Project of Materials (Nature and Properties of Materials: III)
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Lecture 30
Strain Hardening

So, welcome again to the new lecture of course Properties of Materials. So, let us just briefly recap what we did in the last lecture, before we move on to the contents of this lecture.

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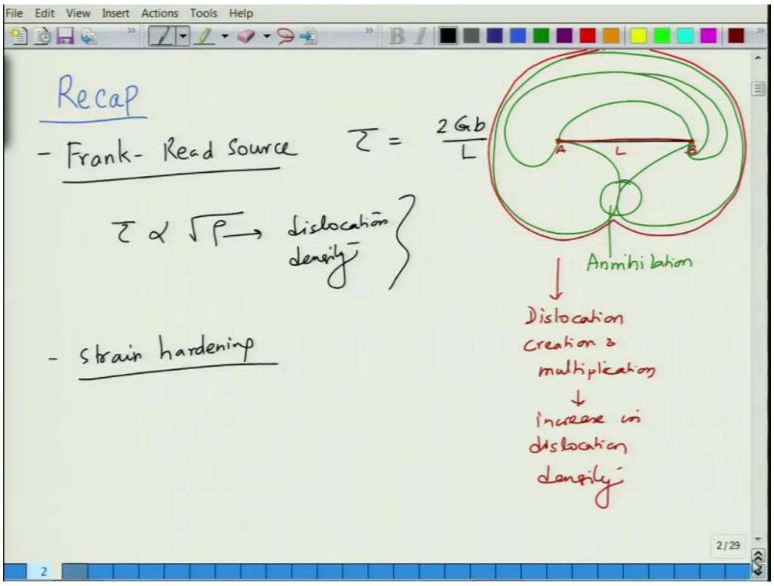

So, in the last lecture we looked at the stress that is required to operate a Frank Read source and we saw that this stress is equal to 2 Gb divided by L where G is the share modulus, b is the Burgers vector and L is the length between the two pinning sites.

So, if you have this is the dislocation, this is L, this is points A and B and when you move the dislocation it goes in this fashion, goes in this fashion. Then finally it comes like this full circle and this where annihilation. So, it leaves basically a loop like and this segment goes back to its own state.

So, this leads to basically you can say dislocation creation and you can say multiplication. So, basically increase in dislocation density and we also saw that this stress is proportional to square root of rho, which is rho is dislocation density. So, more the dislocations in the materials are, more is the strength and this mode of strength is called as Strain Hardening.

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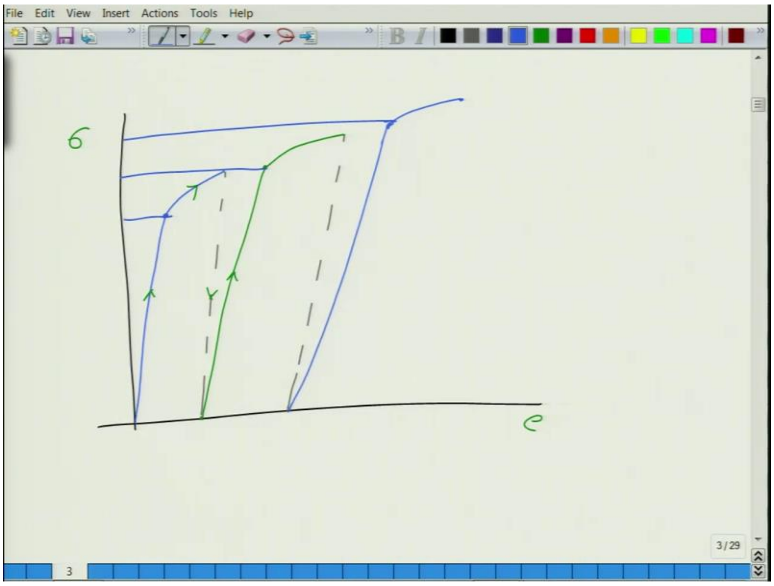

So, basically what happens is that as you deform the material more and more. So, this is let us say the deformation, let us say you go up to this point then you come back to this point, again you start the deformation you will go back to this point then you again start and let us say if you want to come back to this point again.

