Mechanical Behaviour of Materials-1
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Lecture – 41
Strain Hardening: Dislocation Multiplication, Intersection and Locks

Welcome back students, so, in the previous lecture we looked at strain hardening mechanism. And we looked at the relation given by Taylor. Taylor-hardening relation which says that shear strain is proportional to under root dislocation density. So, here the assumption was that as we increase the deformation and the strain dislocation density is increasing. So, how does the dislocation density increase when we increase the strain?

So, we will today look at that aspect, dislocation multiplication and related to it intersection and dislocation locks. So that is the purpose that is the objective of the lecture. So, let us look at dislocation multiplication.

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So, the dislocation multiplication mechanism which is one of the mechanisms which is very well known and widely accepted is the Frank-Reed Mechanism. So, what this mechanism is saying is that let us say you have a dislocation which is pinned at two points. So, in here you have a dislocation like this and these two points are pinned. And the rest of the dislocation must exist somewhere else.

So, this is only part of the dislocation and we are only looking at the region in between these two pinned points. Now, if you apply a stress such that the dislocation has to extend in length, therefore, it will look like this and if you keep applying the stress then the dislocation would loop like this and you keep applying the stress then eventually it forms something like this. And then you can see already that the dislocation length is increasing.

So, as we are applying more and more stress, leading to more and more strain the dislocation length is increasing but that is not all. You would see that it multiplies even further. So, at this point, what is happened? What will happen is that this is these are in opposite the budgers vector over here or the line vector here is in opposite direction. And therefore, there will be attractive force. And therefore, these two will merge and what we will get is something like this.

And if there is a grain then the this dislocation would move on and this the stress would keep acting on this part of the dislocation. And therefore, this will again form a loop and it will keep on forming a loop and there is a very nice animation which shows this particular mechanism and how it leads to pile-up. And this will clearly show you how you are when you are applying strain when you are applying the stresses, the strain is increasing and which, in turn leads to increase in the dislocation density.

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So, here you are looking at this. This is the these are the two pin points and this is one green this has been shown over here and you can see that these this forms a loop and then again you are now, since you are applying a further stress, you can see that it is again forming a loop. And this part remains over here, so, it acts like a source and over here it keeps on forming new and new loops. And if you look at this cross section, what you would see is a pile-up.

So, this is the grain boundary in this region and these are the dislocations which are piling up near the grain boundaries. And the distance is increasing and you would see that new and new dislocations are forming and it is it keeps pushing. So, the every new dislocation that forms you will need even higher and higher stress. This is what we said and is very evident from here.

So, this clearly shows or this animation clearly shows that what we had said earlier that with increase in the stress and when the strain increases dislocation density increases. And this animation was able to show that very beautifully. Now, this if, in a grain you may have even some more type of obstacles. And when you have a source like this, it would lead to even higher increase in dislocation density.

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So, here these are like precipitates and here you have somewhere here you have a source and as you are applying stress, these stress are for causing the dislocation to become loops. And the loops keep on going and it is forming loop around the precipitates also. And therefore, a new dislocation is formed around the loop and all the loops a new dislocation loop is forming all around all the dislocations.

And the original dislocation still keeps appearing over here. And it leads to even higher increase in the dislocation density and we know if the dislocation density increases then tau is equal to alpha Gb under root rho. So, higher the dislocation density higher will be the shear stress required for every new dislocation

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So, this mechanism clearly this is clearly a very well established mechanism for dislocation multiplication. And so, is that higher stresses lead to higher dislocation density. And Taylor hardening has already established that strengthening with increasing dislocation density. And in these two we have seen clearly dislocation pile-up leads to strengthening. So, these two animations have further corroborated of what we said that the dislocation pile-up leads to strengthening.

Now that we are talking about dislocation multiplication, it is proper to also state that there are other mechanisms of dislocation multiplication. Although they are not as frequent or as probable, particularly in from the point of view of material processing.

