Defects in Crystalline Solids (Part-II)
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Lecture - 17
Cottrell Atmosphere and Yield-Point Phenomenon

Today we will look at a completely different phenomena and this is called Yield-Point phenomenon. So, this arises because of a phenomena called Cottrell atmosphere.

$$C_{(xy)} = C_o exp\left[-\frac{E_{I(xy)}}{KT}\right]$$

So, the property that we are discussing is, yield point phenomenon and the underlying principle behind this is Cottrell atmosphere. In the previous lecture we saw when you have interstitials or substitutional atoms inside the matrix, then they will interact with the dislocation. And because of that interaction they tend to get attracted to in some region and they will be lesser in quantity in another region.

So, we can write down the overall change of this change in concentration as this. Let us say C naught is the equilibrium concentration and C x y is a changed concentration because of this interaction. And even is what we had earlier described E interaction not E 1 E interaction the energy of interaction between the point defect and the line defect which is the dislocation. So, this will be as a function of x and y and this is like a Arrhenius equation like this. So, at x y point where the interaction energy E I x y, the concentration there will differ from C naught and it will the new concentration can be given like this.

So, the most important thing is here that, interaction energy is changing the overall look not the overall the local concentration of the point defects. So, the important point here is, usually what is the form of the equation E I we know E I is of the form 1 over r f theta. We particularly saw this relation with respect to substitutional solid atom and interacting with the edge dislocation. In the last class where we saw, we where we showed that the larger solute atoms tend to segregate below the glide plane and the smaller ones tend to segregate above the glide plane. Now we could not show it because it is a little complex derivation, but even the interstitial atoms for example, the carbon in steel or the nitrogen in steel tend to segregate below the glide plane.

So, the interstitial atoms also find that to be the lowest energy position and their concentration overall concentration at that particular region just below the glide plane would be very high. In fact, one can calculate and show perhaps using some complex, it will require a complex derivation, but you can show that there will be concentration below the dislocation, which can be which can describe like this. So, like I said that the interstitial atoms also tend to segregate below the plane. So, you can have contours like this. So, this is the increasing concentration of interstitials. So, here let me make one more thing clear that when we say the point defect interaction, we are particularly talking about interstitial defect with edge dislocation.

And so, it may get this particular one here you may see that which is a iso value or the similar same value locus point. So, here you may get concentration has high as 0.9. Meaning most of the elements most of these substitutional sorry the interstitial elements would like to attend to be just below this dislocation line, which implies huge interstitial solute concentration below the glide plane. Particularly below in the; particularly near the core region.

Now, when I say that this is the solute atoms or the local distribution has been disturbed, it means that the solute atoms must migrate because you if you assume that there they were initially no dislocations, then there the then the solute atoms would have been distributed uniformly. But now there is dislocation suddenly the point defects C that there is a dislocation. So, they will tend to migrate to the core region and it this implies that the temperature must be high enough for migration, but let us say if you increase the temperature too high then what will happen? Then we know that the configuration entropy starts to dominate.

So, we do not want the temperature to be so, high that the entropies begins to dominate, but at the same time it should be high enough that migration of these atoms can take place. So, when we say that this segregation takes place, it happens at a sufficiently high temperature, where temperature is sufficiently high so, that migration can take place. But T should not be so, high that configurational entropy starts to dominate ok. With this understanding now let us look at how a dislocation would actually look like with a lot of solute atoms just near the core region and below the glide plane.

So, let say this is a glide plane, and I will draw a edge dislocation. So, this is the edge dislocation line and somewhere below this you would start to see a lot of solute atoms. In fact, many a cases almost all of these sides would be filled with solute atoms. And based on the equation that I showed you earlier there will be a core region. So, it will not exactly be at the dislocation line, but in the core region where it will like to tend to segregate. So, this distance is usually given by the term r naught. And now when you have a dislocation like this and the lower energy configuration of the solute atom is such that they have moved over to here, it means that interaction energy for each of the solute atoms is there.

