**Materials Science and Engineering**
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**Lecture – 32**
**Strengthening mechanism IV**

Hello friends, we will look at the next strengthening mechanism is now and this strengthening mechanism is on grain boundary depending upon grain boundaries, and one of the very famous relationship is there to explain the grain boundary strengthening and that is grain boundary means grain size strengthening. So, and that is called hole pitch relationship, so basically when you apply the shear stress ok, so maybe there will be some source here.

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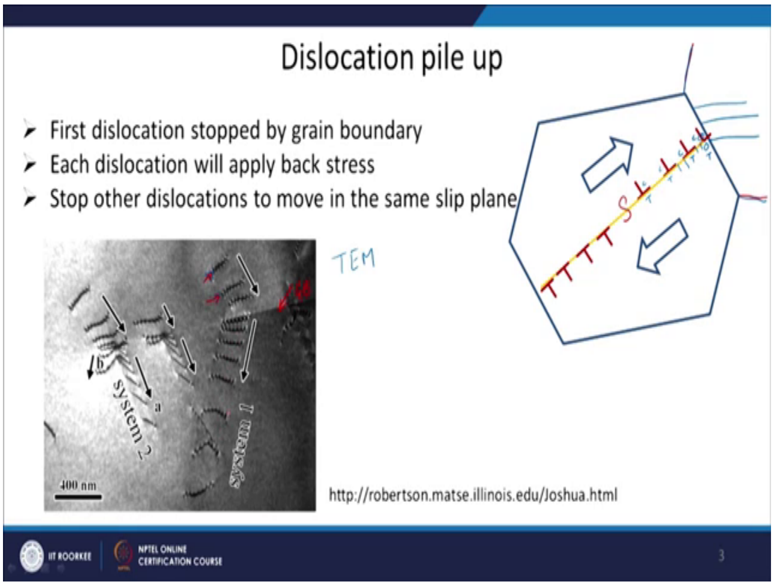


And the source is emitting the dislocations when you are applying a shear stress like this, and this dislocation will move and when they see a barrier grain boundary is a very strong barrier. The reason is that suppose my dislocation is moving on a crystallographic plane like this ok, in the next grain suppose is the next grain .

So, this is my next grain boundary. Now in the next grain boundary as I already told you that the grains are basically the difference between this grain and the next grain close to it, is that there will be a change in the orientation. So, in the next grain may be this particular plane is oriented in some other fashion for example, like this ok.

So, now the dislocation when it is moving in this plane it cannot just start moving in the another orientation ok. So, a grain boundary is a very strong barrier, so what will happen is that that dislocation will pile up because of this grain boundary. And so, first dislocation will be there because of the strain field associated with this, we have already discussed that that you will have a compressive strain field here and tensile here, so this is compressive tensile. So, if the same type of dislocation goes same type of a dislocation with the same sign ok. So, extra half plane on the upper part, again in this case also you will have a tensile and compressive field.

So, now this compressive and tensile field of both the dislocations is interacting. So, and of course, compressive will repel the other compressive fields is similarly a tensile field repel the other tensile field ok. So, this will repel this and combined these two this dislocation will see again now the combined strain field of the these two dislocation. So, for this dislocation because it sees the a combined strain field the distance has now increased between that these two dislocation as compared to these two ok. So, slowly you will see the pile up is there, but slowly you will also see that the dislocation will stop much before the other dislocations ok.

So, for example, this for these particular dislocations, now it sees the strainfield of all the three dislocations together, because it sees a larger strain field it will stop much before the pileup ok. So, this is how the dislocations kind of gets arranged. So, this is what we are writing here that first dislocation stopped by grain boundary is dislocation will apply a big stress, stop other dislocation to move in the same slip plane and then there is a very nice transmission electron micrograph TEM ok, and you can see that these are the dislocations.

So, these are all dislocations, these are all the dislocations and how they are and this is my grain boundary ok. So, they are getting arranged and also they are kind of initiating the dislocation in other, other in the next grain close to each close to that and the arrow indicates the movement of the dislocation a very nice micrograph taken from this particular website ok.

So, this is how the dislocations will go and gets stopped by the grain boundary ok. So, that is why how the grain boundary strengthens the material.

