Materials Science and Engineering
Dr. Vivek Pancholi
Department of Metallurgical & Materials Engineering
Indian Institute of Technology, Roorkee

Lecture – 29
Strengthening Mechanism I

Hello friends, today we will start with the new topic on strengthening mechanism. As I told you when we were discussing plastic deformation that this is one of the motive of our understanding of how the crystal deform ok, so that I can design or tailor microstructure or if I can do something in the material by which I can increase the strength of the material ok. Basically, I want to alter the properties of the material and all this understanding helps me to do that.

So, we will start with the strengthening mechanism ok. So, there will be different strengthening mechanism which we are going to discuss. So, my objective when I want to define a when I want to discuss strengthening mechanism is to increase the strength of the material that is my objective.

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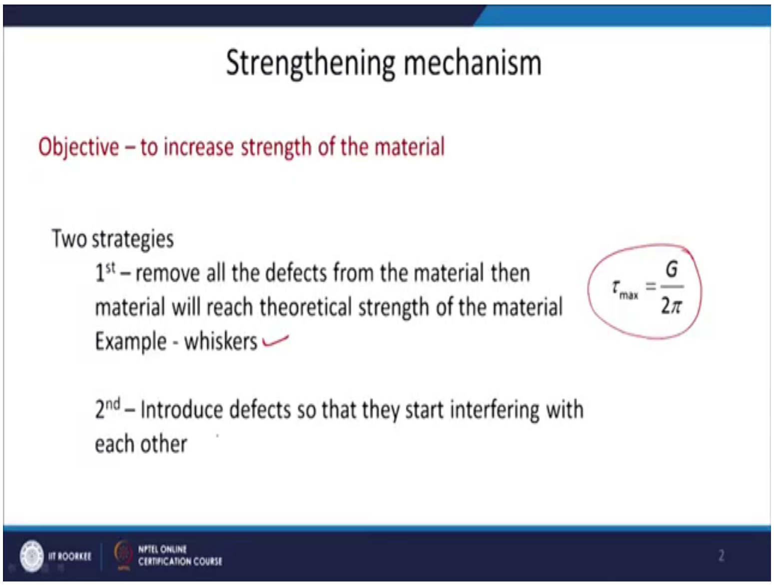

Now, there can be two strategies to do that. First is remove all the defects from the material ok. If you remember we discussed that the strength of the material, theoretical strength ok, shear strength for example, of the material is shear modulus divided by some constant here 2 pi. Now, shear modulus is in Giga Pascal. So, if you divide it by 2 pi also order of magnitude will almost remain same; it will be in Giga Pascal. Whereas, all our experimental strength shear strength is in mega Pascal. So, there is a three order of magnitude difference between what is theoretically calculated and what do you have found out experimentally. And we said that there are some defects in the material which is bringing down the strength and these defects we called as dislocations.

So, first stage it is obviously for me is to remove all these defects. Because these defects are bringing down the strength of the material ok, which is of course not a easy task to do when you are talking about bulk material, because during the processing itself you generate so many defects in some material people have achieved this kind of condition, which are called whiskers. So, the idea for whiskers is that you make the dimension of the materials so small suppose the mean free distance between two defects right is in some micron let us say 10 micron or 20 micron or so.

So, one dislocation, another dislocation, there is this much distance is there or one point defect to next point defect some distance will be there may be in micron, 5 micron, 1 micron whatever. So, if I make my dimension of one of the dimension of the material in that range ok, so let us say I make a material whose diameter make a make a wire which has a diameter equal to around 1 micron let us say. Then my dimension is lower than the mean free distance of the defects ok.

So, I am practically eliminating all the defects from the material ok. Of course, I have to go to that kind of length scale to do that. And this is done in some type of materials which are called whiskers which are very fine basically wires, and then you will combine them together. And in those material where we could achieve no defect kind of condition when people did experiment and found out the strength, they were in the range of Giga Pascal ok. So, basically defects are the main reason to bring down the strength.

Now, this is a very expensive business to do all these things. Another way to do is this is second strategy is that I introduced too many defects. If I am not able to remove them, let us introduce large number of defects in the material ok, so that they can start interacting with each other ok, they will start cutting down each other kind of and that will increase the strength ok. So, the all the strengthening mechanism is based on the second strategy that increase the number of defects let them interact with each other and thereby you can increase the strength of the material.

So, we know that the strength is intimately related to dislocation motion ok. So, yield at yield also what we say a slip starting in place, the plastic deformation start taking place, and we know that slip takes place because of dislocation motion ok. So, strength is intimately related with dislocation.

Similarly, UTS also if you see we say that the material is strengthened from yield stress to UTS because of strain hardening. And strain hardening is because dislocations are interacting with each other. So, again there is that dislocations are the main important unit, you can say which decides the strength of the material. So, if I can hinder the motion of the dislocation by any mechanics ok, then I am increasing the strength of the material.

