Mechanical Behavior of Materials
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Lecture - 32
Strengthening Mechanisms in Crystalline Materials - V

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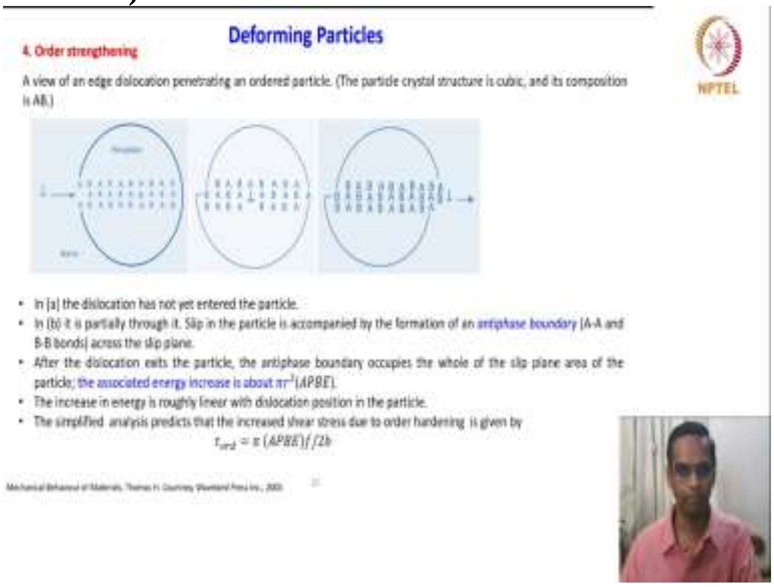

Hello, I am Professor S. Sankaran in the Department of Metallurgical and Materials Engineering. Hello, welcome to this lecture again we will continue our discussion on strengthening mechanisms in the last class we stopped with you know particle hardening even in particle hardening we looked at some of the aspects like coherency hardening, chemical hardening and then surface energy contributions from chemical hardening etcetera.

In that aspect we also looked at the idea of you know, the similar hardening mechanisms involving surface energy is another two mechanisms namely stacking fault energy as well as order hardening. These two concepts are all similar to surface energy hardening or chemical hardening. So, the physics of this surface energy the stacking fault energy and order hardening they are all similar. So, we will look at order hardening one more closing. So, what we are seen here is a particle which is an edge dislocation is approaching this particle.

And this particle is a precipitate and this is a matrix and this is not simple precipitate. This is a particle of ordered precipitate the particle crystal structure is cubic and its composition is AB that means you are going to have AB AB AB atom in a single plane and then the subsequent planes are going to be like this that means, the surrounding of the A and B will be similar. So, B surrounded by A and A is surrounded by B something like that. So, if the edge dislocation if it enters the particles then what happens to this the atomic arrangement is the question.

So, what is happening here we are seeing that the moment the edge dislocation cuts through an enter the particles. The bond which is already there original bonds AB AB will become BB AA BB and AA so, this is going to create a new interface something like this and then the moment the dislocation exit the particle then the whole interface is going to become AA BB AA BB kind of a bonds, what is special about this. So, the slip in the particle is accompanied by the formation of antiphase boundary.

That is so the boundary which we are now looking at is called antiphase boundary which consists of AA and BB bonds across the slip plane why it is important. So, after the dislocation exists the particle, the antiphase boundary occupies the whole of the slip plane area of the particle the associated energy increase is about πr^2(APBE) that is antiphase boundary energy.

This is important because thus the energy of the system is raised. So, this interface will have a higher energy that is why it is of important to discuss the increase in energy is roughly linear with the dislocation position in the particle. The simplified analysis predicts that the increase the shear stress due to order hardening is given by $\tau_{ordering} = \pi(APBE)\, f / 2\, b$.