So, it has lowered the overall energy of the matrix and in turn; that means, that if you want to move this dislocation, then the dislocation you must apply a higher stress you must apply more than what if there were no solute atoms below this. Because now you have to break you can say in effect the bond between the dislocation and the solute atom and therefore, extra energy or extra stress needs to be applied. And therefore, you can move it and if you move it will look like this. So, here because of some random distribution you may have one or two solute atoms along the line, but on average it is now unpinned. So, dislocation un pinned on application of very high stress.

And at this point I will show you the manifestation of the locking of this kind of dislocation with the solute atom. It that manifests like we said earlier in what is called as yield point phenomena which you observe in usually medium carbon steel type of material. So, now, let me draw the physical manifestation of this effect. So, we have what we have drawn here is a true stress to true strain sorry the engineering stress engineering strain curve.

And what you see is that instead of being a uniform stress strain curve as you would see where, it goes to elastic region and then you start to see the yield point and after a yield point you see a uniformly plastic region and after then (Refer Time: 11:26) you would see instability. Here instead there is a region something like this, which is very different from any other material. So, the material usually let me. So, this is very common for medium carbon steel.

Even in other materials this kind of behaviour can be seen and which will come to later on. But this is one of the materials where you would have initially or been exposed to this kind of phenomena. So, this is what is called as yield point phenomena and where is it arising from? It is rising from this which is called as Cottrell atmosphere meaning the presence of. So, actually it should i should put this as a Cottrell atmosphere. So, this is Cottrell atmosphere. The presence of solute atoms in the region around the dislocation core that creates a Cottrell atmosphere and that we are seen is based on that equation, where the local concentration gets disturbed because of interaction energy.

And this is Cottrell atmosphere which manifest itself as yield point phenomena. So, what are the things that we see over here? We see what is called as upper yield point what we see here again more of it? We see lower yield point and this is called yield drop where it goes from here to here, this is called yield drop. Apart from this we will we will I will explain to you some more phenomena that take place. But let us first start with what is the upper yield strength or upper yield point.

$$\tau_o = \frac{3A\sqrt{3}}{8b^2r_0^2}$$

So, like I said that why do you need a upper yield point because the dislocations are pinned. So, because of the (Refer Time: 14:10) dislocation which in effect you can say that, that this mobile dislocation density is reduced. So, low mobile dislocation density. So, it is as good as saying that the number of dislocations which can cause the deformation in the system is not sufficient. And therefore, you are approaching if you remember from the very first class in the first part that, your yield strength increases when your when the dislocation density is very very small. It approaches that of an ideal material. So, that is what we are heading towards when we do not have sufficient number of mobile dislocation and therefore, the yield strength required is much higher.

In fact, you can show this that the tau, the stress required to move the dislocation can be written as A r naught x r naught is the distance that I described earlier, below the distance from the glide plane below which the solute atoms are segregating; b is the burger vector x square plus r naught square x is the distance along with along the glide plane where you want to move the dislocation. So, this is the usual shear stress variation. So, it will look like this and this is the x distance, and if you plot this as a function of x what you would get is. So, let us say your dislocation was somewhere over here. So, it had a stress tau or you needed to apply stress tau to begin with and this you need to keep increasing this tau until a point where the maximum stress is tau naught.

And then once you have crossed this stress, then you can come back to the position where it will again be at the same stress level where it was there initially and it can be shown that. So, this is the if you maximize this tau this is what you will get; the maximum tau naught maximum tau is equal to you can take A as a constant. So, you can see that a much higher resolved shear stress is necessary to get the dislocation moving.

