**Mechanical Behavior of Materials-1**
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**Lecture - 38**
**Solid Solution Strengthening: Yield Point Phenomenon**

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Welcome back class to our course, Mechanical Behavior of Materials. So in the last lecture, we discussed about how substitutional and interstitial atoms are going to interact with edge and screw dislocations, okay. Now let us consider if we have an edge dislocation, where the substitutional and interstitial atoms are going to set, okay.

So here I am showing an edge dislocation, you can clearly see here, right. And this is your extra half plane, this particular plane is your slip plane, okay. Now we are considering both substitutional and interstitial, okay. Now let us consider first interstitial atoms. So interstitial atoms are going to be sitting at the bottom half of the slip plane.

So before that, let me tell you and you already know Professor Shashank Shekhar has already mentioned about this that on the top, so if you have edge dislocation here, on the top part you have compressive stress, right. So this part is under compression and the bottom here you have tension. And then in these regions, you have shear also right, okay. So now depending upon the size of the atoms, they are going to sit either in compression region or tension region, okay.

So now the solute atoms they are going to be sitting here, okay. So if we have an interstitial atom, then they will be sitting, they will be sitting below the extra half plane. Why? Because then you are going to reduce the lattice strain. Remember this portion is under tension. So if you want to fit something at this position, then there will be some expansion in the lattice. So it is going to reduce the lattice strain, right?

So interstitial atoms are going to sit below the extra half plane. Now let us talk about the substitutional atom. So if we have a very large substitutional atom, so suppose I choose this particular atom, and I replace it with a larger substitutional atom, okay. Now you can also see the tension region here at the bottom of the extra half plane.

The strain in this particular region is going to be reduced if I am going to put a larger substitutional atom. On the other hand, if we have a smaller substitutional atom, like suppose I choose this one, so if I have a smaller substitutional atom, then they are going to sit on the top of extra half plane okay, on the upper side, okay.

So this is how the interstitial atoms and substitutional atoms they are going to go to, go in the lattice and choose the positions. And overall what they are trying to do, they are trying to do two things. The first one is that they are trying to reduce the overall strain in the lattice. So I can write impurity atoms are attracted.

And why they are attracted? Remember, in the last lecture we discussed both are associated with the strain field, right. So edge dislocation also has a strain field, stress field and these impurity atoms they also have stress field, right? So they will be, the stress field will be interacting with each other and these atoms will go at the core of edge dislocation to reduce the overall strain and energy of the system, okay.

So impurity atoms are attracted to dislocations to reduce the overall strain energy. So if you see they are actually cancelling out the strain in the lattice, right. So partially cancel the strain in the lattice, okay. So I can write another table. Let me make one more table.
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So for substitutional atoms, depending upon the size of the substitutional atom they will sit either on the top of the half plane or at the bottom of the half plane. That means, if the size is larger they are going to sit at the bottom of the half plane so that they can reduce the overall tensile strain in the lattice, okay. So we have point defect, okay. Since we are talking about edge dislocation, so I have two regions, tensile and compressive, okay.

Now we can have smaller substitutional atom or we can have larger, okay. So now the smaller substitutional atom they will be repelled in the tensile region. So they will be more attracted towards the compressive region because they want to reduce the overall strain in that particular region, right. So here I can mention, so repelled. And they will be attracted towards the compressive region.

And the larger substitutional atom, they will be attracted towards the tensile region and here they will be repelled, okay. Now interstitial atoms as I mentioned they will be preferably sitting at the bottom of the extra half plane because they want to reduce the tensile strain in the lattice.

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So interstitial atoms will mostly go below the dislocation line, okay. So both whether it is interstitial or substitutional atoms they will be attracted towards the core of a dislocation line okay or core of a dislocation. Now since they are sitting there and they are being attracted towards the dislocation, if I want to move the dislocation you have to remove those atoms from there, right?