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So, what are these so, for example, due to accident growth so, other mechanisms for so, it may be, for example, when you are doing crystal growth at that time there is because there may be stacking sequence, fault and because of that those general because of those faults there may be dislocation that may get generated. So, due to accidents it is as it is called due to accidents in crystal growth.

Now, dislocations can also be nucleated by homogeneous nucleation. Just like the nucleation of precipitates there is also possibility of homogeneous nucleation of dislocation. But the stresses required are again very high so, it is not very probable. And there may be stress concentrators in the crystal and that can lead to dislocation generation, like the mechanism which was proposed by patrel near the pile-up of the dislocations.

That there is a stress concentration which will lead to source generation in the neighboring grain. So that kind of stress concentrators can also can aid in dislocation multiplication. And if we look at the dislocation multiplication then if you from one of the books by Leeter, you would see that by just deforming a material by few percent. So, if you are applying a strain of few percent, the length of dislocations become as high as 50,000 kilometer in each cubic centimeter.

So, just to put it in perspective, metal which has been plastically deformed a few percent not even severely deformed in strain contains approximately 50,000 kilometer or more dislocation line in each cubic centimeter. So that is the effect of dislocation multiplication when you are doing the deformation. So, if you are, if you have done just a few percent, straining of the metal then dislocation length that would be inside the material would be of the order of 50,000 kilometer.

And you can imagine the effect that it will have on this location density and hence the strength of the material. So, this is dislocation multiplication and what we observe here is that one way or the other, the dislocation must get pinned to give this kind of mechanism free Frank-Read Mechanism. So, this also leads gives us the question of why at all would there be a pinning of the dislocation? So, we can look at some more mechanisms which lead to this kind of pinning.
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So, in this respect, let us first let us look at dislocation intersection. Now, dislocation intersection in itself is a mechanism which would lead to strengthening of the material. Because you are increasing the you are causing a step in the dislocations, as you would see when we look at in more detail. And because that is extra step is created which requires extra energy therefore, overall higher stresses, are required.

Now, at the same time, some of these steps that are formed are sessile in nature, meaning they do not move and if they do not move, it means that the rest of the dislocation will have to move but these will not they will remain pinned at that place. And hence you can have that kind of frank-reed source, where some part of the dislocation is pinned and the rest of it is looping around and giving rise to higher and higher length of dislocation.

So, let us try to get an understanding of dislocation intersection, so, two straight dislocations can intersect and when they intersect, they will leave behind jogs and kinks. Now, these extra segments in a dislocation line, cost energy and hence require work done by external force which is where we will would mean that we need extra stresses to be applied or in other words there is hardening of the material. We will also look at what this extra energy cost, means implies hardening of the material.

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Now, the simple rule when an intersection is formed is that the size of the step is equal to the magnitude of the budgers vector of the other dislocation. So, this is the rule based on which we will be able to find out the size of the step and the budgers vector. So, budgers vector, of course, budgers vector will never change. It will always be same for the as for the original dislocation and the size of the step would be equal to the magnitude of the budgers vector of the other distribution.

Now, in order to explain this, we will take examples of 4 different types of intersection. So, first we will look at edge dislocation where the budgers vector are in perpendicular direction. So, let us say we have one plane like this and the other plane like this. Now, over here we have a dislocation line like this and for the sake of for and for this one we are assuming that both of them have edge dislocation.

So, this is the edge dislocation over here and this is the edge dislocation over here and let us say that this one is moving in this direction. And over here the budgers vector for this one is like this, so, this is budgers vector 1, d 1 e and this is d 2 e. So, now this is moving so, at some point it will intersect here and then it will keep on moving. So, how does it look like? That is the question.

So, first again let us draw the two planes and over here so, I have made a mistake this will not be any more like this. This will actually be now two planes and I will explain in a moment. So, this is intersecting or attaching to the original plane over here and this one over here. Now, this particular dislocation is this particular dislocation here, burgers vector like this which means the step formed on this will have a magnitude.

Will cause a step with a magnitude of burgers vector b1 on this direction which means this will be the step that will be formed over here and it will look like this. So, the intersection results in step whose size is equal to the magnitude of the budgers vector of the other dislocation. And so that size is equal to b 1. So, this size is b 1 and also it is in the direction of the original budgers vector.