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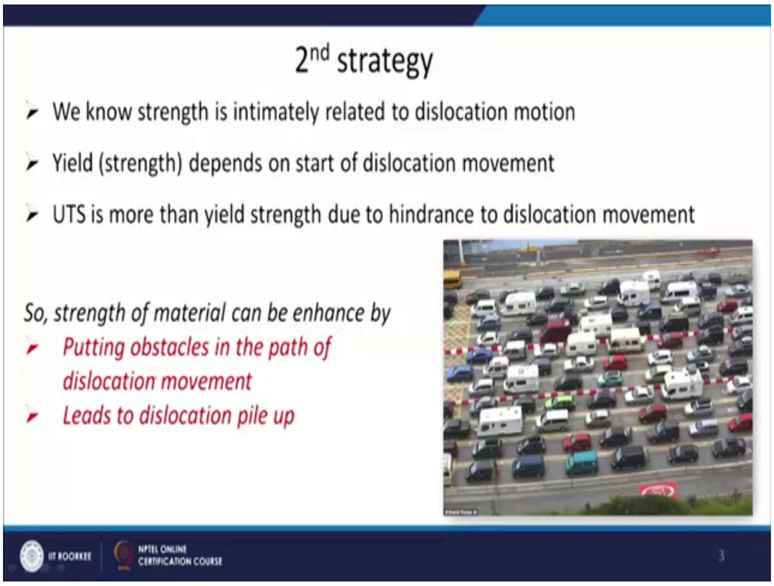

So, the idea for increasing the strength of material or strengthening mechanism to understand strengthening mechanism is to put the obstacle in the path of dislocation movement. You the input some barriers basically and that is what you can see that all these cars have piled up because there is a barrier here ok. And they are kind of getting piled up. And of course, you can see that the lead dislocation as they are piling up and then the there will be lot of stress on the lead dislocation, and there will also be a back stress on the other dislocation which are going to come ok.

So, for example, a new car comes it sees that there are there is so much pile up maybe it will like to take some alternate route rather than standing in the line maybe some [FL] if it is available close by it will try to take that. So, that it can somehow get rid of this pile up. Similarly, the lead one so the front car will see the kind of pressure of all the cars, so some it is not able to it is the engine has stopped, but because of some reason. And it is not able to start, all the others will start honking ok, they will start putting pressure on the lead one ok.

So, there is a back pressure and there is a stress concentration on the lead one also from the all the dislocation which are behind it ok. And the dislocation which are coming they will see that there is a back pressure building up. So, by doing that we are making it difficult for dislocation to move. So, when it sees so many dislocation, the next dislocation will find it difficult to move because there is a lot of back pressure build up there is a lot of stress concentration because of the all the dislocation which are in the queue ok, so that is the strategy.

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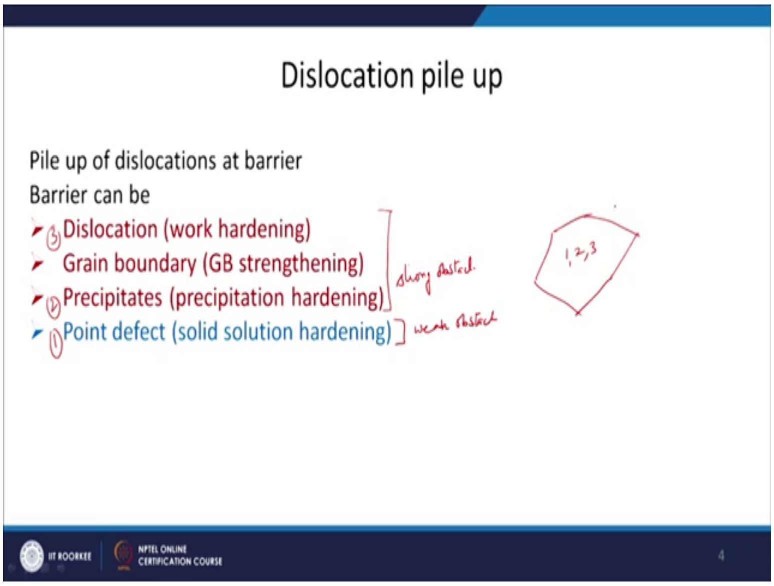

So, dislocation pile up takes place at the barrier ok. So, barrier can be another dislocation ok. If the if the barrier is another dislocation and because of that if you are getting strengthening then it is called work hardening, so because of dislocation interaction. If the barrier is a grain boundary then it will be called grain boundary strengthening. If barrier is precipitates then it will be called precipitation hardening; if barrier is point defect then it will be called solid solution hardening.

So, we will see each one of them I have grouped this three a actually these three are the ones which are you can call as strong obstacle. And this is a actually a weak obstacle. So, these are strong obstacle; this is a weak obstacle. Actually, I can also divide them in different way or I can group in different way ok. If you see these three the point defect, and the precipitate, and the dislocation these three barrier come within the grain. So, they provide the barrier within the grain itself whereas, grain boundary provides the barrier at the boundary of the grain ok.

So, you can make another group of this like this also that this point defect precipitation hardening solid solution hardening and work hardening, they provide the barrier within the grain ok. So, you have a grain, let us say I am just making a hexagonal kind of grain ok. So, all these defects will be this 1, 2 and 3 will be within the grain; and the fourth one the grain boundary strengthening is only at the grain boundary. So, I can divide this into this way also. Now, my dislocation can also do a can overcome this pile up. as I told you that if car comes and it sees a so many there is a pileup of cars or there is that queue of cars, it will try to take some other route that is what dislocation can also do.