And this will require an extreme amount of energy or extra amount of stress, is it not so that we can cause further plastic deformation in the material, okay. So I can write if a dislocation wants to move, it has to tear itself from the impurity atoms okay and this will require extra energy. That means higher stress, okay.

So you are actually giving some strengthening to the material because of the presence of these solute atoms at the core of the dislocation, okay. And this is the genesis of something called yield point phenomena which we are going to discuss now, okay.

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So there is some terminology we call a Cottrell atmosphere, okay. So now we know that the interstitial atoms they are going to sit at the core of the dislocation that too at the bottom of the extra half plane, okay. Now if you talk about steel they will contain carbon atoms is it not? So these carbon atoms they are also interstitial atoms right, impurities. Not impurities, interstitial atoms.

So they are also going to sit below the dislocation line at the dislocation core. So if I have a dislocation line something like this, okay. So these atoms will be sitting here. They will be attracted towards the dislocation core, okay. So these are carbon atoms say in the steel, okay. So what they are doing, they are actually making a cloud at the dislocation core, is it not? They are making an atmosphere at the dislocation core.

And this was proposed by Cottrell, so the name is given as Cottrell atmosphere and we also call it Cottrell cloud, okay. So now this Cottrell cloud is also going to affect the movement of dislocation. So if you want to move this particular dislocation you have to apply higher amount of stress so that dislocation can leave this Cottrell atmosphere and move ahead, okay.

And that is what we use when we try to explain something called yield point phenomena, okay point phenomena. So let us discuss what is yield point phenomena.

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And typically you are going to observe this yield point phenomena in medium carbon steel, okay. Now when Professor Shashank Shekhar was teaching you tensile testing, he must have shown you the plot of say polycrystalline pure aluminum and if you have a sample of polycrystalline pure aluminium and you do a tensile test you are going to have a plot like this, not up to the scale, but something like this, is it not?

So this is the engineering stress, engineer strain plot, say polycrystalline aluminum, okay. This you know and this is the general curve we are going to observe for almost all alloys, say copper alloys, magnesium alloys, even aluminum alloys, all polycrystalline alloys, right? But in medium carbon steel we are going to observe something different.

So if I again plot engineering stress and engineering strain, we are going to observe a elastic raising initially okay, but then you are going to see a drop and then some fluctuation, something like this. And then it is going to follow what you have seen in polycrystalline aluminum, something like this, okay. Again not up to the scale, but this is a schematic for understanding, okay.

So you can clearly see now the difference between the tensile curve of polycrystalline pure aluminum and this is for medium carbon steel. And this is happening because steel has carbon and nitrogen atom as interstitial atoms, okay and they are sitting at the core of the dislocation especially when you have annealed it, okay. So you can see a maximum point here and this corresponds to, let me change the color.

So this is called upper yield point. This particular point is called lower yield point, okay. And the fluctuation what you see is because of propagation of Luder bands. So the fluctuations this is because of propagation of Luder bands. We also call it as Stretcher strains, okay. So we have upper yield point, then lower yield point, and then we have a fluctuation which is because of the propagation of Luder bands.

And I am going to explain each one of these terminology and then we see what you have already learned in the case of say polycrystalline pure aluminium. So you see strain hardening, then this particular point on the top, we have UTS and then this is your fracture point, okay. So this is the difference between polycrystalline pure aluminum and medium carbon steel, okay.

So now let us understand why do we upper yield point then why do we see lower yield point and then why do we have this fluctuation okay and the formation of Luder bands, okay. So what is happening? You have, say you have a dislocation, right. And then this dislocation has a cloud of impunity right, impurity atoms in this case say carbon atoms or nitrogen atoms, okay.

Now to have a plastic deformation, all these dislocations which have a Cottrell atmosphere around it, this dislocation need to leave these atoms right, and they have to move so that you can cause a plastic deformation. Now when you start stretching a sample, when you start applying you know strain rate, you apply strain rate what is happening? You have a very nice elastic region that all of us know.