And this translates to upper yield strength this higher requirement of the resolved shear stress is what translates to u y s. Upper yield point or what you want you can put it like the way you want. So, here we have put it in terms of i p. So, I will continue with UYP. So, now you can understand that you will have something called as a upper yield point, but now why should there be a lower yield point? Now let us first understand what is yield drop.

$$\dot{\epsilon}_p = \frac{s - k\frac{dF}{dt}}{l_o}$$

Now, this is a little extensive. So, there bear with me here. Now yield drop happens you can say as a manifestation of the fact that there is now suddenly there is a burst of dislocation along with the fact that you in the equipment that we measure which is u t m you want to keep the strain rate constant. So, let us see what we mean by yield drop. So, let us say that your equipment now in your equipment what you keep constant is the strain rate. So, the strain rate and before that there is something called a strain. So, if that strain per unit time has to be the elongation displacement of the cross head is what you will control. So, usually the displacement rate will be constant at a given time at a given point of time.

And this displacement can be divided into two groups; one because of the elastic components and one because of plastic components. Now this elastic component arises not only from the sample, which will also see elastic elongation, but also because there will be some elastic elongation in the whole equipment this is called compliance of the system. So, we will put all these elastic elongation into one quantity and we will represent it has a spring. And next part is your sample where your plastic deformation is taking place. So, like I said we will distribute or divide it into two parts. The elastic displacement and this can be very much modelled as a spring because spring is a elastic. So, it can be modelled as KF.

So, it is if you are applying f amount of force, and the spring constant is K then this is the displacement. As soon as force goes to 0 this displacement comes back to 0. On the other hand the plastic deformation does not come back to 0. So, we are putting it differently this is epsilon p l naught. So, whatever the strain that has accorded until that point of epsilon p into the not the strain; so, this is the strain times the l naught so, that will be the total displacement. So, this is elastic displacement and this is plastic displacement. Now this one of this two is usually the moving end which is called crosshead. So, the cross head displacement which is equal to KF plus epsilon p l naught.

Now, here if we say that s this is the total displacement and s is equal to d l by d t which is crosshead speed then, when we can say that s into time t. So, we have started experiment and then we have taken at t amount of time. So, s into t is the total crosshead displacement and therefore, this is equal to this or we can write it as epsilon p equal to s t minus KF by l naught. So, now, we have written it in terms of epsilon p and usually it is the strain rate. So, here we have strain and what you what we want to keep constant in a test tensile test is the strain rate. So, epsilon so we will convert it to epsilon p which is the strain rate.

So, this is differentiated t then it becomes s, this differentiate with t it becomes d F by d t. So, this is the strain rate that we want to keep constant when we are doing a test. Now let us go to the next step we want to we should now relate it with the shear stress.

$$\dot{\epsilon_p} = \frac{s - k\frac{dF}{dt}}{l_o}$$

$$\frac{d\tau}{dt} = \frac{1}{2A_0}(\frac{s - \dot{\epsilon_p} l_o}{2A_0 k})$$

So, resolved shear stress this can be given by F by 2 A naught where A naught is the cross sectional area of the sample or a specimen. Now, if we want d tau by d t which is how the strain sorry how the resolved shear stress acting on the specimen is changing with respect to time, we can write it like this 1 by 2 A naught which is A constant d F by d t and from here we know what is d F by d t we can put it like that. So, d tau by dt and from above we can write. So, this our second set of equation which we are interested in finding out.

Now, here epsilon p dot like we said is the strain rate which we want to keep constant, and d tau by d t is the strain rate or sorry the shear stress resolved shear stress changing with respect to time.

$$\frac{d\tau}{dt} = \frac{1}{2A_0 k}(1 - \frac{\dot{\epsilon_\phi} l_o}{s})$$

$$\dot{\epsilon_\phi} = f(\rho_m, \overline{V})$$

We can also write it in terms of resolved shear stress as a function of change in the length as a function of change in length which will be hardening rate shear hardening rate. And in that case you can write it like this, d tau by d l is equal to d tau by d t into 1 by d l by dt. But you remember what is d l by d t? d l by d t is our s which is the crosshead speed. So, we can write it like 1 by s d tau by d t. So, it is not very different equation from what we have seen earlier, it is just that we are trying to evaluate one shear stress in terms of time, the other time we are trying to do it put it in form of how it changes with change in the overall length.