So, to make the, so this is sigma this is e, so this is first pass you come back again start then it comes back, then let us say you come back again, recover the elastic strain maintain the, then again you increase the, suppose I am not considering the strain rate kind of thing here. But then again, so this is how the yield strength keeps increasing.

So, this is the end strain to begin with, so it is gone from here to here to here. But what happens is that in reality, as you keep deforming the materials, material will also become stronger but they also become less ductile.

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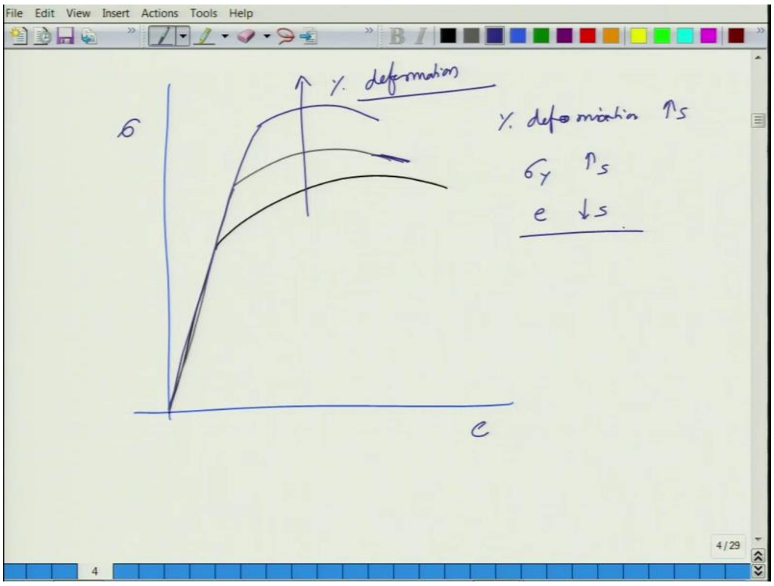

So, if your first pass shows a behaviour like. So, let us say the first deformation is like this, you do not deform it, you do not let us say break it next one will lead to yield stress which is like this and the third one as you make stronger it will lead to like this. So, basically you can say the materials become stronger. So, this is sigma this is e and this is increasing percentage deformation.

So, as you increase the percentage deformation with percentage deformation. So, as percentage deformation increases sigma y increases but e decreases. The overall strain decreases the plastic strain decreases. So, that is something which you have to keep in mind. So, now let us see, so we will come back to this maybe later on.

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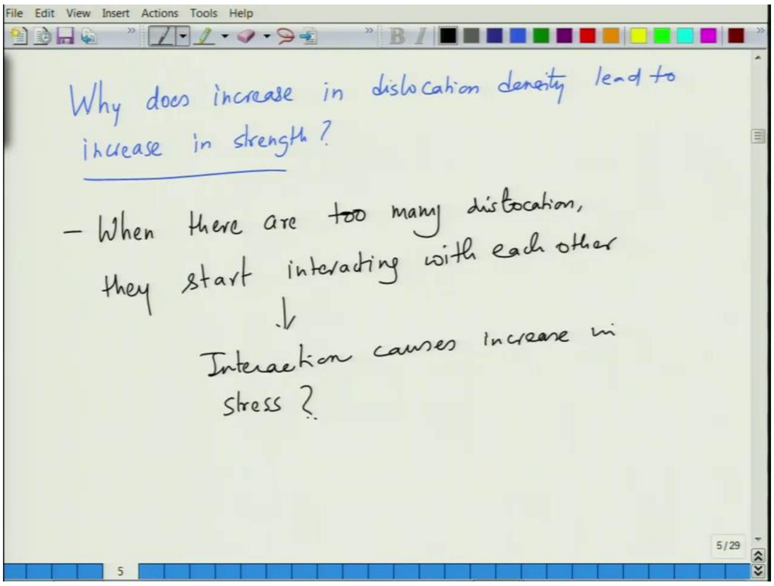

But what is the reason that why is the question was, why does increase in dislocation density lead to increase in strength and this we said is counterintuitive because you know we said that dislocations are weaknesses they give rise to lower stress. So, why is that when they increase in number they give rise to increase in strength.