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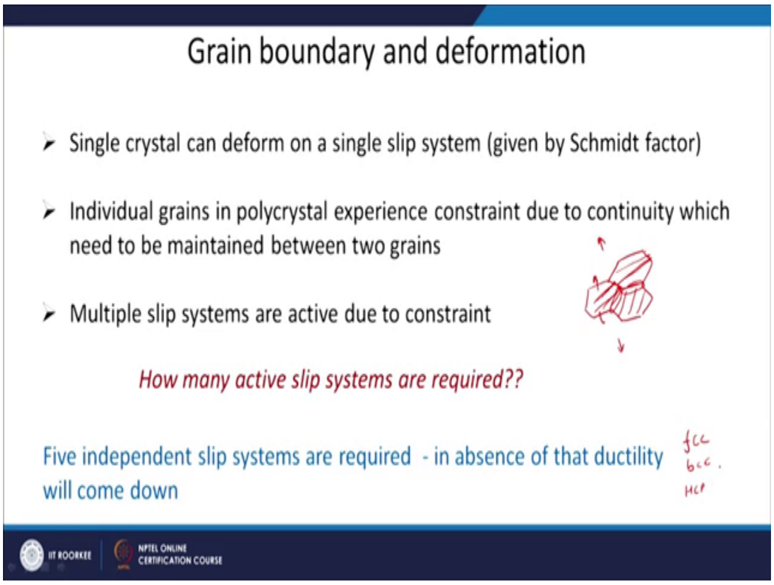


So single crystal can deform on a single slip system which is given by schmidt factor individual grains in poly crystal experience constraint due to continuity, which needs to be maintained between the two grains ok, now how the grain boundary and deformation are connected to each other ok.

So, if I have a single crystal and dislocation is moving ok. So, because the, the single crystal will only have free surface the dislocation will go and create a step at the free surface. Now when you have poly crystalline material ok. So, basically you have let us say take the simple example of hexagonal grains here ok. So, this is how the grains will be arranged close to each other ok.

So, now if I deform this grain suppose it becomes elongated it goes in these directions suppose the deformation I am applying like this ok or in terms of shear stress may be it will it will shear in this direction.

So, you will create a step in this direction. So, because after deformation I am not going to see any cavities in the material, it is going to be a continuous arrangement so; that means, that there has to be some constraint, which has to be applied to maintain the continuity between this grain and this grain ok. Because this grain will be deforming according to the Schmidt factor, if we take example of single crystal if we consider each one of them as single crystal, it will deform according to where the Schmidt factor was maximum.

So, maybe in this case it is for these planes, in this case maybe for the it is for these planes, in another case it is may be for these planes. So, the deformation will be indifferent direction, but still they have to maintain a continuity across the grain boundary, so that you do not form any cavities ok.

So, that kind of imposes a additional constraint on the deformation when we talk about a poly crystalline material. So, multiple system slip system are active due to these constraints, so, so what happens is that instead what we have seen in the single crystal that you have only one slip system satisfying the Schmidt factor maximum Schmidt factor condition.

So, that will deform in poly crystalline material actually you will have multiple slip system activated to maintain this continuity or two to satisfy this constraint ok, and how many sectors of system will be there? According to again tailor criterion is there, which says that there has to five independent system are required to maintain this continuity or to satisfy this constrain to ok.

And if you do not have this five independent slip system then the ductility of the material will come down ok, and that is why the f c c materials are very ductile because they have twelve independent slip systems and you just need five independent slip systems in b c c f c c b c c of course, does not have any slip system which satisfy the close condition, but at least it has more slip system then h c p which has again twelve, but out of those twelfth only three satisfy the close packed condition other nine does not satisfy that ok.

So, that is why f c c is very highly ductile, b c c comes in between the f c c and h c p h c p is least ductile of these three crystal structures ok. So, to maintain this continuity as I was just discussing, so you have a poly crystalline material like this.

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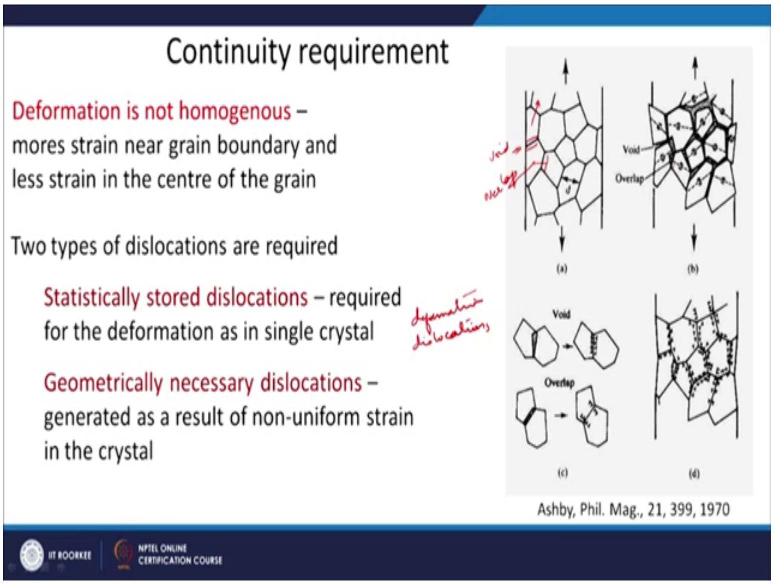


