and beyond that semicircle it again becomes tries to become more and more circular in shape. But the maximum stress that is required is when it reaches the semicircular state. So, tau 3 is maximum stress required that is when shape is semicircular. So, if you apply a stress which is at least equal to tau 3. So, let me write down.

Then, what will happen? Then it means that first you are AB segment will become semicircle which is what we solve and then it will become unstable because now the stress required is less, but you have already you are still able to apply that kind of stress. So, it will become unstable. Meaning beyond this it will automatically as soon as it reaches the semicircle it will automatically start increasing in shape and it will envelope the whole thing. You just look let us look at how exactly this will look like.

So, we said that, these are the two fixed points, now this is your semicircle and if you are apply if your stress that you are applying is larger than this, what will happen is like this. So, first it will become like this, then it will become like this. Now, here what do you see? This is the same dislocation let me highlight it because we will need this; we need to look at it in more detail.

So, this is one of the later positions and the burger vector we have assume let us say one in one direction it is something like this for the whole dislocation line that you see the dislocated the burger vector remain same, but if you look at the line vector, ok. So, what is the line vector? Say, if is this is the line vector for this if you consider this as the line vector then this is a line vector for this section. So, these two points these have the same burger vector, but opposite line direction and you remember how is the forces when you have two dislocations of opposite kind or opposite direction. Meeting at one place or coming very near then it will be a attractive force acting over here. Let us call it D and E, on two segments D and E there is a attractive force acting and therefore, what you will eventually get is a structure like this.

So, what do we see here? Now, this one is one separate dislocation and this one is one separate dislocation or in fact after sometime. Now, because the force and the b direction remain the same. So, as tau sorry the shear stress remains in the same direction therefore, they will still be forces acting on it in this way. So, these are the direction of force which is normal to the line vector and it will it is acting to again keep the loop increasing in size. And for this it is keep it will keep moving it or trying to keep moving it in the in this direction in the with respect to the page in the positive y direction. And eventually what you will get? So, the first thing to note here is that important thing a new dislocation segment in fact I should say loop and new dislocation loop has been created and there will be repulsive forces between these two. So, because they have a same burger vector and they will be in the same line vector direction, so there will be a repulsive force. So, it will that will also act to make the outer loop become larger in size.

And if you keep applying the stress what will happen? This will become a straight line, so the next step would be like this.

$$\tau_{min} = \frac{Gb}{l}$$

So, this will become a straight line and on the outside you will have dislocation loop like this, this is a new dislocation loop and this is as if your dislocation original dislocation remains as it is. So, this is a very nice experimental theoretical explanation of how the dislocation loop can or dislocations can generate and multiply. In fact if this mechanism goes keeps going on what will happen is that eventually you will get more and more dislocation loops and the original dislocation line will remain intact.

So, lot more can be created like this. And what was the stress requirement? So, the tau minimum stress that will be required will be equal to alpha Gb by 2 R it was not 2 R, 3 and if we call this length which is a fixed length as L then this 2R 3 becomes L. So, this becomes alpha Gb by we said R not 2R, so this is R 3 and this becomes L by 2. If you take alpha approximately 1 by 2 which is the case most of the time therefore, tau min required for this source to be activated is Gb by L. So, this is the minimum stress required for Frank-Read source to operate, ok.

Now, here it will look like a very attractive mechanism and a more very meaningful mechanism, however, it is not as widely seen or observe observed when people have seen in the tm or other experimental method. So, this is not a very effective mechanism that has been found experimentally. So, this is not a very effective mechanism. So, what is an effective mechanism? There is another method by which dislocations can multiply or basically their lens can increase and that one is Called Multiple Cross Slip.

So, how we can visualize this? It is very simple if you remember from our earlier part one course that dislocations the particularly the screw dislocations can cross slip from one plane to another place and particularly in FCC if you remember it can cross slip from one to another and back to plane parallel to the first one. So that, way you can have a dislocation on 1 and the same dislocation of part of the same dislocation can now also be on 3.

Now, let us here first stress is being applied which is causing this dislocation to become a loop just like the way we saw here where the other two ends are pinned then there will be some dislocation increment in the dislocation length on plane 1 and then also one plane 3 which is parallel to plane 1. And therefore, the length can keep increasing or not only one plane, but also on the other planes, as they are all parallel and oriented in a configuration where the resolved shear stress is applicable and it is causing the dislocation to increase inside. So, let us try to understand the same thing in with a little bit more drawing, schematics.

So, let us say this is one plane and for the sake of simplicity or for the sake of relating it will say that this is a FCC system therefore, this is plane one of the 111 type of plane 1. This is also plane, this is plane 2, but on of another of the 111 type plane; plane 3 which is parallel to plane 1.

And, now, let us say that dislocation is moving; now it cross slips from plane 1 to plane 2. Now, any cross slips on to another plane then these two positions can be assumed or can be looked or looked at as if these are the two pinned points and therefore, if you allow the stress to act on this particular plane this dislocation will start to form a loop. So, you will have a loop forming over here like this and loop forming over here like this. And let us say at this particular point this plane again moves on to another plane 3 which happens to be plane one in this particular FCC system.

So, it will again move over here and here again these two points as you can see they will act as the pinning points. So, this is equivalent to our A B A prime B prime and you will have another dislocation loop like. So, in effect what you have now let us try to look at it from another from a little bit different configuration. So, let us say you have a cylinder, single crystal cylinder and there is one particular plane on to which is on with the resolved shear stress is lowest and therefore, the slip should get activated on the on to this and therefore, let us say the slip starts on to this particular plane.