So, the other thing that I forgot to mention here and in the direction of other budgers vector, on the other hand for this one the step will be created which will be equal to the burgers vector. In this direction and also equal to the magnitude of the this budgers vector. And in effect that would mean that we will have one step, so, it has moved just one step in this direction which is which means that nothing has happened to this particular dislocation.

On the other hand, this one has caused a step over here which is jog in nature. You can see jog, meaning it has left the original plane and it has therefore, there are two different planes. And the burgers vector remains like this over here. So, this is the line vector and this is the budgers vector therefore, this is still edge dislocation. So, this is s 2 and there is s 1 just theoretically speaking, there is not much actually happening for s 1.

So, if we want, we can write it like this s 1 magnitude is equal to so, we are calling the step s 1 which will be equal to the budgers vector b 2. And the b 2 is over here in this direction which is in the line direction for this and therefore, it implies no change for this for dislocation D1.

On the other hand, for s 2, the step size is equal to budgers vector 1 and also the step s 2 is parallel to b 1 and which is what we see here which is jog or edge. It is a jog type dislocation and it has edge character. Now, if you look at this dislocation, it would want to move in this direction and this is the glide plane and for this dislocation this is the glide plane. So, overall, when this dislocation wants to move, it can easily move along with the step size step s 2.

Similarly, for s there is nothing like s 1, so, we need not to worry about it. So, in this case we can say that step that is formed on dislocation 2 aids in glide. This will become clear when we look at case 3 and case 4, where we have screw dislocations and where you would see that the steps that are formed are do not aid in dislocation. So, this is case 1 where we have two edge dislocations but their budgers vector are perpendicular.

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Now, let us look at another case. Case 2, again this time we are looking at two edge dislocations but, as you would see, their budgers vector are parallel. So, yes, it is possible to have two parallel edge dislocations and they are on two different planes. So, to begin with, let me draw the planes. So, I have already drawn the two the before and after planes. And now, I will draw the dislocations on them.

So, this is my first dislocation and I will term it b 1 e edge dislocation and this one is b 2 e. And this one is moving in this direction. So, eventually it will intersect and the step that will be formed on b 2 will be equal to the budgers vector. So, I can draw on the direction. So, this is the budgers vector. So, both the budgers vector are parallel. So, it will form a step which will be in this direction and of magnitude equal to b 1.

And in this one step will be formed in this direction which will again be of the magnitude b 2. So, how does it look like after it has intersected? So, for that let me draw a dashed line over here. And as mentioned this will have a step which is this is the step that will be formed on be to b 2 e and there will also be a step formed in b 1 e. Again, it will be in this direction. So, this is s 2 and this is s 1.

And s 2 is of course, the magnitude is equal to b 1 and s 2 is parallel to b 1. On the other hand, s 1 is magnitude is equal to b 2 and s 1 is parallel to b 1 and as you can see, both of them are kinks. So, it is in the same plane, so, it both of them are kinks, s 1 and s 2 are kinks. And as you can also see that this is the budgers vector so, it is along the dislocation line.

So, if both of them are screw character, so, both of them are screw character. And this dislocation would want to move in this direction and the kings would move in this direction. So, overall, it can move and help aid in the movement of the dislocation along its original glide plane. Therefore, both aid in glide, so, in this case also, there is no problem with the steps that are formed.

They do not cause any hindrance to this movement of the original dislocations. Now, we will add a little bit of complexity. We will now have a screw dislocation also into the mix of things.
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So, case 3, we have edge and a screw dislocation. So, here it is a little bit difficult to or I should not say difficult but here I will have to make certain assumptions because screw dislocations do not have a defined plane as per say. So, we will assume that there is a certain plane and accordingly we will define whether what we are forming, what we are getting is the steps are kink or jogs.