So if I allow these each of these grains to deform independently. So, there is no constraint what will happen that this will want to deform in whatever manner it will go it will go in this direction, the this one would like to go in this direction some some other gain will like to go in any direction.

So, what will happen is you will have some in some cases you will have overlap and in some cases you will form the voids because each one of them is independent to deform ok. So, for some grain maybe it would like to go in this direction, so there will be an overlap here ok.

So, let us say there will be an overlap here this one want to go in this direction, so there may be a void here in this case I have an overlap ok. So, all these differences will be there ok, so sometime you will have void formation is there in some cases the overlap formation is there. So, what will happen is locally to maintain this constraint and there will be some dislocation only to maintain the continuity ok. So, one there will be two type of dislocations now one which is required for the deformation as in single crystal So, for a given deformation to maintain that deformation what dislocations I need that I can get easily.

The other is geometrically necessary dislocations this is these are generated as a result to non-uniform strain in the crystal at some places you will have overlap at some places you will have wide formation, so to maintain this geometry ok. So, this is geometrical constraint that they it cannot have overlap it cannot have wide ok. So, to maintain that geometry additionally now the there will be some dislocation to fill this void there will be some dislocation to remove this overlap ok.

So, these are the additional dislocations which are present in the material, and these are called geometrically necessary dislocations and statistically stored dislocations or the dislocation which are required to do that deformation. So, if we look strengthening from grain boundary ok.

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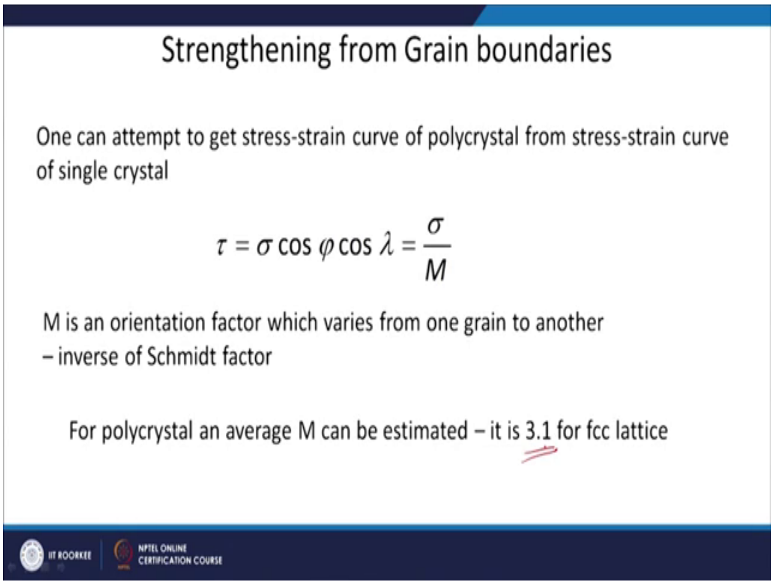


Ah you can give relationship, similar to what we saw in the single crystal that tau is equal to sigma cos phi cos lambda ok, and this cos phi cos lambda you can replace by sigma by m ok, where m we are saying is an orientation factor which varies fromone grain to another and this is a inverse of a schmidt factor ok. And for poly crystal and average m can be estimated it is around 3.1 for f c c lattice.

So, for b c c it will be a different number for hcp it will be a different number ok. So, you can give that what will be the increase in the strengthening due to grain boundary if I know this m the Taylor factor ok, for a poly crystal now coming to the hole pitch relationship now hole pitch relationship says that sigma naught.