So, this is a simple analysis for the order hardening and this is not the I mean the simple analysis not the going to not just going to help us in a great way because this assumption whatever we have just looked at a edge dislocation straight edge dislocation entering into the order precipitate and then it pass in entries and it does not consider the second dislocation which can enter this particle.

Suppose if you imagine a second dislocation of similar kind enters this particle and then moves away then what happens then the original lattice will get restored. So, if you recall what will happen to the lattice when edge dislocation cut through in our dislocation lecture if you recall, in fact I put some schematic where letter A was you know drawn and then we made that edge dislocation to cut through that lattice.

Which is containing the letter A and then you see that the complete displacement happens though the lattice will restore its original configuration, but your pre atom will find its new neighbour. So, that is a passage of one into dislocation will result in. So, here we are now talking about a second dislocation because the first dislocation, edge dislocation has created an antiphase boundary in the second dislocation comes in a way.

Then this antiphase boundary will be eliminated and the ordered crystal will be restored. But the question here is suppose what we have learned from the dislocation theory the dislocation theory says that if the two edge dislocations of the similar sign what will happen we are going to repel each other. So, when the two edge dislocations are going to repel each other, then this two dislocation.

You know will try to keep the independent dislocation far away depending upon the energy consideration. If the dislocation proportion is high enough then it will be the dislocation will be well separated but still you can just analyse you know one dislocation cutting through this particle and then look at the energy how it changes but that is not going to be the case suppose if you think that the two dislocations.

You know the antiphase boundary energy is low or high depending upon that these two dislocation can come or cut through the particle together or travel together that is going to be decided by the antiphase boundary energy. So, we are going to just look at the details in a minute, but before that if you assume that these two dislocations are going to travel together then that configuration is called super dislocation.

Because the Burgers vector is going to be not the having the normal magnitude it is going to be double. So, it is that is why it is called super dislocation. So, for a normal circumstances if you take you know 1 / 2, 1 1 1 like you know it is a lattice translation vector in a BCC for example, I am saying in order crystal they are not going to be the lattice no longer going to be the lattice translation vector but it will be a complete full, two times the normal virtual sector. So, that is why it is called super dislocation this is one idea you have to remember.

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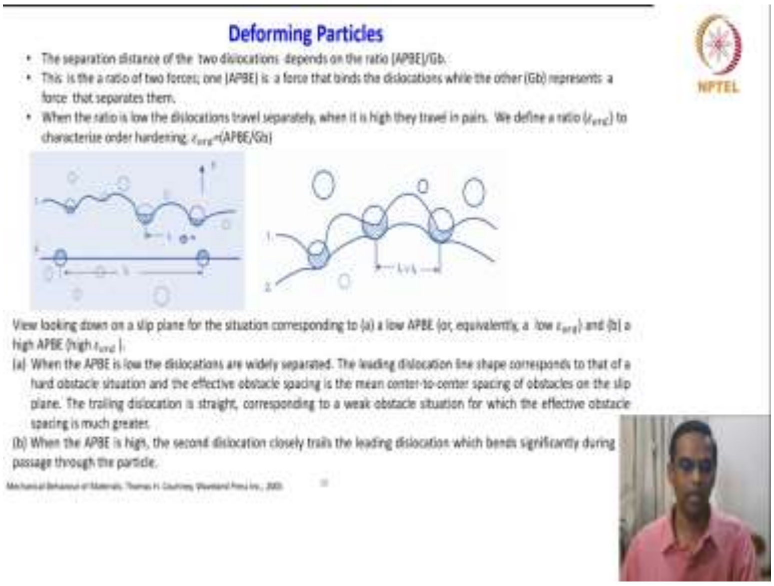

So now, the separation distance of the two dislocationS depends on the ratio of antiphase bounding energy(APBE) /Gb. This is a ratio of two forces one antiphase boundary energy is a force that binds the dislocation while the other Gb represents the force that separates them. So, depending upon the ratio the separation of these two dislocation will be decided when the ratio is low the dislocation travelled separately.