So, let us say that this is a plane which has screw dislocation over here. So, let me draw it like this and let us say this is a edge dislocation like this, so, this has the budgers vector, of course like this. So, I will name this as 1 b 1 e and it must have its budgers vector along the line direction so, it is b 2 s. And I will assume that this one is moving, so, this one has a defined plane.

I do not have need to define it for this one I will assume that this is the plane on which it moves. So, what happens to this after the intersection? And again, let me draw, so, here the budgers vector is along this direction, so, the step would also be formed along this direction and the budgers vector for this one is along this direction. So, the steps must be formed in this along this direction, so, how would it look like?

Let us see, so, this is b 2 s and thus edge dislocation which was like this. But now because of the budgers vector for this one, it has to move out of the plane. And therefore, now it will part of it is in a different plane and this is its budgers vector b 1 e. So, this is the jog, now, you can see that this is the line dislocation line and the budgers factor is like this. Therefore, this is a gene character now over here.

This is the dislocation line and this is the this is the dislocation line and the magnitude of course, we will look at in just a moment and this is the burgess vector. So, this is also edge in character. And this is step one this is step two. So, s 1 with just for the sake of completeness, we will write s 1 is equal to budgers vector b 2, s 1 is parallel to b 2, s 2 is equal to b 1 magnitude-wise and s 2 is parallel to b 1.

And in this case, what do we see? Is that this particular dislocation that we see over this one this step? This has to this dislocation wants to move in this glide plane and for this is the glide plane, so, it can move along with the rest of the dislocation and hence it can aid in glide.

However, for this one, what we see is that this is the dislocation and this is the step and for this was the original plane on which it wanted to move.

But for this one this overall, let me draw it over here. So, this highlighted plane is the glide plane for this step s 2 but that is not the plane on to which the dislocation 2 screw dislocation wants to move. And therefore, this will not aid in glide and this will become a sessile this step will become sessile. So, this is what we had mentioned earlier so, this is sessile. Does not aid in glide. On the other hand, this is glissile, like all others.

So, I have not mentioned explicitly but when I say that it is it aids in movement, it means it is glissile, so that is case 3.

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Now, there is still another case that we can look at and which will be even more interesting. It would be when we have two screw dislocations moving with each other. So, we will have two screw dislocations. And let us draw it like this, so one is over here with budgers vector like this and the other one is like this. Now, let us say that this one is moving along this direction, so, this has a step vector this has a budgers vector like this.

So, it will form a step along this direction and for this one there it will be a step along this direction. So, after intersection, this is how it should look like, this is the step and clearly part of it was moving on this plane and part of it has moved to the bottom plane and therefore, this is a jog. On the other hand, this one we will assume that this is the glide plane for this, so and for this one this was the glide plane.

So, this has clearly moved out of the glide plane. On the other hand, for this one, so, this still remains in its glide plane and therefore, it is a kink. So, this is s 1, this is s 2, s 1 magnitude wise, it is equal to b 2 and s 1 is parallel to b 2 and it is a jog. And s 2 magnitude wise it is equal to b 1, s 2 is parallel to b 1 and it is in the same plane so, it is a kink. And here, as you look as you can see, there is a line dislocation and this is the budgers vector.

So, this is jaw and therefore, and it is also a edge dislocation, edge jog. And over here the line dislocate, this is the budgers vector and this is the line vector, so, it will also be edge. So, in this case, both of them for a screw dislocation whenever there will be step, it will always be edge dislocation. And like I said that this is in the same plane, so, this can move and hence it can allow this dislocation to move.

Therefore, it aids in movement but this one is a sign. So, now I missed writing down the character of the steps over here, so, this is so, over here if you look at this one, this is a jog and if you look at this one, this is also a jog. So and this one is also an edge dislocation. So, let us complete this that this is also a jog and it is the edge dislocation. Here we have written, both of them are kinks and they also are screw character and here we have written jog and edge character, so, we have summarized all these.

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And we can actually make a table to put this all at one place where we will be able to identify whether it is a jog or a kink, whether it is screw dislocation or edge dislocation and whether it is glissile or sessile. So, in case one, the when I say dislocation one, it means the step on the dislocation one it is, we have seen it is jog and it is of edge character. For dislocation 2, we saw that it is not applicable because the step was formed along the line direction which does not mean anything.