So, it can now be written as, now here at any given time l naught it is constant epsilon p dot is constant because you have kept as A naught is constant K is constant, but s is something that is changing continuously that you have to adjust so, that the crosshead speed remains adjusted to maintain the strain rate. So, this is if it were a usual equation, then what you would get is that d tau by d t is changing uniformly or monotonically.

But in this case what will happen is that epsilon p dot which we have written here is actually a complex function of rho and as well as velocity of the dislocations. So, at one point rho m will be high. So, the velocity will be low at another point rho m may be low. So, the velocity will be velocity of the declaration would be high. But overall our epsilon p dot must remain same and with that if we write if we know this we can say that we have the two points the upper yield point and the lower yield points.

$$V = k\tau^{m}$$

So, we can say that epsilon dot u is equal to rho u, which is the dislocation density for the upper dislocation velocity is u and for lower dislocation density we know that the mobile dislocation density is high which means the velocity will be smaller. So, let us see what will be the ratio now we know that it has to be same. So, let us say it is a constant epsilon dot which could imply rho u by rho L is equal to v by.

So, this is what we are getting the density of dislocation in the upper yield point what is the density of dislocation in the lower yield point is equal to the velocity of dislocation in lower yield point by velocity of dislocation in upper yield point. And we also know that v velocity of dislocation is actually proportional to the shear stress applied.

So, it is of this form of the equation and therefore, what we get is that now this brings us a relation between tau the velocity and hence the strain rate. So, tau u by tau L from this equation, we know is equal to v u by v L to the power 1 by n and from this equation we know that it is equal to rho L by rho u 1 by n. And remember when we are writing dislocation density rho L or rho u we are only referring to mobile dislocation density.

So, what do we see here that the shear stress that you need to apply if you have one set of or one value of this mobile dislocation is different from the shear stress that you need to apply when you have another set of dislocation density. So, here at the lower yield point you have this is higher value because mobile dislocation density has increased and over here the mobile dislocation density is lower. So, this is lower value what does this imply?

Tau u is larger. So, tau u is greater than tau L and this implies you will experience a yield drop.

So, the one thing that we see is that, you will see a yield drop another thing is that this yield drop would be proportional to difference in mobile dislocation density. So, this equation is giving us two important informations that why there should a yield drop, and when there is a yield drop it is proportional to the mobile dislocation density and this has been actually observed.

If when people have experiment where they took materials with different dislocation density, this is what they have observed. So, on y axis you have tau resolved shear stress and on the x axis you have displacement rate sorry this is crosshead displacement so, s t. So, you see there is a this is the yield drop for this system, this is the yield drop for this one and this is the yield drop for this one. So, from this can you say which one had a smaller mobile density to begin with and the answer would be this one.

Here the dislocation density was of the order of 10 to the power 6 per metre square, here the dislocation density is a little higher 10 to the power 6 10 to the power 7 per metre square and here even higher 10 to the power 7 per metre square sorry 10 to the power 8. So, what do we see that as you keep increasing the mobile dislocation density, yield drop reduces. We have already said that the yield is proportional to difference in the mobile dislocation density here the initial and the final mobile dislocation density will be smaller.

So, you do not see as much yield drop as you keep increasing. Here the drop is increasing here you have even larger difference. So, it starts with 10 to the power 6 and probably you have something like 10 to the power 10. So, this is a much larger difference therefore, this will be a larger yield drops that you observe. Now, that we have understood the yield drop. So, we know that there will be upper yield point. And there will be a lower yield point.

So, now let us come to the next topic which is lower yield point ok. Now let me again draw this yield point phenomena that we observed. So, we know there should be upper yield point and once a dislocations have been unpinned, a lot of them will become free and you will see this yield drop something like this. So, what happens here? Now that we know that there will be a larger dislocation density or some saturated dislocation density over here. So, what is happening inside the sample?