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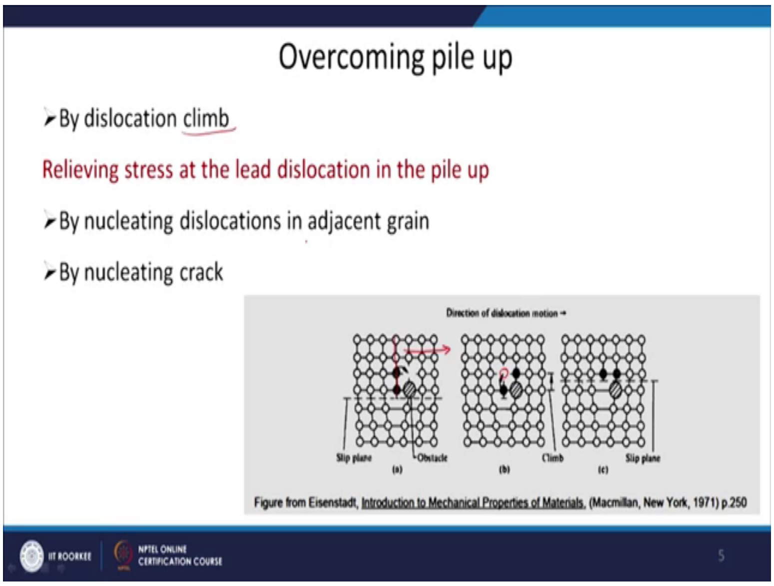

For example, one of the mechanism is called dislocation climb ok, which is dependent on the vacancy concentration in the material ok. So, for example, you have a dislocation like this, this, this is the extra half plane ending here and there is obstacle here. And these dislocations want to move in this direction. What happens there is a vacancy for example, suppose there is a vacancy around here next to this obstacle ok. So, what will happen this atom above this where the dislocation is ending, it has jumped into this vacancy.

Creating thereby creating a vacancy now at the where the its earlier position was there, and the atom which is at the end of the dislocation core that has now jumped up in the vacant position ok. So, thereby you have a dislocation climb now ok, dislocation has climbed by one atomic distance. So, instead of ending here now it is ending in this plane and thereby it has circumvented this particular obstacle. So, now, it can move in this plane without any problem. So, this is one way of circumventing the barrier by dislocation ok.

So, it can also relieve the stresses at this location in the pile up by nucleating dislocation in adjacent grain or by nucleating a crack. So, these are other way of relieving the stress or it can do a climb process to overcome the pile up. Now, as I told you that there are three mechanisms which are within the grain. So, let us start with the dislocation point defect interaction that means, one of the method by which we have strengthening it is called solid solution strengthening. So, it will come under point defect ok.

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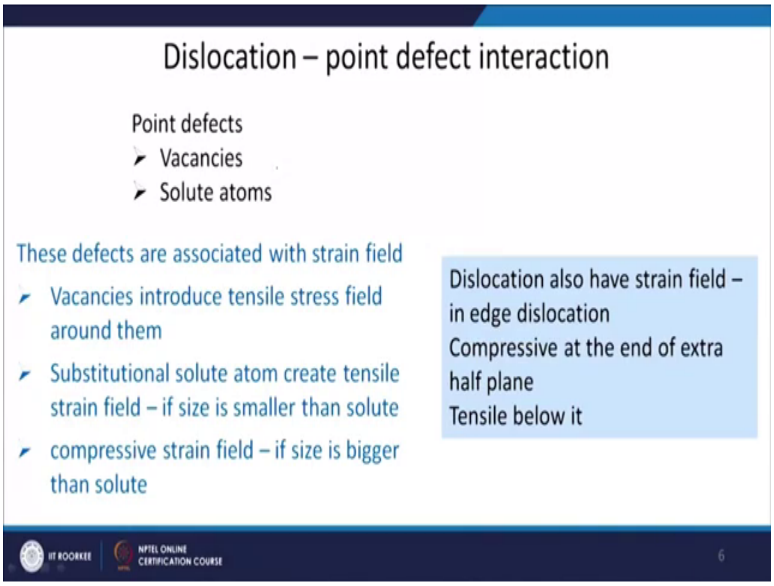

So, you have point defects like vacancies or solute atoms. So, what how they provide strengthening ok. So, these defects are associated with a some strain field around them ok. For example, vacancies introduce tensile stress field around them substitutional solute atom create tensile strain field if the size is smaller than the solute. So, it will in that sense these two are going to be same. Whatever is the means by which vacancy is introduced tensile stress, the same will be true for a substitutional solid atom having a smaller size.

Then there can be as a compressive strain field if the size is bigger than the solute atom ok; so this for substitutional solute atom. For interstitial atoms also this is will be true. If the atom is having a larger size and the interstitial position ok, then it is going to put strain on the nearby atoms ok, and they that will be a compressive stress ok. So, this will be true for interstitial atom also whose sizes is bigger than the size of the interstitial site. So, you have different tensile and compressive field associated with different type of defects. We also know that dislocation also have a strain field. For example, in edge dislocation there is a compressive at the end of the extra half-plane and tensile below it. So, I will just show you all the images for these three cases in the next slide.