So, basically what happens is essentially dislocations when there are too many dislocations they start interacting with each other and this interaction causes increase in stress. So, what is this interaction type?

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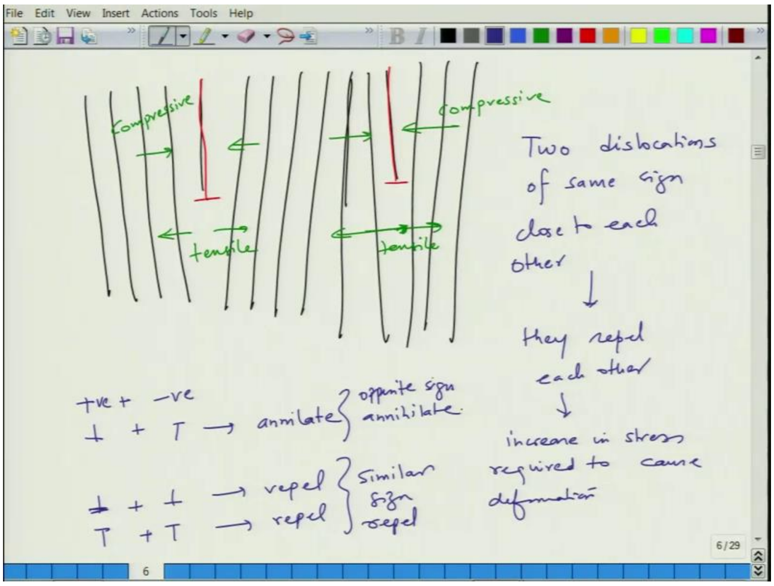

So, let us say the first interaction could be, let us say you have this a dislocation like this and you have another dislocations somewhere here which is, which is let us say. So, this is first edge dislocation this is another edge dislocation. So, these are both two edge dislocation one edge and two edge.

If you look at the stress field around this dislocation, this is compressive but this is also compressive this is tensile but this is also tensile. So, the reason, so when you have two edge dislocations. So, if you have two dislocations of same sign close to each other they repel each other because their stress fields are similar, so you have compressive-compressive, tensile-tensile when you want to put them together they do not go close to each other because they start repelling each other because of similar stress fields as a result this leads to increase in stress require to cause deformation.

So, now that you have so many, so many dislocations in a crystal, the dislocation are bound to come close to each other of course you will have instances when you will have positive and negative. So, if you have positive plus negative, so that is this and that they will annihilate each other. So, they will make the crystal perfect and if you have this plus this they will repel or if you have this plus this they will repel. So, basically you can say similar signs repel and opposite signs annihilate it. So, this leads to increase in the stress that is required to cause a dislocation.

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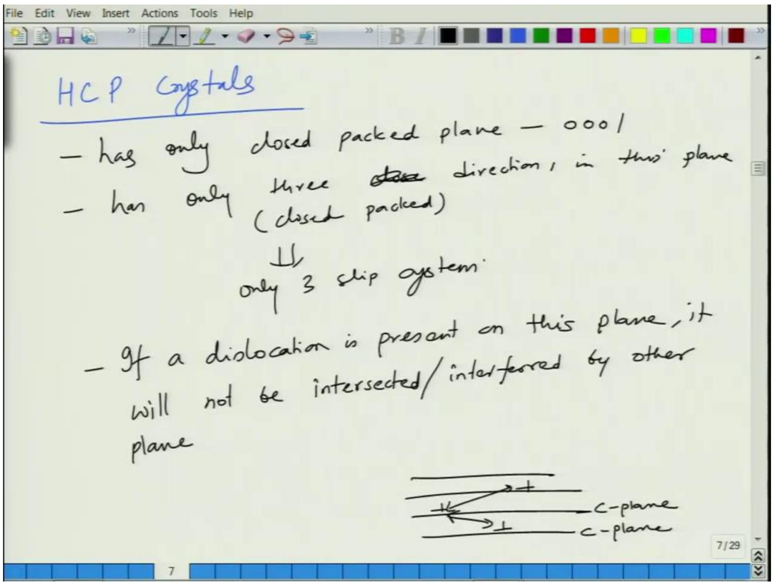

But there are other methods as well, so imagine for example if you take HCP crystals the problem with HCP crystal is, if you look HCP has only one closed packed plane that is 0001 and it has only three direction in this plane, in this plane which are closed packed. So, which gives rise to only three closed packed slip system.