Let us try to understand and. So, let us say this is our sample for which we are doing testing. The first thing that you must realise here is that, this is not a single crystal sample this is a polycrystalline sample. So, there will be lots of (Refer Time: 35:34) inside it. So, the yield stress or the sorry the critical resolved shear stress for a set of these grains across them should be reached before they start to the deform and that happens in the form of what is known as Luder band. So, you get something like this and what is Luder band?

This Luder band is a region with high mobile dislocation density. So, you have this region which is corresponding to lower yield point. So, you reach the upper yield strength point where there was enough stress to create mobile dislocation across a one touch or one stretch of the sample, you see a Luder band formation. And this is the Luder band around in which the dislocation has continuously sorry not continuously it has increased to the extent that now uniform dislocation or uniform deformation can take place. So, sufficient to cause uniform defamation.

Now, if you increase it further what will happen? If you increase the stress or you try to increase the, what you are increasing is not really the stress what you are increasing is the displacement.

So, what will happen when you keep increasing the displacement beyond lower yield point? And keep in mind that our strain rate is constant. So, what happens is that, you do see something like this. Now let me draw again and this time I will exaggerate this picture to show the band. So, the first that happens is that small amount of uniform deformation takes place inside n the Luder band. Now they will reach our point when the dislocations come and accumulate at this at the end of these bands.

So, there will be dislocation accumulation; across all the depending on the orientation they will different planes and they will cause along different planes there will be dislocation accumulation. So, dislocations accumulate because beyond this they are not able to go ok. So, for one thing that you need to realise why are they accumulating. Because over here they are not this is not a uniform deformation region this is the uniform deformation region sorry this is the uniform deformation region this is our Luder band where uniform deformation can take place, but very quickly they reach a point take they cannot the dislocations cannot move any more.

So, dislocation accumulation takes place what does this do? This causes stress and what will be the effect of these stresses? There can be two things that can happen here a that (Refer Time: 40:53) regions where the stresses are high over there because of this high stresses mobile dislocations may get generated. So, dislocation this implies propagation meaning now the yield sorry the Luder band that we talked. This is the Luder band at this end and at this end there is dislocation accumulation and because of that created stress the region beyond just next to it is also becoming dislocation or increasing in mobile dislocation density.

And hence the width of the Luder band increases. So, this is equivalent to saying that the propagation of Luder band takes place. So, propagation in a narrow zone, it is a very very small region ahead of Luder band. But this is not the only thing that may happen other thing that may happen is that, now that you have increased the stress because of that increase stress second or third Luder band may form.

However, if you realize that if you have seen the stress strain curve you know that the region where this Luder band the Luder band region in the stress curve we do not see a second very high yield strength point or the upper yield point again. It means that we are not raising the stress to that level it implies that it is very unlikely that a second or third Luder band will form. So, this is unlikely, but what is likely is that, dislocations because they are accumulating at the neighbouring grains or the border of the Luder band they force a increase in the width of the dislocation Luder band.

And therefore, we can now explain the remaining part of the curve like this. So, this was the upper yield point which we saw why it happens, then we have the lower yield point once the dislocation density has increased. And this is the region where Luder band propagation takes place. So, if I where to draw this schematically, let me draw three or four of these then i can compare. So, this is the first Luder band form where is it? This is at point A when you keep propagating you may have now extended the Luder band to something like say this.

So, this may be point B this is A. So, this b point may be somewhere over here and if you keep increasing the displacement, eventually all of this region would become get included in the Luder band. So, all of this is now high rho m region. So, in affect it is all Luder band has now extended from the one end of the gauge length to another (Refer Time: 45:34) end and this we can call as point B. So, this point will be represented over here beyond this what will happen?

Now, your deformation will take place as it would have in any you can say common material where you say see the usual stress strain curve. So, you will start to see elongation uniform elongation for the whole gauge length. So, if is region D, this D region would lie somewhere over here. So, this looking at this now we are in position to understand the various points that is observed in the yield point phenomena upper yield point, lower yield point yield drop propagation of the Luder band and then the uniform deformation. Now because of this unique feature where the dislocations are (Refer Time: 46:41) dislocations some of the some very interesting phenomena can arise let us look at some of these interesting phenomena.