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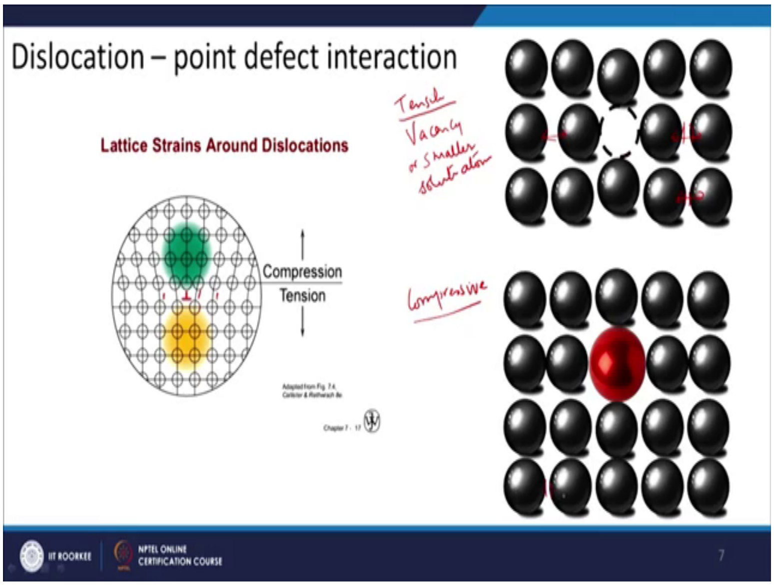

So, for example, if you look at the dislocation, so lattice strain around dislocation, so this is the edge dislocation ending here. So, you have compressive stress field on the top, because you are introducing a extra half plane there. And there will be a tensile strain field in the bottom ok, because now these bonds are stretched you can see here ok. All these bonds are stretched in a stretched condition. And there because of that there will be a tensile strain field around that. And similarly because I am putting then extra half plane here. So, all these atoms are going to be in compressive condition ok. So, there is a compression tension strain field associated with edge dislocation.

With the screw dislocation, you do not get a two different strain field, there is a spherical strain field or a circular strain field around the dislocation. So, in that case, it will be different then what you are seeing in the edge dislocation. Now, if you look at the point defect suppose there is a vacancy or there is a solute atom which is a of a smaller size ok, what will happen all these atoms which are next to the vacancies they are in stretch to position now.

So, you can say the distance between the atom has increased, whereas the distance between where it is it has not affected the atom the distance is small, and here the distance is between the atom is more. So, all these atoms which are next to the this vacancy is there in strained position ok. And this strain is of tensile nature. If I put a bigger substitutional atom ok, so this is for a vacancy or smaller solute atom, so both cases. In this case, you have you are going to get so in this case I have tensile strain field in this case I will have compressive strain field ok.

So, you can see that all the atoms are pushed very close to the next atoms. Of course, this will propagate, I am not able to show it I am just showing it for the next neighboring atoms ok. So, this is actually the distance between the equilibrium distance between the two atoms supposed to be there. Now, the atoms which are next to this bigger atom they are in compression. So, now, this compressive field or this tensile field will interact with the tensile or compressive field of the dislocation.

So, dislocation will feel a very nice if it is if the tensile part is seeing the for example, here the compressive part of the strain field around this particular atom. So, the tensile part will get canceled out by the compressive part here or if it sees this vacancy here then the compressive part will be canceled out by the tensile strain field of the. So, thereby dislocation will be able to reduce this strain energy ok, so that is what it wants to reduces its strain energy ok, and that is how they are going to interact and that is how they are going to the dislocation is going to see a kind of a barrier. So, it will like to be there because it is comfortable there.

So, vacancies is like what will happen that when you there has a dislocation, sometime vacancy will like to go and sit where the compressive strain field is there to the tensile strain field of the dislocation sorry it will should be vacancy (Refer Time: 17:40) with the compressive.

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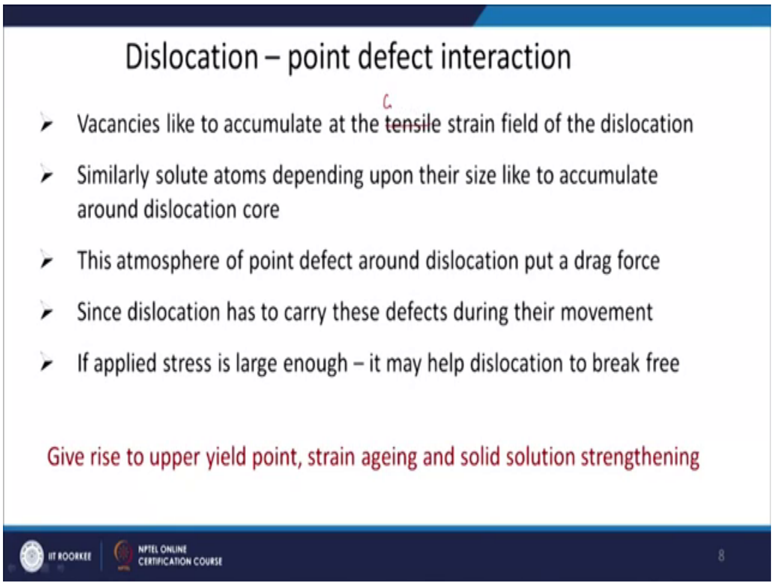

Similarly, solute atoms depending upon their size like to accumulate around dislocation core; this atmosphere of point defects around dislocation put a drag force. Now, if I want to move dislocation now with these defects around the dislocation core ok, my dislocation has reduces its strain energy. And if I want to move it. so it would like to carry those defects with it ok. And with this will create a drag force on the dislocation ok, because now it is not only at the moment of dislocation the point defect alters also need to be move together.

If we increase the applied stress to a very large extent may be dislocation will be able to break free from these defects ok. So, we that is also possible that I apply a very large stress this shear stress and that will help the dislocation to break away from these defects. So, it give rise to what this dislocation point defect interaction does other than giving solid solution hardening is that it gives rise to upper yield point strain ageing and solid solution strengthening ok. So, all these three things are possible with this interaction between dislocation and point defects.