There are other slip systems as well the planes which are not necessary closed pack but there are closed pack direction line those planes. But there are, there is only one slip plane, so if you have only one slip plane the dislocation will not, so if a dislocation is there, so if a dislocation is present on this plane it will not be intersected or interfered by other planes because there is no, because 0001 planes are basically parallel planes. So, this is HCP structure, so this is C plane basically.

The C planes are all parallel to each other, so as a result if you have a dislocation here, if you have a dislocation here, if you have a dislocation here, they will not intersect each other they will be, so there may be instances that they have to be far enough if they are similar signs and because there stress fields will overlap but they will not intersect into the part of each other.

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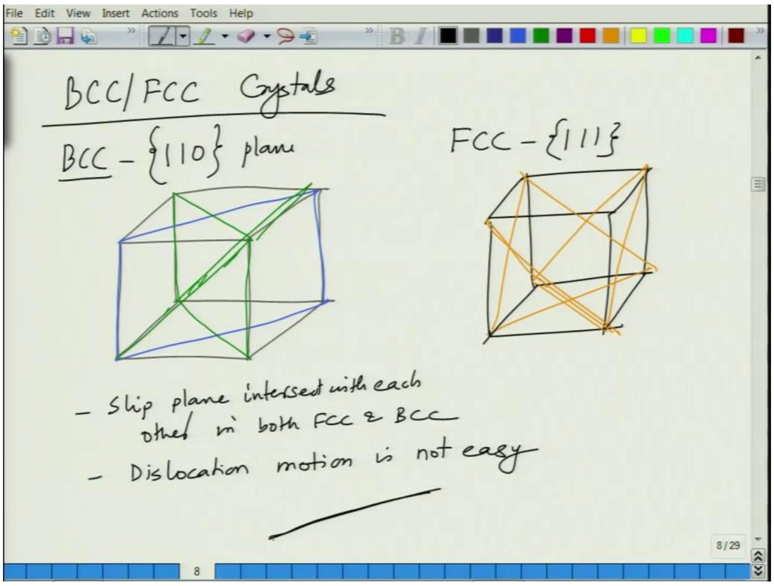

However, if you take example of BCC and FCC crystals. In BCC you have a slip plane which is 1 1 0 type slip plane, 1 1 0 plane. So, we can write this as this fashion. In FCC we have a slip plane of 1 1 1 type. Now if you look at BCC basically, you have there is a possibility you may have this as a slip plane.

So, this is one slip plane you may have another slip plane which is this slip plane you may have another slip plane which is, which is you may have another slip plane which is basically you can say this is the slip plane. So, there are multiple slip planes. So, basically some of these slip planes intersect with each other. So, basically you can say slip planes intersect with each other.

Same here in this case also in FCC if you draw the FCC unit cell you may have 1 1 1 planes intersecting. So, you have this is 1 1 1 plane you may have another 1 1 1 plane which is like this, you may have another 1 1 1 plane which is like this. So, the 1 1 1 may intersect. So, slip planes will intersect with each other in both FCC as well as in BCC.

When they intersect each other the dislocation motion is not easy because when it moves one plane let us say its moving one plane. So, so there is a plane here, so let me just go to the next one.