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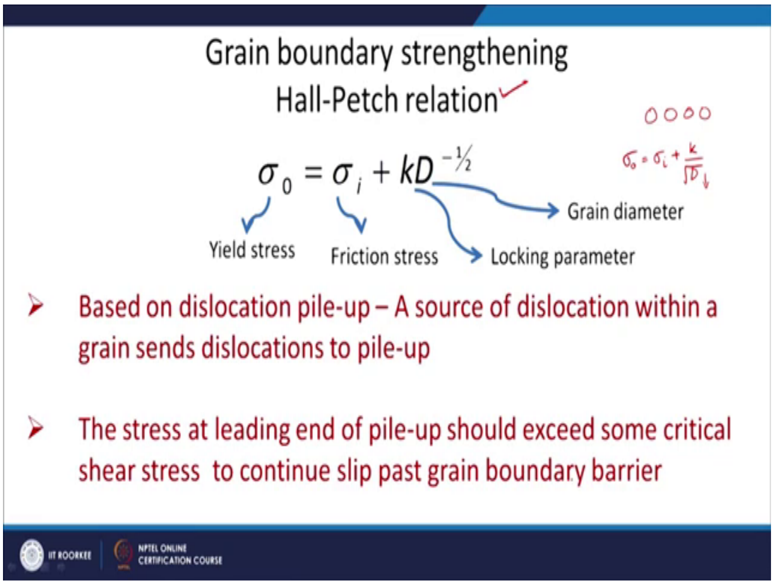


Or you can say sigma y also that is equal to yield stress depends on the sigma i friction stress, frictional stress is nothing, but for example, when I have an atomic arrangement and I have to move the dislocation ok. So, from for the movement of the dislocation i there is kind of a friction imposed by the lattice ok.

So, that that friction stress is always going to be there ok, it is just like that you have a car just for moving the car I need a certain kind of force on the car to overcome the friction between the tire and the road ok, minimum power I will always require for movement of the car the remaining power which you are going to give is going to give the velocity to the car, but one minimum stress or when minimum force will always be required just to overcome the friction between the tire and the road ok.

So, that is this friction stress k is the some locking parameter and D is your grain diameter and to the power half minus half ok. So, basically d is in the denominator here and with a square root ok. So, in another way I can write it like this ok, so it is like this. So, if I reduce the grain size; that means I am increasing the grain boundaries then my yield stress will increase ok. So, finer grain size will have higher yield stress a coarse grain will have lower yield stress.

So, that is what is the grain boundary strengthening or grain size strengthening and the relation this particular relationship is called hole pitch relationship given by two scientists on their name this is known as all pitch relationship ok. So, again it is based on dislocation pile up model only ok, a source of dislocation within the grain sense dislocation to pile up the stress head leading end of pile up should exceed some critical shear stress to continuously pass grain boundary barrier ok..

So, this pile up should impose a stress on the next grain to initiate the or to continue the slip process across the grain boundary, so this is based on that idea ok.

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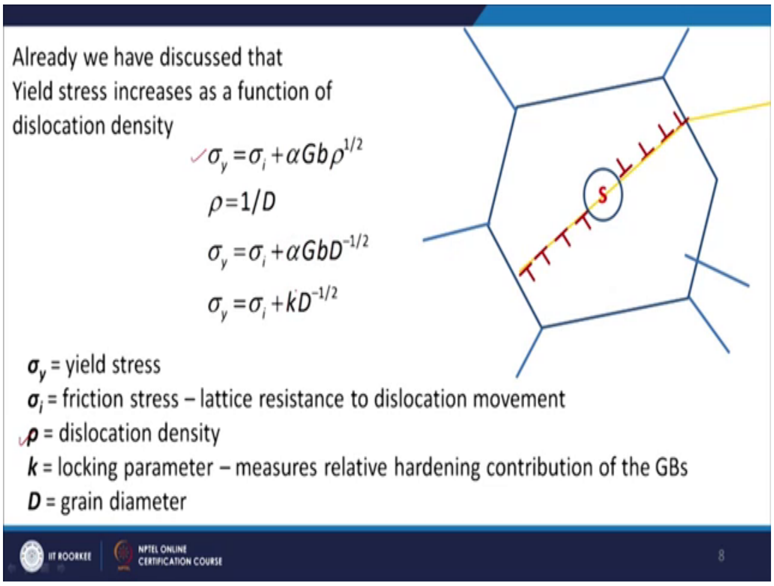


So, if we see that how I can just rationalize the relationship here ok, so already we have discussed that yield strength increases is a function of dislocation density when we were discussing work hardening also we said that when the dislocation density is going to be high it will have higher yield stress ok.

So, sigma y equal to sigma I plus a relationship like this alpha g b rho to the power half rho is your dislocation density and of course, G is your shear modulus b is your burgers factor and alpha is some constant here ok. So, my yield stress always depend on the dislocation density, now when you are deforming and there is a barrier the dislocation density will increase in the grain and since my dislocation cannot cross the grain or cannot cross the grain boundary the pileup will be remain within the within the grain.