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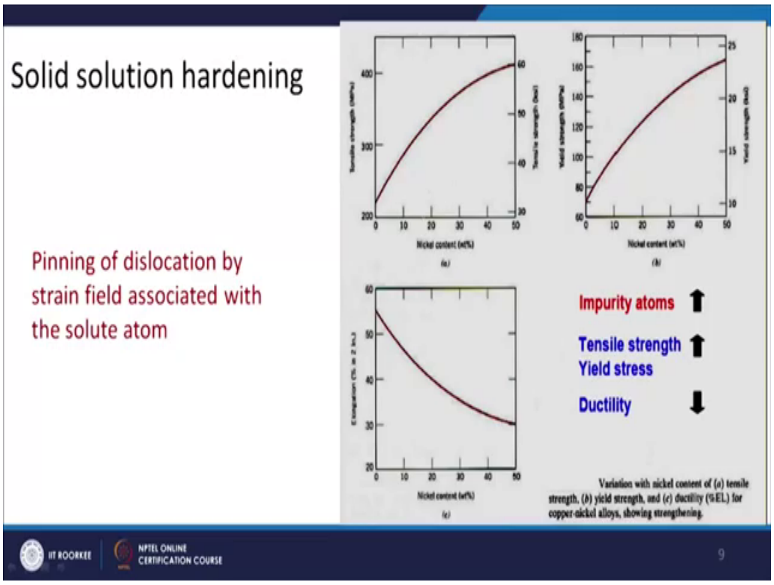

So, if you look at the solid solution hardening as I told you dislocation will reduce its strain energy if these kinds of defects are there around the core ok. So, you can see that there is a comparison. So, if I keep on increasing the nickel in the in a copper nickel system. If you remember when we were discussing copper nickel system we said this is the isomorphs system that means, I can add any amount of copper and in a and any amount of nickel in to make an alloy ok. Because it is isomorphs system, there is no solubility limit ok, so that is why you can see this is a nickel content is increasing.

As nickel content is increasing my tensile strength is increasing. Similarly, my yield strength is increasing. However, my ductility of the material is decreasing ok. So, if I increase the amount of nickel in this copper nickel alloys then my tensile strength and yield strength increases, ductility reduces. This is usually the case with all the strengthening mechanism, most of them that when you increase the tensile or yield strength, your ductility reduces.

So, as I told you that why this solid solution hardening takes places because of pinning of dislocation by strain field associated with the solute atom ok. So, between dislocation and solute atom the interaction is there and that is helping you to increase the strength. As you can see from 0 to 50 percent of nickel here, I am increasing the tensile strength from around maybe 225 mega Pascal to to 400 mega Pascal or so.

Similarly, yield strength I am increasing from around let us say this is this 50, 80, around 70 or 60 or 70 to around 160. So, a very big difference in the strength of course, the ductility is reducing from a value of 55 to around 30 percent.

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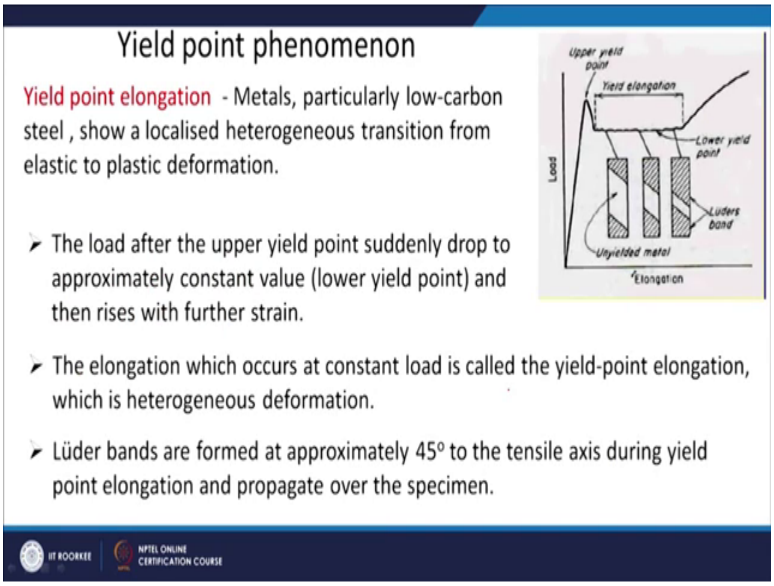

Now, if you remember when we were discussing tensile curves of steel and aluminum, I said in steel actually you get a very prominent yield point phenomena or very clear yield point you get. So, this is your elastic part linear part then very sharp yield point. And at after that there is a drop in the stress, and then there is some kind of you can see serrations are there ok.

So, it is like these kind of serrations. This is what we call as yield elongation ok. And this is my upper yield point, this is my lower yield point and after certain elongation then the strain hardening starts ok. So, this is this whole phenomena is called yield point elongation sorry yield point phenomena. And yield point elongation is that they show a localized heterogeneous transition from elastic to plastic deformation.

So, why we are calling it as heterogeneous, because it starts from one end and it goes to the another end ok. So, as you can see that the hedged region here is the is the is the location where the yielding has started. But in some of the portion of the material yielding has not started yet, so it is starting from for example, some end here and then it is propagating. So, you can see in the next stage somewhere here the yielding has increased up to this portion of the material and this much is remaining the annealed metal.

And the third stage if you can see the most of the material has yielded, but still some portion has left and then at the end of course, the whole material will be yielded. So, you can see that this is a heterogeneous transition from elastic to plastic deformation. It is not uniform deformation throughout the sample as we said that a deformation is going to be uniform throughout the sample and this banding which you see here there are two bands are moving towards each other these are called Luder's bands. The scientist gave the name first discovered them so, on his behalf of it is named like this.