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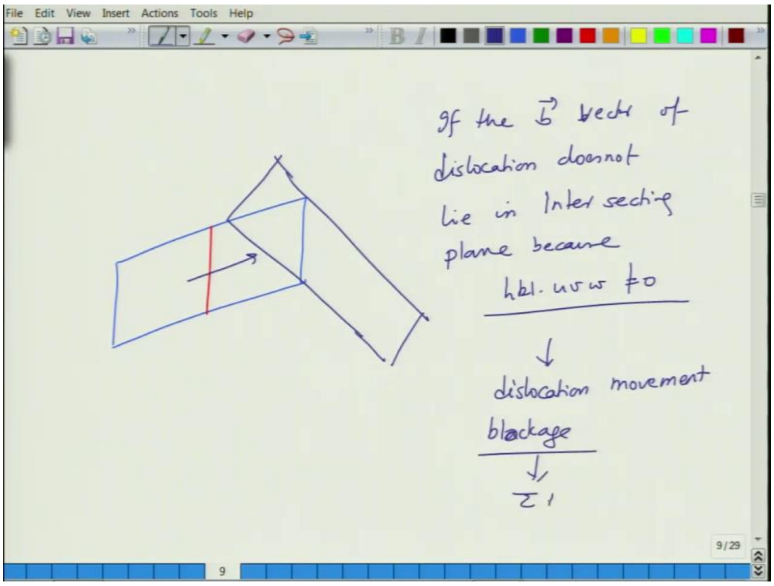

So, let us say if it moves in one plane. So, this is the dislocation line which is moving into it intersect another plane which is let us say this is another plane, so it intersect another plane now the moment it encounters another plane, if the Burgers vector, if the Burgers vector of dislocation does not lie in intersecting plane there is a possibility it might move, but if it moves it may not move, it may not be able to move in that plane.

Intersecting plane because of hkl dot uvw may not be equal to 0. So, that Burgers vector may not lie in that plane, if that happens, because you know dislocation is nothing but bunch of atoms. So, bunch of atoms which is basically faulty region, the faulty region may move from one plane to another.

It may happen that Burgers vector does not lie. If the Burgers vector does not lie, it will not move. So, this will lead to dislocation movement blockage. If that is the case you will have to increase the stress required to move it to another plane where it finds easy to move. There is a possibility you can also form what we call as sessile dislocation.

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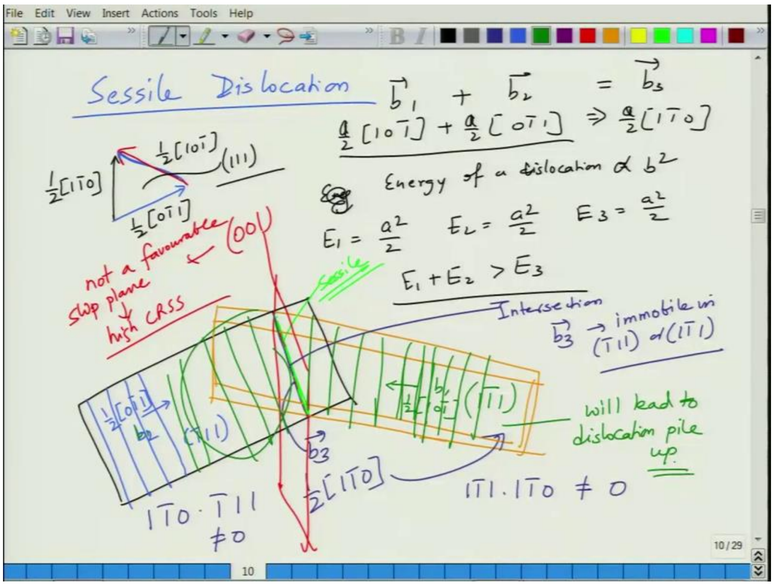

Sessile dislocation is basically a dislocation which does not move which is essentially unable to move. So, let us say you have, let us say we have these three vectors there three burgers vector. So, one is red one, one is a black one and blue one. So, let us say this is, this one is half 1 bar 1 0 this one is half 1 0 bar 1 and this one is half 0 bar 1 1. They all lie on one plane that is 1 1 1 plane. So, the plane is 1 1 1 and these are the Burgers vector.

Now it is possible that two of these may give rise to another one. So, if you put them together half 1 0 bar 1 plus half 0 bar 1 1 they can give rise to you can write them as half of 1 bar 1 0. So, if that happens then you form a new dislocation and the energy of a dislocation is given as is proportional to B square. So, basically its half Gb square, so is proportional to Gb, b square.