Now the upper yield point correspond to a point where dislocations in a particular set of grains are leaving the Cottrell atmosphere, okay. Now remember the medium carbon steel what we are talking about is a polycrystalline material. So some set of grains are going to be favorably oriented towards the tensile axis. That means they have a higher Schmid factor.

So a set of grains they are going to deform much earlier than the other grains, is it not? And there you are going to observe that this dislocations in this set of grains they are going to be freed from the Cottrell atmosphere. But this will require higher amount of stress as we have discussed earlier because you have to free from this Cottrell atmosphere, you have to free the dislocation, right.

And that is the genesis of upper yield point, okay. So why do we see upper point?

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So as stress goes up some dislocations in a set of grain or in a set of favorably oriented grain, so these dislocations are freed from the Cottrell atmosphere, okay. And now to do that to free this dislocation from the Cottrell atmosphere you require higher amount of stress, okay. And this is why we have upper yield point, okay. Now you have freed the dislocations and they are going to move easily right, in a particular set of grains, okay.

And what you are going to see, you are going to see a burst of plastic straining okay, more or less in a narrow region. And that particular narrow region is called Luder band. So when this happens, you are going to see a burst of plastic straining in a narrow band okay and or say region. And this is called Luder band. So let me draw a sample so that you can understand it better.

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$$\dot{\epsilon}=\mathbf{b}\rho v$$

So suppose you have a dog bone sample and you are doing tensile test, okay. So some set of grains will be favorably oriented towards the tensile axis. That means they have higher Schmid factor. So those sort of grains will be activating first, okay and the dislocations they are going to be freed from the Cottrell atmosphere. So say we form a Luder band here.

So you have a burst of plastic straining in this particular narrow band, so you start forming Luder bands. So say in this two regions we saw. So this is Luder band, both of this, okay, if you can image a sample, you know sample surface, you will be able to clearly see a nice band which will have a different contrast from the rest of the sample. When you do a tensile test of medium carbon steel, okay.

So you have formed a Luder band. So that is the genesis of upper yield point. Now why do we see lower yield point, okay? So the strain rate can be given as b rho v where rho is the dislocation density and v is your velocity of the dislocation. So this is dislocation density and v is velocity of dislocations, okay. Now v is related to the stress. So higher the stress the velocity is going to be higher, okay.

Now remember whenever we do tensile test, we always try to do it in a constant strain rate, okay. So we have, we apply constant strain at say 10 to the power -3 per second, 10 to the power -4 per second something like that, okay. So constant strain rate is on the left side. So we try to maintain this term epsilon naught as constant, okay. B is also constant.

Now we are increasing the dislocation density in the region of Luder band right, these two regions I have shown here, the Luder band formation. So there in that particular region you have increased the dislocation density, okay. That means to maintain the constant strain rate the velocity of dislocation needs to be reduced okay, because you have increased the dislocation density.

So what is happening? Rho is increasing in the Luder band region. So v has to decrease because you want to maintain epsilon naught, this guy here, constant. Now if v is reducing, see on the right side, then tau the stress is also going to reduce is it not? And that is the genesis of lower yield point, okay.

So because of the increase in dislocation density the velocity of the dislocation needs to be reduced so that you can maintain a constant strain rate and this leads to the reduction in the stress, right. And that is why we see a reduction in stress to lower yield point from upper yield point, okay.

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$$\dot{\epsilon} = b\rho v$$

So you have something like this, okay. So you saw already upper yield point. Now this is lower yield point, okay. And this lower yield point is happening because of the reduction in the stress to maintain constant strain rate. So let me write down, lower yield point, and this happens okay reduction in the stress to maintain constant strain rate, okay.

And this drop from upper yield point to lower yield point, this particular drop is called yield drop, okay. So the more the reduction in the stresses you will observe the yield drop to be more, okay. So this is the genesis of upper yield point and lower yield point. Now let us understand why do you see the fluctuation.