So, if you want to see that what this yield point phenomena is the load after the upper yield point suddenly dropped to approximately a constant value lower yield point, and then rises with further strain. The elongation which occurs at constant load is called yield point elongation which is heterogeneous deformation. Luder bands are formed at approximately 45 degree to a tensile axis during yield point elongation and propagate over the specimen. So, again 45 degree is coming back here ok. And why 45 degree again you have maximum shear stress acting in that direction to the principal stress that is our tensile stress and that is how the Luder band forms and then it grows and then it consumes the whole material. So, this is one-way of yielding in plain carbon steel or low carbon steel which takes place.

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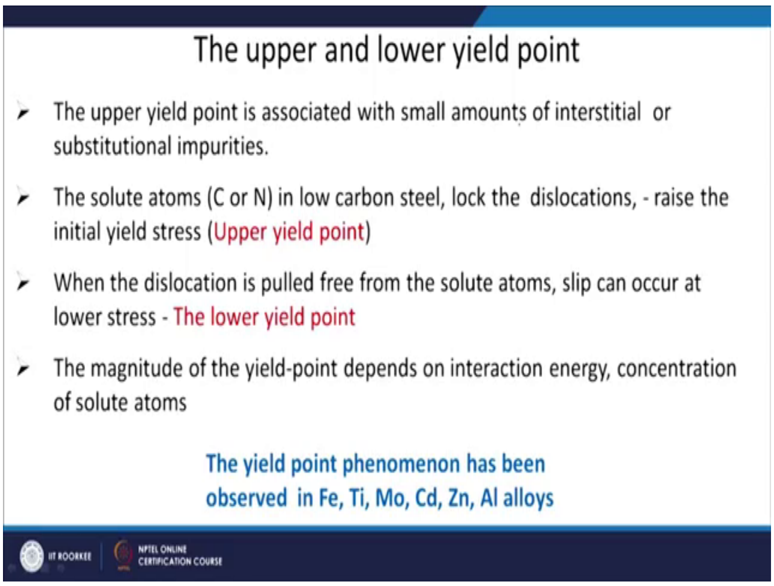

The upper period point is associated with the small amount of interstitial or substitutional impurities. Now, why this yielding this type of phenomena takes place ok; the reason is that the solute atom either carbon or nitrogen endo carbon steel see that a for any material whether if it is a annealed material also dislocations are always going to be there in the material ok. So, to start with the dislocation is going to be there in the material.

Now, as I told you that dislocation has a strain field, and the solute atom also have a strain field. So, these atoms like to go and sit at the core of the dislocation depending upon what kinds of strain fields are there ok. So, all the dislocations are already decorated or there is a kind of atmosphere of this solute atom at the core of the dislocation.

So, when we start the deformation process ok, as I told you that there will be kind of locking of this dislocation, because of this solute atom. So, if I keep on applying the stress on the material ok, so you are forcing the dislocation to move, but these atoms are the solute atoms are pinning the dislocation. But at some point, you will have sufficient stress on the dislocation, so that it starts moving and it will be it will be pulled away from these solute atoms.

So, where it starts breaking away from these atoms that is my upper yield point; so my stress is sufficient, so that it is allowing the dislocation to get rid of this solute atoms, so as soon as they get rid of this solute atom ok, they are free to move. So, suddenly there is a drop of the drop in the stress because now they are free to move ok. And then they are moving, so the luder band will start from two end then it will progress, so that yield point elongation at that time the whole material is getting consumed by the yielding process.

And when the whole material is yielded ok, now the dislocation has started moving in whole of the volume of the material then the strain hardening part will start ok. So, it will raise the initial yield stress. So, this carbon and nitrogen because of locking when the dislocation is pulled free from the solute atoms, slip can occur at lower stress. The magnitude of yield point depends on the interaction energy and concentration of solute atoms. The yield point phenomena has been observed in iron, titanium, molybdenum, cadmium and so on, sink aluminum alloys.

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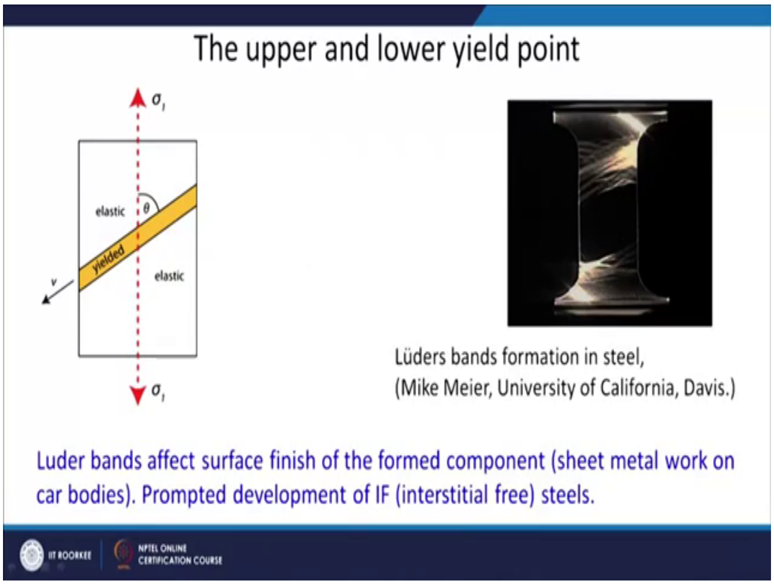

In some aluminum alloys, you will see yield point phenomena. So, the upper and lower yield point ok, if you see this is an actual image of a Luder band formation in the steel, the source is also given here. So, you can see that how they are forming, and they are going to progress over each other and then they will consume the whole material. Now, the problem with this Luder band is that it affect the surface finish of the formed component ok. You can see that they are going to leave some this kind of stretch marks on the on the surface ok.