So, essentially if you look at the energy the E1. So, basically E1 is you can say if this is a by 2 a is the lattice parameter let us say. So, this will become a square divided by 2, E2 will become a square divided by 2 and E3 will become a square divide by 2. So, if you look at the energetics wise then E1 plus E2 is greater than E3.

So, which means the reaction is favourable, the two dislocation of these Burgers factors. So, basically this is B1 plus B2 giving rise to B3. So, basically what we are saying is that when two burgers vectors react with each other sought of a chemical reaction like reaction, when two Burgers vectors or you can say two dislocations meet with each other, they give rise to another dislocation with a Burgers vector which is different which is not the same.

So, let us see what does it mean? So, we may have first plane let us say we defined one plane which is this plane. So, in this plane we had a dislocation which was let us say half let us say 0 bar 1 1 and let us say this plane was bar 1 1 1 and if you take the dot product they make 0. So, which means this this was earlier moving in a plane which is bar 1 1 1 plane.

Let us say we had another plane intersecting plane this another intersecting plane was something like this and in this we had a dislocation which was, so this was b1 and in this case b2 and then we had b1 this b1 was half 1 0 bar 1 and let us say this plane was 1 bar 1 1. So, the dot product is again equal to 0 when they meet each other at the intersection point, so this is the let us say, let me just broaden this a little bit. So, this is the plane let us say.

At the intersection point this is let us say intersection this is the intersection, at the intersection they move and they create this be b3 which is half 1 bar 1 0 and this half 1 bar 1 0 does not lie in this plane because 1 bar 1 1 dot 1 bar 1 0 is not equal to 0. Similarly 1 bar 1 0 dot bar 1 1 is not equal to 0. So, which means the third dislocation which has been formed by these two dislocations does not have its Burgers vector lying in any of the original slip planes.

So, which means this becomes immobile. So, what is this dislocation, so this b3 basically immobile in bar 1 1 1 or 1 bar 1 1 and this lies probably in a plane which is a different plane, this lie in a plane, this lies in a plane which is let us say this plane and this plane could be 0 0 1 plane. So, if this is 0 0 1 plane 0 0 1 is not a favourable slip plane and for which 0 0 1 is not a favourable slip plane. So, which means it will have high CRSS.

So, basically what we have done is, you have done is, you have created two dislocations which were moving nicely into two different planes, but when they meet each other they give rise to another dislocation whose Burgers vector is different it does not lies in any of the origin slip plane. The Burgers vector lies in another plane which is not a slip plane.

So, as a result you increase the share stress required to move the dislocation. So, essentially when you form this kind of dislocation let us say you form this dislocation at this point. So, this is a, let us say we call it as a sessile dislocation, sessile or immobile dislocation. So, when you form sessile dislocation at this point all the dislocation which were moving behind it and all the dislocation which were moving here behind this when they pile up they create many of these, so what, so this is this cannot move.

So, this is become immobile, so which means all of these dislocation they will get piled up. So, this will create sort of a when they reach they all, they all will reach at this point. So, basically this will create a situation, will lead to dislocation pile up. So, as you have seen on the intersection when some vehicles go and if the vehicles are not able to move then anything that comes from.

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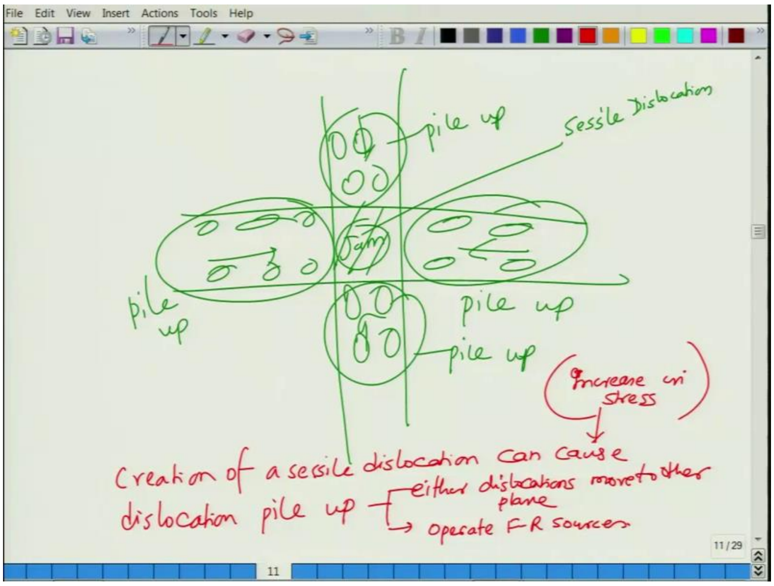