For case 2, the step was kink and it had screw corrector. In fact, both of them had screw character and they were kink. For case 3, we saw that it was a jog for dislocation 1 and it has edge character and we saw that for dislocation two which was a screw dislocation. So, for the screw dislocation also, we saw it is jog and edge. For case 4, where we had both the screw dislocations we saw that for the first one, it is a jog and edge.

And for the second is screw dislocation it is kink and edge. Here it must be specified that we have made certain assumptions about the glide plate. So, look like glide planes were assumed and the only steps which we saw were not glissile. Are this one and this one all the others where I have not written s, s means the sessile, meaning does not aid in movement of the original dislocation.

So, all other steps are due aid in measurement of dislocation. So, what we see again here is that these can form or can pin the dislocations and when you pin this dislocation then again you can have that when you keep applying the stress, the dislocation length will increase and eventually it will form a loop. And loop around and extra length of dislocation will be formed and it will at one point break away.

And then again original dislocation will stay there and if you keep applying and there this is how the dislocation density keeps increasing.

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$$E_{step} = Gb^3$$

And the other part that we said that whenever there is a step form there is a cost, energy cost. So, what do we mean by that? So, let us look at that part also. So, when so, this is something we have already mentioned and based on this, what we can write is that if the we know that energy per unit length of dislocation is given by alpha Gb square. But if we want to know the total length, if we know the total length we can put it there which is in this case, is equal to b.

And therefore, it becomes alpha Gb cube. So, energy of step is equal to Gb cube. So, this is the energy cost of adding a step. So, whenever there will be dislocation intersection, this much additional energy needs to be provided which means next time you will have to apply higher stress for dislocations to move. So, overall There are certain things that we can summarize regarding the intersection of the dislocations.

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So, let us put those in words over here. So, whenever edge dislocation and edge dislocation intersect it gives rise to glissile step that can aid in motion. When you have a step in the screw dislocation which is jog in character then it is sessile and also it is jog means it will be edge type. On the other hand, if the step is kink then it would mean that it is screw dislocation and it would also mean that even the kink would be edge character and it will be glissile in nature.

Edge dislocation we have said that are always glissile in nature but about the nature of the steps it can be either jog which will has edge character or it can be kink which can have screw character. So, screw dislocations always give well for edge dislocation. it can be both edge or screw depending on whether you are forming jog or kink. So, in this lecture we have looked at the step formation, intersection of the dislocation which leads to step formation.

And some of these steps can be sessile which means they which can pin the dislocation. And hence those pin part can as we have seen earlier can lead to frank-reed sources. There can be other nature of the pinning of dislocations also but this is one way that the dislocations can get pinned. And there is still another way of pinning of the dislocation which is the point where we move on next and that is called dislocation locks.

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So, what happens is that in dislocation locks, certain dislocations get or intersect, not intersect but interact and result in a dislocation which is on a plane where it cannot move? And therefore, it becomes long it can either move away, nor it will give way for other dislocations. And therefore, all the dislocations would then pile-up over there and it is in this process that we see a dislocation lock.

So, in this context, let us look at one particular type of dislocation lock which is called as Lomer-Collrell Locks which is observed in FCC material. So, to understand this first list up all the dislocation slip planes for 1 1 1: it is all the dislocation budgers vector for 1 1 1 slip plane and 1 1 bar 1. So, we know there are 4 different slip planes in FCC. So, out of these four, let us first list up take up only two first.

And the same kink can be extended to the other pair of this other pair of slip planes. So, here we are taking 1 1 1 slip plane and 1 1 bar 1 slip plane. So, let us called b 1 equal to a by 2, 1 bar 1 0 and of course the negative would also be the purchase vector for the for this particular plane. If you remember the Thompson's tetrahedron, it has three directions, so, there must be three budgers vector and the negatives.