So, suppose, if you are doing a sheet metal forming ok, you have a sheet which contains lot of dislocation already carbon is there and it is hitting in the at the core of the dislocation. And you want to deformed for making some car body for example, and if this Luder band formation takes place it will affect the surface finish of the sheet. Because of the formation of this you will see some kind of marks on that ok. And a customer when you shows and he sees those marks, he will not like it he will say that there is there is some defect in the material.

So, this has prompted development of another class of steel called interstitial free steel ok. So, this is another type of steel. So, you get rid of all interstitial atoms ok, so that you have an interstitial free steel. And you can get rid of this Luder band formation if there are no solute atoms in the or these interstitial atoms are there in the material ok.

So, now nowadays all the sheet forming you will see that these interstitial free steels are used and that is why I now the painting jobs also become simpler. Earlier old automobiles if you see they used to put a putty over the sheet of the surface to make a very smooth finish on the surface and then they used to paint it. Nowadays, the painting is directly done over the sheet because all these problems are not there ok.

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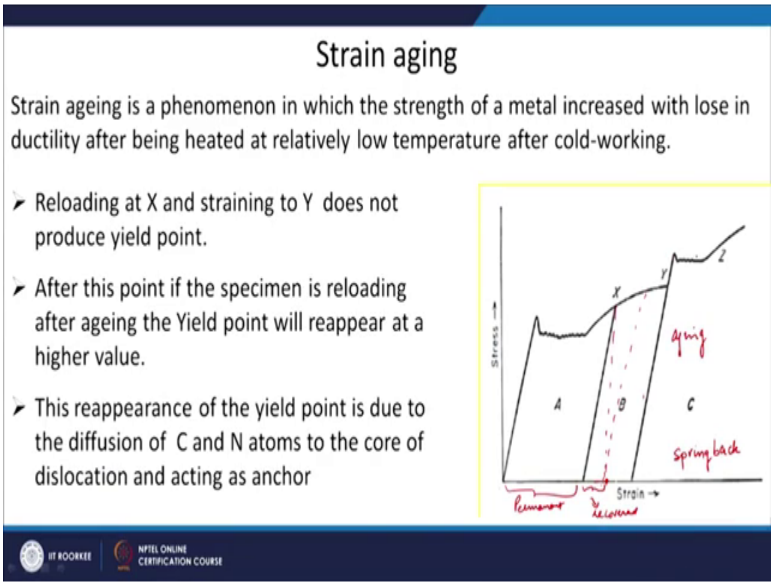

Another problem with solute atom and dislocation is called strain aging ok. So, the what do we mean by that. So, these phenomena in which the strength of a material increase with the loss in ductility after being heated at relatively low temperature after cold-working ok. So, what does it mean? For example, if you can see this is a normal your elastic part, then upper yield point, lower yield point, yield elongation, yield point elongation and then strain hardening.

Suppose, I stop the deformation at this point and I bring it back to the if I remove the load for example, so my load is removed I am but this much strain will remain because this is the plastic part. And one more interesting thing you can say that this is not going to be the strain in the material I have shown the strain of the material by a slanted curve here ok. So, for any deformation process, there is always going to be some strain which is going to be recovered. So, this is my recovered strain, and this is my permanent strain ok. So, this is permanent and this is recovered.

So, whenever I will stop the deformation ok, the total it will not be this much strain which I can plot get by and drawing a perpendicular line to the strain axis it will always be some strain which is going to be recovered. And this phenomena is called spring back. Just I forgot to tell you maybe earlier that is why I am bringing it here now that. This much is strain is recovered and this phenomena is called spring back.

Why it is important is because when you are doing deformation, and when you remove the load some material some deformation will be recovered ok. So, if you are designing a part ok, and you suppose you have designed by the total strain ok, so it after deformation its length should be this much. And this is going to be attached to another part ok, and this part is also going to be attached to another part and this is what you wanted to have the strain in the material after deformation.

So, suppose if you are taking the total strain what will happen there will be some recovery. So, you will find out after the reformation that the length of the part is smaller than what you wanted to attach ok. So, what you have to do is if you want this much strain in the material always deform to a higher extent ok, so that you can get this much total strain. And how you can get this line they actually this line is parallel to the your elastic part the linear part ok.

So, basically where you have whoever you have stopped the deformation from there you plot a line parallel to this linear elastic part ok. And wherever it is cutting this axis, and this will be your total strain, this much is record this much is permanent. So, if I want this much as the total strain is permanent strain in the material, I have to have a higher total strain in the material then I can have this much as the permanent deformation. This is something just a kind of a I have rerouted something here anyway.

So, what we are doing here is you have deformation operator point, and then you started deforming under the strain hardening part. And you have stopped the deformation here and you have removed the load. Now, you have after stopping again you have loaded the sample and is started deforming it ok. So, you can see that it has started from the same point where you have left.