So, this like you know that the typical intersection, so if you have vehicles coming from this direction, this direction, this direction, this direction. So, these are the vehicles which are coming and if there is a jam here and all of these basically pile up. So, this is pileup, this is where you will have pileup. Then this is where also we will have pileup.

So, basically this is what is sessile dislocation and all the dislocation which are moving from other direction, they get piled up because they do not, because next dislocation cannot move, because the dislocation which is lying here at the intersection cannot move, so as a result you have what we call as dislocation pileup.

So, basically creation of a sessile dislocation can cause dislocation pileup. So which means, so either dislocations move to other planes which are favourably oriented or you also operate Frank Read source sources. So, essentially all of these lead to increase in stress. So, basically when you have these dislocations piling up, after one another the dislocation pile up leads to creation of this.

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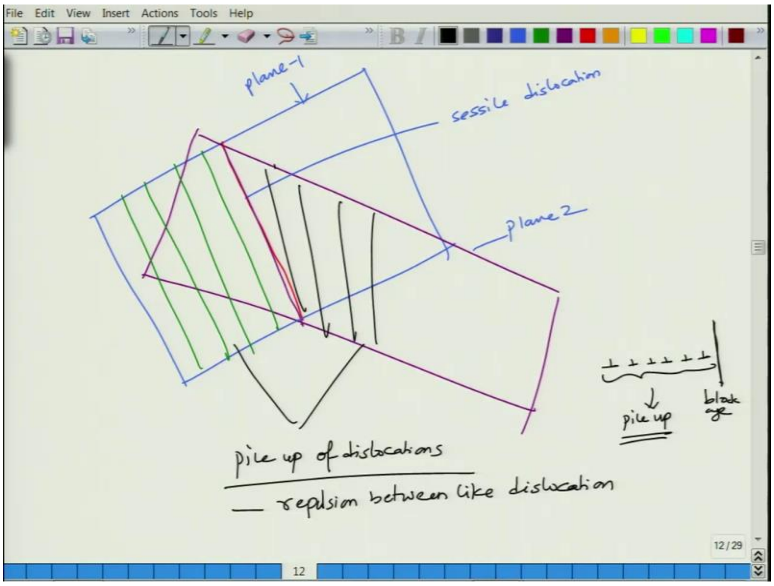

So, just to simplify this point if you have one plane like this and you have another plane like this lets say the intersection has let us say this is the intersection. So, this is the intersection, so on both sides of this intersection, this is sessile dislocation this is plane 1, this plane 2 and the dislocation in both of this planes in this plane and the dislocation in this plane, they all get piled up.

So, basically you create a pileup of and pileup of dislocation is going to lead to one another thing if they are all are similar the kind of dislocation if they have similar signs that means there will be repletion between dislocations. So, let us say, if you have multiple dislocations pilling at a source.

So, this is let us say the blockage, this is the blockage and you have multiple dislocations piling up like this. So, this is what is the pile up and you will have repletion between the like dislocation as a result, this will lead to increase in the stress that is required to cause the further deformation. So, basically deformation requires motion of dislocation and if you have basically obstructing the dislocations to move.