But then, because it faces some resistance, perhaps there is a inclusion or a precipitate over there therefore, it may start to move on a parallel slip. So, this is coming. So, the light green one is the dislocation here it is moving on plane 1, then it moves on two plane 2 then again it starts to move on plane 3. Let us say it again faces some resistance it can again go back to some other parallel, and so on so forth.

So, now, primarily the dislocation is moving on the slip plane with the lowest resolved resolution lowest resolved shear stress however, because it faces some resistance in each of these it moves on to another plane and comes back to the parallel planes where that is resolved shear stress is lowest. And in the process what it what is happening is that not there is not only dislocation on one plane, but it is on this plane, this plane, this plane, this plane and this plane. So, from the outside it would looked like there are several dislocations which are acting here which is causing dislocation on this plane, this plane, this plane and this plane.

So, you see this is there was just one dislocation slip which was activated, but because of that now there are multiple slip planes. Of course, they are parallel that will be the case and in each of these the dislocation can become larger in size we just like the way I mentioned here these two points can become the pinning points and because of the forces that dislocation can keep expanding like this. And in effect what you will have, so first thing few dislocations can cross slip on several planes and total length may increase tremendously.

Simultaneously, there will be increase in the dislocation loop, and the same dislocation loop may exist on several planes of which will again lead to the overall increase in the length. And therefore, although here we are not showing effectively the increase in number, but the total length of the dislocation is still increasing. And if you look at it more closely what you would see is that since A and B are acting as a pining point. So, just like in the previous case there can be another set of dislocation around it which is completely independent of the original dislocation. So, both length and number can increase, and this is a more effective mechanism of dislocation multiplication.

Now, since we have talked about the Frank-Read source, I will talk about something similar that you can observe when you have precipitation strengthening.

So, let us talk about Precipitation Strengthening. Now, what happens in a precipitation strengthening? Let us say you have again let me draw. So, we are just looking at precipitation strengthening in what you can say aged condition. So, let us say the precipitates are very large in size and there is a dislocation which is coming along in this direction and let us say there is another dislocation another precipitate over here. So, this is a precipitate. So, these are precipitates and that this is a dislocation line which is moving over here.

Now, this dislocation line comes over here and then it finds that in the plane on which it was moving there is some obstruction it cannot keep on moving like this, because this section it cannot happen that this section does not move under rest of the section moves.

One thing possible is of course, if we are talking about edge dislocation then and its it was happening at higher temperature then what you may see is that a climb can take please. So, just in this local region you may have a climb of the dislocation and then eventually it can get back to its position, climb back. So, it is climb up and then it can climb back. So, climb up and climb down mechanism can allow dislocation to go past the precipitates. But then where at what temperature does do these climb take place? At high temperature. So, possible only at high temperature.

What is the possibility at room temperature? Let us see now. Coming back to the similar situation you have dislocation line like this and you have precipitate over here and the dislocation line is moving like this. What is the possibility? It will come very close to this and then if you keep applying the stress to the forces are acting normal to the line direction and you keep applying the stress which means the forces are acting on the dislocation in the normal direction and this one is also forces acting, but then this there is a opposite force acting over here and in a in effect this will cancel out. And so, this is stage 1. In stage 2 what you may see is let me use. So, like I said that the forces are acting normal and they are been cancelled over here in effect. Now, you can see the direction of the forces. What is the direction of the forces in between these two? There are causing it to become curve giving it a curvature. So, there will be a radius over here.

And the equation we have already derived it is similar to the Frank-Read source, only that we have the R is not the length of the dislocation, but our R is not the distance between the pinned location. Here this two precipitate average precipitate distance will become the 2 R distance. And now let me draw the final thing that will happen. So, something like this will happens. So, this is step 1 it encounters a precipitate, step 2 curvature starts to form, step 3 curvature reduces in size meaning though you have applied minimum amount stress and step 4 when these two curvature pinch off and this dislocation.

So, now you can again look at it if you there Berger vector is same, but the line direction is of opposite direction. So, what will happen? This will become one dislocation loop this will become another dislocation loop and this will become an independent line.

$$\tau_{min} = \frac{Gb}{l}$$

So, again what do we see here, that dislocation loop has been generated and it is now completely independent of the original dislocation? And that is original dislocation is able to pass through all though at a highest stress required. What is that highest stress required? If the average distance between these is L then you need to apply tau min equal to Gb by L.

So, this is the minimum stress that must be applied over and above the lattice resistance. So, this is additional stress required to pass obstacles. But this is also a strengthening mechanism because eventually what you may end up getting and this is something very frequently observed that if you have precipitates then there are dislocation loops around it, several of them in fact. And more the dislocation loops, more is the interaction between thus dislocations and it will apply more back stress on any new coming dislocation and therefore, a much larger stress would be required. So, not only the stress required to pass or form this loop, but also because they will be back stress form other existing dislocations. So, this is also a precipitation strengthening mechanism.

So, now that we have talked about two different mechanisms one was the strength hardening mechanism and here, we should you the how the nucleus dislocations are generated and in the process, we also showed you precipitation strengthening mechanism. The next topic that we will touch which is again related to the application of dislocation is the solid solution strengthening mechanism. So, we will come back to that topic in the next lecture.

Thank you.