And you can check that the dot product of this would give you 0. So, these are the budgers vector for 1 1 1 and these are the budgers vector for 1 1 bar 1 0 1. Again, you can check that the dot product of this and this would be 0 as you would expect. Now, let us say that two of the budgers vector two of the dislocations with these burgers vector intersect. So, there is no meaning of dislocation intersection within a plane.

Let us say that there are dislocations which intersect one dislocation from here and another from here.

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So, let us take a combination of b 1 which can be positive or negative and b 5 per b 6. So, we are taking this one and this one. So, both the dislocations are moving in their own plane but they may intersect or they will may always come up a line which will be common to both and that is where we are looking at. So, b 1 + b 6 what you would see comes out to a by 2, 1 0 1 which is nothing but b 5 because b 1 is same as b 4.

So, some of these combinations would result in the budger vector another budger vector of the same slips plane. Similarly, if you look at b 1 + –b 5 you would get a by 2, 0 bar 1, bar1 equal to – b 6. Now, let us look at b1 + b 5 and what you will get is a by 2 2 bar 1, 1. And another one is b 1 + –b 6 and this would be a by 2 1 bar 2 bar 1. So, this is something you can try on your own and this one does not mean anything these two. If you look energetically, it is not energetically favourable.

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And there is a cube I have drawn here I will use this a little later, so, let me just pull it down for the time being so, now we, what we see is that combination of b 1 with b 5 b 6 is not leading anywhere. In fact, if you do the same thing with b 4 + b 2 b 3, it will not lead to nothing interesting. But now, let us move on to another combination which is b 2 and b 5, so, b 2 + b 5 or b 6.

So, this gives us a by 2, 0 0 2, b 2 + –b 5 these are all possibilities, a by 2 bar 2 0 0, b 2 + b 6 and b 2 + –b 6. Now, let us look at it energetically. If you compare it, I am not going through the all over all action. But if you compare energetically what we mean is doing the b square, comparing b square plus b square and the b square of this one. What you would see is that this is equal. So, this is equal this is equal.

This is not energetically favorable but this one is energetically favourable. Meaning if two dislocations, with one with budgers vector b 2 gliding on plane 1 1 1 and another dislocation with budgers vector – b 6 gliding on plane 1 1 bar 1. They happen to intersect at some place interact or react at some place, I should the better and the most suitable what would be react because they are not combining the two budgers that are combining to form this budgers vector.

Then this budgers vector is actually energetically favourable. So, this dislocation would indeed be formed. So, this is something that we need to look further. What does it mean? What will be the glide plane of this particular dislocation? What would be the would it be on its native plane, meaning one of the 1 1 1 plane and so on? So, let us analyze this resultant dislocation.

First of all, let us find out let us try to visualize this dislocation. So, it is on two different plane, 1 1 1 and 1 1 bar 1.

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So, let us see this is one of the planes and this is another one of the planes and over here you have some dislocation with line vector u 1 and the budgers vector is v 2. And over here you have a dislocation with line vector u 2 and the budgers vector is b 5. And somewhere over here these two combine and the line on which they will combine is this one. So, we can define or understand what is the line vector of the resultant dislocation by finding the intersection of these two planes?

What are these planes? Again, these were 1 1 1 and 1 1 bar 1. So, if we take the cross product of these two, we will be able to find the line vector which is the u r. So, u r is equal to 1 1 1 cross 1 1 bar 1. And I have taken it as a vector here, so, this comes out to bar 1 1 0. So, this is the line vector of the dislocation and this is the budgers vector. So, this is badges vector and let me write down the budgers vector again here and this is the line vector.

So, if these are the line vector and budgers vector, what is the plane on which it is lying? Plane on which it is lying is equal to b r cross u r and you would see that this will happen to be 0 0 1. But is it a glide plane? And the answer is no, so, it is not a glide plane. So, let me draw it so, it would look something like this, so, this would be the glide plane over here and the resultant virtual budgers vector would be probably somewhere over here.