So, one of them is called strain ageing. So, now, let me pose a question to you that once the material or the steel that you are taking has reached the region of uniform deformation meaning throughout now you have mobile dislocations what does that mean? When your mobile dislocations through meaning all of them have been unpinned; so, the solute is somewhere here and the dislocation line is somewhere here. So, it is these solutes are not pinning the dislocation line any more. Now let us say that you deformed sorry provide sufficient heat may be 300 degree Celsius for 30 minutes enough that the solute atoms can migrate wherever they find low energy region then what will happen?

You would expect that the solute atoms will again go back and reach the region where they will have the lowest energy which is just below the dislocation core. And therefore, it will again be similar to the situation, where they have pinned the dislocation and then if you do the. So, if you take the sample at that particular point where the uniform dislocation had started uniform deformation has started and then you age it, and then again do the tensile test what will you obtain, that the material is again showing that yield point phenomenon.

So, you I can show you approximate behaviour like this. So, let us say at this particular you unload the samples you went here you went here and then you unloaded. If you load it without applying any heating treatment what would you see? You would see that it will deform from this point. So, this will become new yield point meaning that yield point phenomena has been breached, you are not going to see that again. This is the case when no thermal treatment is given after unloading.

But now what if you are, when you give a let me write here because ill show it over here a little bit displaced curve when some thermal treatment is given then you know what will happen that the yield point phenomena will start. So, let us say I dropped it here and I just shifting it a little bit. So, that we can clearly see what will happen? So, this will again go back and start showing. So, implies yield point phenomena is observed again. Here no yield point phenomena. So, this is something that you would expect and it is actually observed. So, this is called strain ageing coil.

Now, on last topic on to this which is called dynamic strain aging; in the previous example what we saw that, if you age it if you sorry first you are doing the tensile test you bring it to the region of uniform deformation. Or where you have completely mobile dislocation across the gauge length and then you unload it, and then you age it and therefore, the solutes moved back and pinned the dislocation.

Now, the second scenario is when you move the dislocations so, slowly and there is sufficient mobility in the solutes that they can keep following the dislocation. So, every once every now and then they will pin the dislocation and that you would see is that you will have to every now and then apply a higher yield stress. So, what you see is. So, first let me write down the condition. So, for example, when you are doing at a very tensile testing at very low strain rate, that is one possibility meaning the dislocation velocity I so, small that solute are also able to move or I am doing the deformation at relatively high temperature.

So, at relatively high temperature again the solutes have very high mobility. So, dislocations are moving, but the solutes are also moving and therefore, you would see now let me give it the name. So, we already know what we see it is called serrated stress strain behaviour. And how does it look like? It looks like and this is what is termed as dynamic strain ageing. So, you see that we have a particular condition under which you can even have the dislocations getting pinned every once in a while even though the deformation is continuing. So, in a dynamic condition still there can be pinning taking place and then you will see some serrated behaviour like this.

So, this particular lecture we saw the yield point phenomena and we understood various points arising point from it like the upper yield point, lower yield point yield drop and then we also some unique behaviour like the strain ageing and the dynamic strain ageing. And with this we actually come to end of not only this lecture, but for this course and in this course we have seen the advanced information about dislocation structure in various complex systems and also some more detailed information about dislocations in the basic systems FCC BCC.

And beyond that we have looked at some of their applications, strengthening behaviour that arises particularly it can be because of the interaction between dislocation and dislocation or because of interaction between point defect and dislocations. There are lot more kind of interactions that take place and we have just given a brief overview of this. So, that you are able to appreciate the importance of dislocation in determining not only the mechanical behaviour, but also their physical behaviour their functional behaviour and so on.

So, with that we come to an end thank you and I hope you like the course. And please do register for the exam and like I said the part 1 is still available, you will you can always go back and refer to the contents over there.

Thank you.