So, as the dislocation density is increasing my yield stress should increase ok. So, dislocation density will depend upon the diameter with this relationship. So, if I have a smaller diameter there will be more dislocation pile up isn't it if I have a bigger grain my dislocation density will be less.

So, it will have an inverse relationship, so I will replace rho with 1 by D here. So, it will become sigma y is equal to sigma I plus alpha G b, D to the power minus half now ok. And I will replace this with a constant k which is called locking parameter and this is how I will I am going to write this. So, sigma y is my shear the yield stress sigma is my friction stress. So, earlier I think I have used the sigma naught.

So, let us make this is as also y instead of naught just to remove the confusion. So, sigma i is the frictional stress lattice resistance to dislocation movement rho is dislocation density k locking parameter which measures the relative hardening contribution of the grain boundaries and D is your grain diameter ok.

So, the strength of the material depends on the grain size and the strengthening is coming because of the grain boundary because grain boundary act as a barrier to dislocation movement ok, then there are large number of experiments people have done ok, so you can see that.

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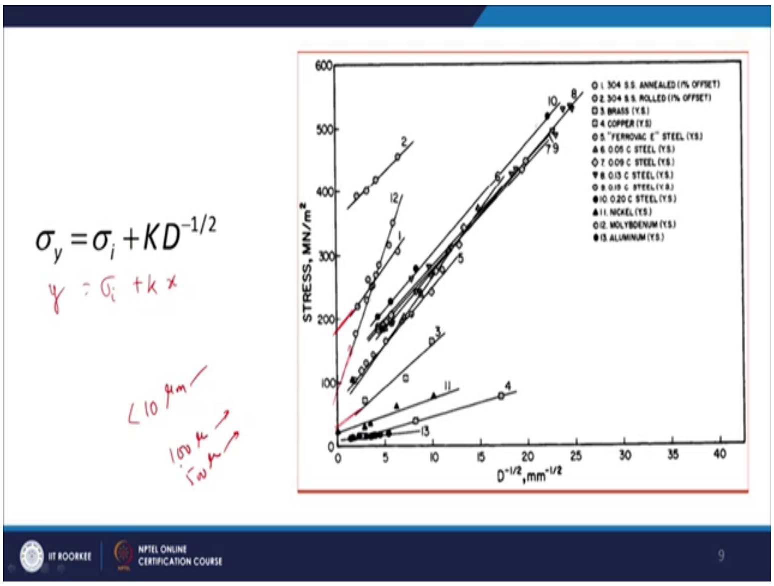


Large number of materials are written here 3 not 4 stainless steel brass copper some 0.05 carbon steel 0.09 carbon steel and so on, some nickel molybdenum and aluminum and you can see that they have plotted this curves with x axis has D to the power minus half and y axis has the yield stress ok.

So, of course, it if I replace this with x ok, so this is k plus this is some constant sigma i and this is my y ok. So, it is a y is equal to m x plus c kind of equation a straight line equation if I directly plot that d to the power minus half if I have plot d then of course, the slope will be different it will not be a linear curve then ok. So, because I have plotted directly the d minus half as x I can get a straight line here ok.

So, if I see here now of course, the slope will be different for different materials ok. So, their locking parameters are different and of course, the the sigma i will be the intercept, so where it is cutting the y axis ok. So, friction stress will also be different depending upon the bond energy between the atoms in that particular material ok.

So, of course, you will have different slope and different intercepts, but the important thing is that when you plot d to the power minus half as a function of yield stress they will all give you a straight line ok, that and that is that was a kind of a empirical relationship as taken from some ideas of pile up and this is a experimental result which kind of validate, that whatever analysis we have done there is going to be is true and that is what you find out in the in the material of course, to have a grain size strengthening you have to have the grain size may be in the range of let us say less than 10 micron ok

So, any size more than this you will not see the effect of the grain size on the yield stress ok, for very coarse grain let us say 100 micron or let us say 500 micron for very coarse grain material if you want to see the effect of grain size reduction it will not be very, very clear when you start getting the grain size in this range ok, then you will start seeing that the effect of the grain size on the on the strength or if you compare plain micron with 500 micron or 10 micron with 100 micron you will see the effect may be 500, 200 micron if you want to see an effect you may not be able to see any effect of the grain size ok, so this is your grain size strengthening ok.

Thank you.