When it is high they will travel in pairs, we define a ratio ε_{order} to characterise the order hardening that is $\varepsilon_{ordering}$ = (APBE /Gb). So, this is very important. So, look at these two schematics one case we are we are showing that the particles are just dispersed in the matrix and the one list of dislocation line goes and then the other dislocation line is straight which follows.

So, you can also now recognise the contours of this line this particular dislocation line try to bind around this particle, but the second one is going straight. So, you know the meaning of this now, so, when you say the dislocation line is going to bend around the particles then that means it is going to form a loop around this that means the particles are harder this is what we have seen yesterday in the last lecture.

But when the dislocation line is remaining straight and then it just travels that means the particles are weaker. So, that is also another idea just I am trying to recall that is not important here we will just see in the context of the ratio of APBE versus APBE to Gb that ratio we will just discussed, on the other hand this particular image shows that the both the dislocation travelled together mostly trying to bow against the particles.

So, this is the view looking down on the slip plane for a situation corresponding to a low APBE or equivalently low $\varepsilon_{ordering}$. So, when the APBE energy is low, these two dislocations are going to get separated and then they are going to travel together and the situation (b) high antiphase boundary energy or high ε hardening then they will move as a pair the distance will not be separated as shown here this schematic.

So, when the antiphase boundary energy is low the dislocations are widely separated the leading dislocation line shape corresponds to that of a heart obstacle situation and effective obstacle spacing is the mean centre to centre spacing of the obstacles on the slip plane. So, this also adjust illustrated clearly in the previous lecture when this particles are considered to be hard. Then the obstacle spacing is centre to centre of each individual obstacles that is l_1 here. The training dislocation is straight corresponding to your weak obstacles situations for which the effective obstacle spacing is much greater. So, the effective spacing comes like l′ we have seen in the previous lecture here it is referred to as l_2 which is much greater than the l_1 when they APBE is high, the second dislocation closely trails the leading dislocation. Which bends significantly during the passage to the particle. So, this is going to happen. So, that means when these two dislocations are going to move as a pair obviously, there will not be any antiphase boundary that you have to remember.

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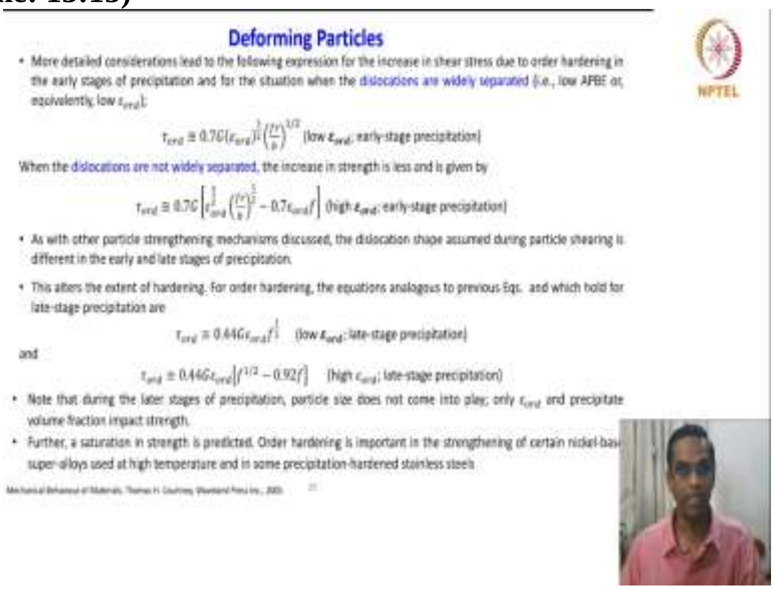

So, more detailed considerations lead to the following expression for the increase in the shear stress due to the order hardening in the early stages of precipitation and the situation when the dislocations are widely separated that means low APBE are equivalently low ε_{order}. So, for this situation there are a semi-quantitative expression is developed and this is given in this form.