So, this is the line vector the budgers vector and this is the glide plane which is one 0 0 1 in this particular case. And the question is whether is it a glide plane in FCC? And the answer is no. Which what does that mean? It would mean that this dislocation would not move, dislocation is glissile. Now, with this information, go back and look at this. This dislocation was very nicely moving on to this plane.

This dislocation was also very nicely moving on to this plane but somehow they happen to be here at the same time and therefore, they interacted and actually the more appropriate term is reacted resulting in this budgers vector b r, resulting in a line vector u r. And therefore, now it is locked into this glide plane which is not a native glide plane and therefore, it cannot move. Now, any other dislocation coming from behind will now not be able to move pass this.

And therefore, it will act like a lock. This cannot move and it will keep. It will remain fixed over here and it will also not allow any other dislocation from this direction or that direction to move further. And therefore, it will lead to you can say again some type of pinning of the dislocations and this again leads to strengthening of the material hardening of the material.

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Now, this is not just one particular combination which will result in a lock for a given set, you can have actually two sets of budgers vector combination which can result in the locks. And it is in this respect that let us look at this cube that I was showing you earlier. So, what this cube is showing you is basically the 1 1 1 planes. So, let us draw it again here, so, this is 1 1 1 plane, as you can see.

1 1 1 family of planes and to be precise, this one would become 1 1 1 and this one would become 1 1 bar 1. Now, here these would be your burgers vector so, these are the edges, this is the Thompson's tetrahedron effect. So, these are the one budgers vector on the second budgers, with a third budgers vector for 1 1 1 plane and this is 1 1 bar 1 plane and this is one burgers vector for 1 1 bar 1, there is another versus vector, this is another basis vector.

Now, let us look at this in a much more closer way. Now, let us say that there is a dislocation which has a budgers vector which is moving on 1 1 1 and has a dislocation budgers vector like this. And at the same time there is another dislocation on 1 1 bar 1 which has a budgers vector like this. Now, what will be the resultant vector for this one? The resultant vector would be this one.

And therefore, this is equivalent to saying this is the resultant budgers vector. Now, if this is the resultant budgers vector and which is the line vector? Because this is this has to lie on the common line. Therefore, this must be the line vector. So, if this is the budgers vector and this is the line vector then this must be the glide plane for that particular dislocation. As you can see, this is a 0 0 1 type of plane and therefore, it is not glissile.

And the dislocation that has been formed by this or lock that has been formed by this would be sessile, it would be a lock. And it is here that when you look at this from this point of view, you can clearly see that the same combination can also be obtained by a dislocation here and a dislocation over here. So, these two would combine to give you the same thing over here and it will be the same final resultant budgers vector.

And the same final resultant plane and also the same this final resultant line vector. So, both these sets would give you the same dislocation lock. Now, this is only for 1 1 1 and 1 1 bar 1. You can go ahead and do the maths for other set of planes, 1 1 1 and the other one, whatever the family of this. So, there is, there are 4 families, you can take pairs of any of these and you will still get the same thing.

You will be able to get a lock. So, this lock is not very uncommon it can be commonly found in the FCC type of system. So, this again gives you an idea that when the dislocations move, when the stresses are being applied, dislocations move and they will intersect and interact and react. And this will lead to dislocation multiplication which is what leads to the hardening of the material.

And also the back stresses when there are locks formed like this or when there is a pile-up, all these lead to strain hardening of the material.

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So, if you look at the stress strain curve of a material this should and on this axis let us say we have percentage cold work and this is stress this is strain. So, it would look something like this and if you increase the amount of cold work then the stress the yield strength and the tensile strength increases. But at the same time ductility decreases and at some point it will become very very little.

So, this is how the stress the strength would increase. So, if you are able to mark the yield strength, probably the yield strength is increasing like this and at the same time ductility is and this is what with increasing cold work, straining an internal resistance. So, there are now more dislocations, more backup stresses, so, internal resistance increases and hence applied stress needs to be increased.

And this is what we term as strengthening strain hardening. So, with that we will close this lecture and in the next lecture we will summarize all the strengthening mechanism that we have looked at. Thank you.