But if I stop this and keep the material at room temperature or maybe a little bit higher temperature for some time, what will happen is that you will see that there is again a reappearance of the this yielding point phenomena. At this point, it has not it was not there, but if I after unloading I at y point, suppose I keep it for some time, and I allow aging to take place maybe artificial aging room temperature ageing, you will see that again the yield point phenomena has reappeared ok. This is because you are giving a time for carbon nitrogen these interstitial atoms to go and sit at the dislocation core.

So, again now dislocation will have to come across this point defects to start the yielding phenomenon. So, if I am not doing the ageing, then I you will not see this yield point phenomena and it will start from where you have left.

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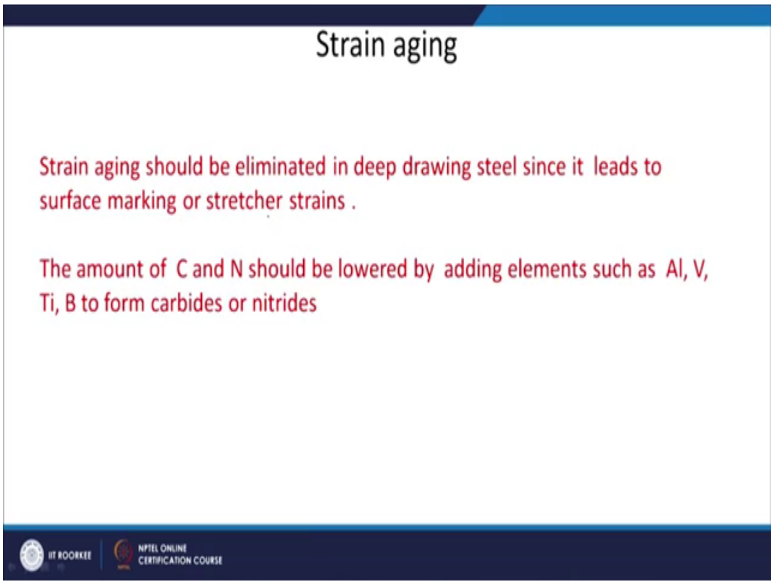

Strain aging should be eliminated for example in deep drawing steels it leads to surface marking or stretcher strains. The amount of carbon nitrogen should be lowered by adding elements such as aluminum, vanadium and so on ok. So, these atoms will react or will form some kind of carbides and so on.

So, there will not be interstitial atoms or carbon has interstitial atom, but it will form either aluminum nitrate for example, with nitrogen or titanium carbide for with titanium and so on. So, they will form carbides and nitrides, and they will not be in free condition not in interstitial position ok. So, and this has to be removed because for example, in deep drawing steel as I told you, but if you to make a car body and so on all these marks will be seen on the surface of the sheet.

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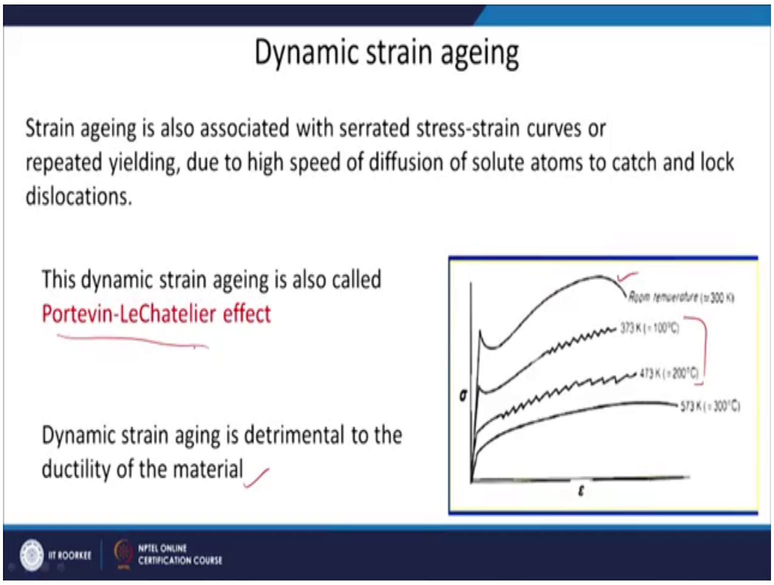

Then there is another problem called dynamic strain aging usually it happens at higher temperature ok. So, for example, you can see at room temperature there is no problem you have a nice flow curve. At some intermediate temperature, you start seeing that there is a serrations on the stress-strain diagram and these serrations are because of dynamic strain aging ok.

So, this is basically repeated yielding due to high speed of diffusion of solute atoms to catch and lock dislocations. So, what is happening is it is like a cat and mouse game between dislocation and the solute atoms. So, dislocation is moving solute atom can also diffuse at high temperature, at room temperature solute atom diffusivity will be very low, we have already seen in diffusion that so diffusion depends on the temperature.

So, this dislocation is moving my atoms can also diffuse ok. So, if the velocity of dislocation and solute atom this kind of matching then you will see that this cat and mouse game is going on between dislocation and the solute atom. And of course, very high temperature there way the solute atom will be able to go diffuse with the dislocation. So, there is no problem. And the problem with dynamic strain aging is it is not good for the ductility of the material ok. The ductility where with you see this dynamic strain aging, the ductility of the material comes down and this effect of dynamic stretching is called Portevin-LeChatelier effect.

So, with this, I thank you so we have discussed the interaction between the point defects and the dislocations. And it can be used as is strengthening mechanism as well as it kind of sometime gives you a problems which we have to understand to get rid of those problems ok, so that is what we have understood ok. Now, next we will see another strengthening mechanism in the next lecture.

Thank you.