So,

$$\tau_{ord} \cong 0.7\, G\, (\varepsilon_{ord})^{\frac{3}{2}} \left(\frac{f r}{b}\right)^{1/2} \quad (Low\ \varepsilon_{ord};\ early - stage\ precipitation).$$

When the dislocations are not widely separated, the increase in strength is less and it is given by

$$\tau_{ord} \cong 0.7\, G \left[(\varepsilon_{ord})^{\frac{3}{2}} \left(\frac{f r}{b}\right)^{1/2} - 0.7\varepsilon_{ord} f\right] \quad (high\ \varepsilon_{ord};early - stage\ precipitation)$$

Where, the ε_{order} is high and this is again valid for the early stages of precipitation.

So, you have to remember all these expressions are derived when or it is assumed when the precipitation happens or the precipitation size is considered at the early stage that means it is not percent enough, that is what you are to remember. As with the other particle strengthening mechanisms discuss the dislocation shape assumed during the particle shearing sharing is different in the early stage and late stages of precipitation.

This alters the extent of hardening for order hardening the equations analogous to the previous equations, which hold for the late stage representations are of this form

$$\tau_{ord} \cong 0.44G\, \varepsilon_{ord}\, f^{\frac{1}{2}} \quad (low\ \varepsilon_{ord}; late - stage\ precipitation)$$

Again, this is for the late stage of precipitation where low $\varepsilon_{ordering}$ is revised on the other hand for the late stage of precipitation again with the high $\varepsilon_{ordering}$.

Then what happens then it becomes the equation becomes

$$\tau_{ord} \cong 0.44G\, \varepsilon_{ord} \left[f^{\frac{1}{2}} - 0.92f\right] \quad (high\ \varepsilon_{ord}; late - stage\ precipitation)$$

Note that during the later stages of precipitation particle size does not come into play only ε_{order}, under precipitate volume fraction impact the strength. So, this is the information this two empirical relation gives as the late stage of presentation.

That means, during the after the portioning particles becomes slightly closer than the size does not matter, but ε, ε_{order} you know the lattice parameter mismatch and the precipitation volume fraction will have huge impact on the strength further a saturation in the strength is predicted order hardening is important in strengthening of certain nickel based super alloys used in high temperature and in some precipitation hardened stainless steels.

All these expressions shown here they are all you know what very well in these ally systems like nickel based super alloy systems some of these stainless steel stainless steel precipitation hardened systems these expressions worked out or predicted the strength pretty well.

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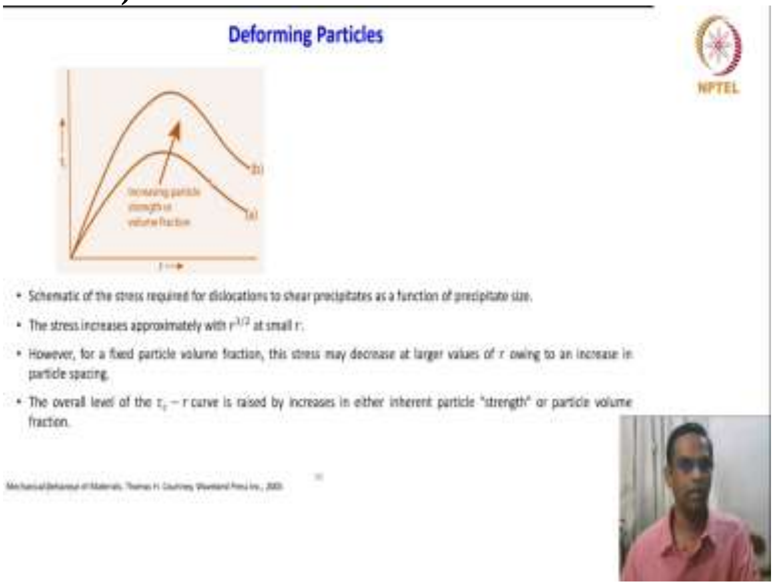

So, if you look at the in general, we have now discussed several strengthening mechanisms this is a critical stressed τ for τ_c means cutting when the dislocation cutting them to the particle that stress versus diameter what you are seeing here is the stress required for the dislocation to shear precipitate as a function of precipitate size. So what does it show the stress increases approximately with r ^1/2 at small r as long as R is small it is strength stresses.