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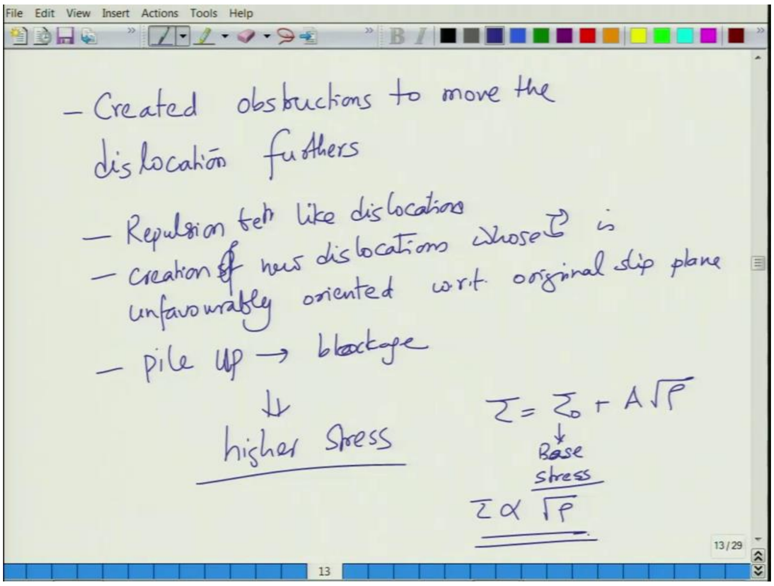

So, all you have done is basically you have created obstruction to move the dislocations further. So, it could be in the form of repulsion between like dislocations it could be in form of creation of new dislocations, whose Burgers vector is unfavourably oriented with respect to original planes, slip planes because of dislocation pile up leading to blockage and all of these lead to higher stress.

So, that is why when we say tau is equal to tau not into some constant A multiplied by square root of rho. So, basically this is the lets say base stress for a virgin material, a un-yield material. So, this tau is essentially square root of rho, proportional to square root of rho. So, as the dislocation density goes up the material becomes harder and harder to deform further that and this is what basically causes the material to become strong and less ductile.

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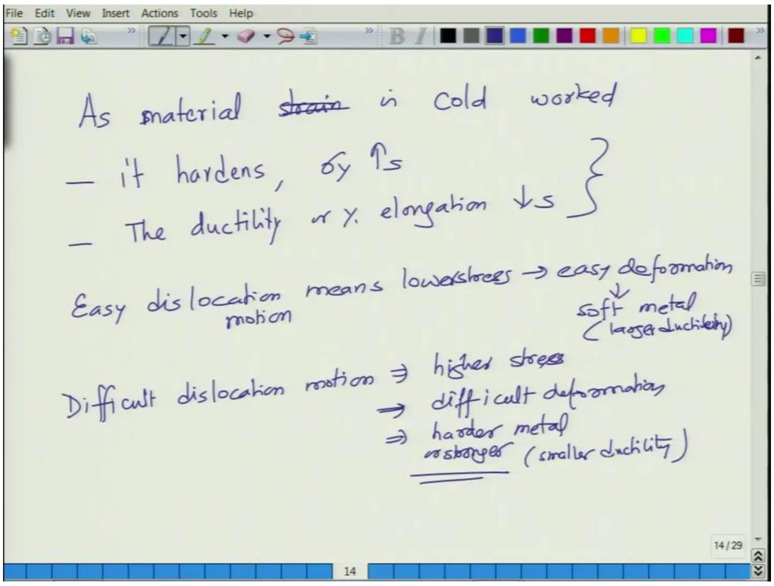

So, as material strain, as material is cold worked it hardens that is sigma Y increases but at the same time the ductility or percentage elongation decreases. So, basically it becomes hard and more and less and less ductile. So, basically what we are saying here is easy dislocation will mean, means lower stress which means easy deformation that is a soft material, soft metal and difficult dislocation motion, motion here, will mean higher stress it will mean difficult deformation and this results in a harder metal harder or stronger metal.

So, here large ductility or you can say larger ductility here it is smaller ductility. So, this is the first very simple method of making material stronger just deform it more. So, this you can do simple experiment at home you just take a wire and just try to bend it few time back and front, back and front, back and front and you will see at the bend material actually becomes stronger.

This is something which you can see very clearly you take this wire and you just bend it once and then release it, then bend it, then release it, then bend it, then release it and you can see at the bend it becomes strong and eventually it becomes, so strong that you cannot deform it further it will break. So, it will actually become brittle. So, this is first method of making material stronger which is called as plastic deformation or work hardening or strain hardening. We will look at the other methods of making material stronger in the next lecture, thank you.