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So the question is why fluctuation, okay. So now let me draw the schematic of the sample again and suppose you have these two Luder bands. You can form actually multiple Luder bands, okay. Now if you see this particular region, say I have marked 1 and 1, okay both are initiation of the Luder bands when you see a upper yield point, okay. Now what will happen?

You have generated lots of dislocations in these two region, both Luder band, both the Luder bands, okay. So stresses near that region can go to very high value, okay so because of the two reasons. One because you have a formation of Luder bands in both the regions and what will happen because of that, there will be slight reduction in the cross-sectional area okay.

So the first point is a higher stress in the region 1 because of a little bit reduction in cross-sectional area. So you are going to see a increment in stress in that particular region and second stress concentration due to high dislocation density, okay. So after you have formed Luder bands right, the first Luder bands, what is going to happen, locally you are going to see a very small change in area in these two region, here as well as here okay.

Now since there is a reduction, slight reduction in area, locally you are going to see stress concentration in both regions okay, near both the regions. But remember, realize it that this increment in stress concentration is not that very high, okay. Now point b is more dominant compared to point a here. So in point b, since you have formed this Luder bands you have generated more number of dislocations.

So this dislocation density increase will lead to a stress concentration near region 1 in both the regions here, okay. This means that locally near these two regions you have a stress increment which can lead to the removal or which can lead to the movement of dislocations near these regions. Dislocations can free themselves from the Cottrell atmosphere because of the stress concentration, okay.

See, ideally if you want to free that you have to go to very high stress, is it not like upper yield point. But since locally, you already have a stress concentration, you do not need to go to that very high value. So instead after upper and lower yield point, you do not need to go to again to this upper yield point value.

Because of stress concentration in this region, you have to slightly increase the stress and the dislocations nearby these two regions they are going to free themselves from the Cottrell atmosphere and you are going to see the formation of Luder bands or propagation of Luder bands. So they are going to propagate in both the regions, okay.

So you are again going to see a yield drop because of again because they have freed, the dislocations have freed themselves from the Cottrell atmosphere, right? Now this process will continue. So you are going to again form a new Luder band for say propagation of Luder band. Since it is happening nearby this region I will say propagation of Luder bands instead of saying new Luder bands, okay.

So you are going to see again increment and then decreasing stress and this process continues till these Luder bands has propagated have propagated throughout the cross-section. So they have propagated throughout the cross-section here, okay, throughout the cross-section. And after that since they have traveled throughout the cross-section or throughout the gauge section, they are going to show the similar phenomena what you observed in the case of pure aluminum, okay.

So the fluctuation now you know why this occurred, okay. So remember that the second Luder band will always form near to the first Luder band because of the stress concentration in the region of first Luder band because of these two points, okay. And this is how Luder bands propagate in a medium carbon steel and finally you see the fluctuations in the stress.

You will not see in pure aluminum because there is nothing there right, it is pure aluminum fields, okay. And even in aluminum alloys you are not going to observe this because those are substitutional atoms rather than interstitial atom. Interstitial atom remember they will give more hardening to the material, we have discussed about that, okay. So this is what I wanted to discuss about the yield point phenomena.

Now one question you know always comes to mind that how can we remove this carbon and nitrogen atoms if they are so much troublesome, right? So in industries what people do, they use carbide formers like niobium, titanium etc., in steel making process and thereby they form carbides. So you are not actually having three carbon atoms which can go and pin the dislocations.

That is one of the ways to remove carbon from the interstitial positions, okay. And the second is that you can use, in steel industry people use RH process, where they use vacuum and then they remove the interstitial atoms, carbon as well as oxygen they also remove. So all these are done in the steel making process itself.

And the third is you can use something called steam pass rolling or we also call it as temper rolling to get rid of this formation of Luder bands or Stretcher strains, okay. So we have completed solid solution strengthening also. And in the next class we are going to start talking about grain-boundary strengthening. So till now we have completed two strengthening mechanisms.

First we started with precipitation strengthening and dispersion strengthening. And then we have completed solid solution strengthening and next we are going to talk about grain-boundary strengthening, okay. Thank you.