You know approximately increases with r ^1/2. However, for the fixed particle volume fraction, this stress we decrease at larger values of r owing to an increase in particle spacing. See, this clearly illustrates the importance of different parameters which is associated with the particle hardening not just particle size, it is a particles spacing as well as the other energy concentration.

You have to remember it is not that simple, we are going to illustrate those parameters in a minute. So, the overall level of τ_c- r curve is raised by increases in the either inherent particle strength or particle volume fraction. So, this direction simply indicates either the volume fraction should be increased or the particle should become hard. So, these are the two aspects which is going to increase the τ_c.

That means these two parameters volume fraction and the hard particles especially at the early stage, they are going to contribute significantly to the strength other than the rest of the parameters.

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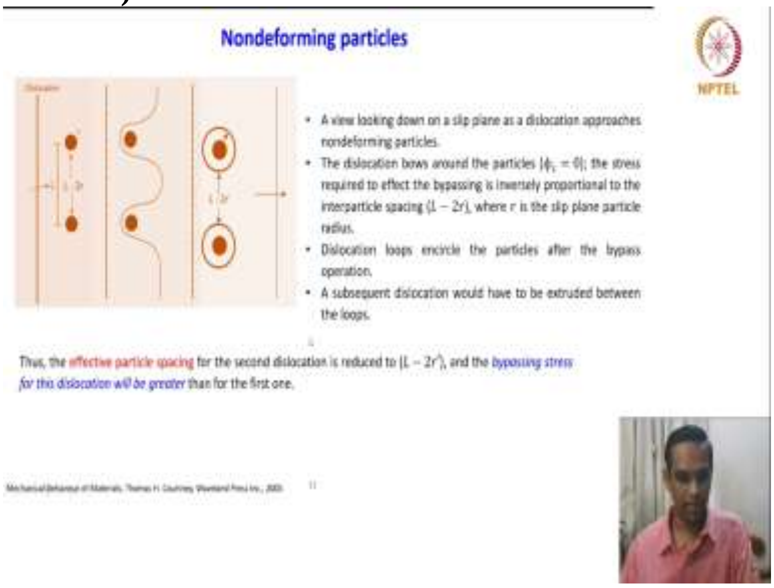

Now, we turn our attention to non-deforming particles. So, far we looked at deform particles. We now look at the non-deforming particles. So, for that we look at this popular schematic which is given in most of the texts all of you must have seen so, this is a two particle which is you know separated by the distance L, and each particle having the radius r and the dislocation line is just approaching this and the distance between the inner distance I would say this is centre to centre distance is L.

The inter particle distance is L - 2r the dislocation is approaching and it is not going to cut this cut this particle because they are all non-deformable so, it is trying to form a loop and then it loop is formed and then it moves further like similar mechanisms what we have seen in the primary source type of thing but now, what you are now see the interparticle distance L - 2r become L - 2r′ the distance is coming down.

So, what are the implications of this kind of system the dislocation bows around the particle that means, $\phi_c = 0$ the stress required to effect the bypassing is inversely proportional to the inter particle spacing (L - 2r) where r is the slip plane particular radius dislocation loops encircle the particles after the bypass operation a subsequent dislocation would have to be extruded between these loops.

Thus the effective particle spacing for the second dislocation is reduced to (L - 2r′) and the bypassing stress for this dislocation will be greater than the first one you see, this is very important point we have to remember the dislocation line comes and it forms a loop around a particle and then it moves away. So, the inter particle distance comes down further to (L - 2r′).

So, this is going to increase the stress for the dislocation which is going to come after this the second dislocation which is going to encounter this, the looped particles they are going to experience significantly higher stress to interact.

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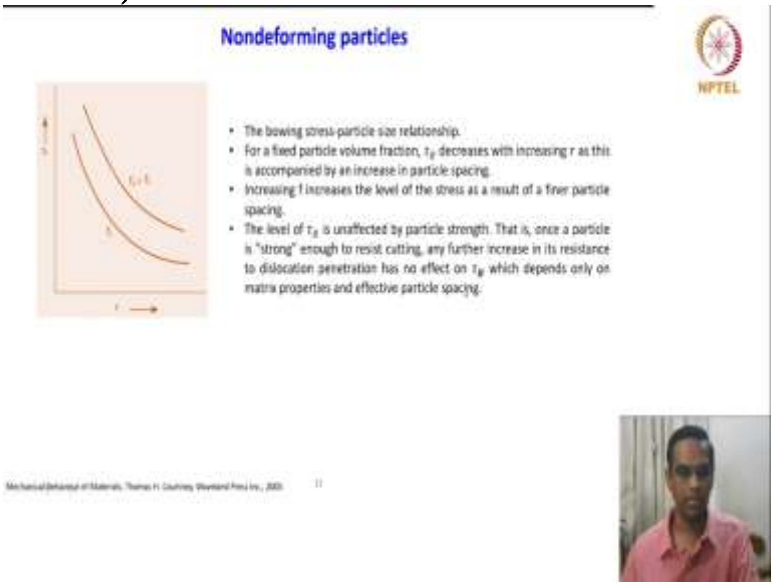

So, what is that this plot shows this is τ_B. τ_B is shear stress required to bow around the particle for the dislocation as a function of r. So, it is called bowing stress particle size relationship for a fixed particle volume fraction. τ_B decreases with increasing r as this is accompanied by an increase in particle spacing. So, increasing f increases the level of distress as a result of a finer particle spacing the level of τ_B is unaffected by particle strength that is once a particle is strong enough to resist cutting any further increase.

In its resistance to dislocation penetration has no effect on τ_B, which depends only on the matrix properties and the effective article spacing this is again very important point as long as the particle strength is concerned.

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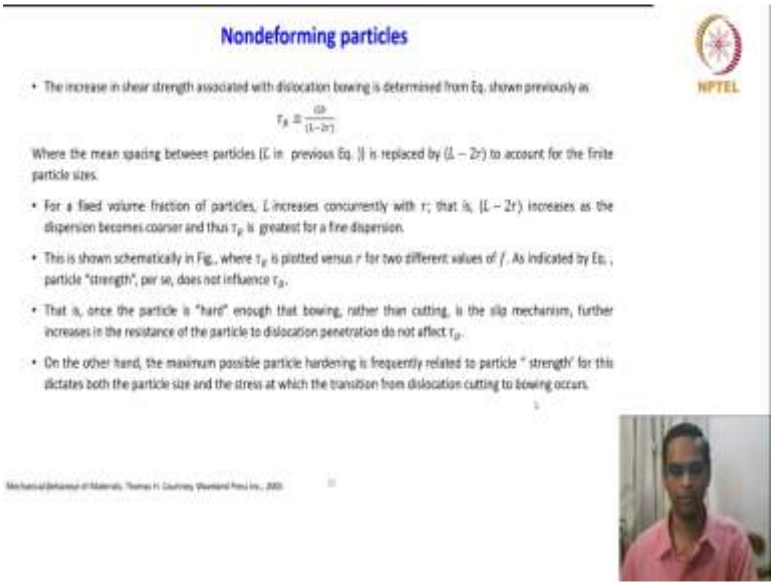

So, the increase in the shear strength associated with the dislocation bowing is determined from the equation shown previously, several equations we have talked about and this the simply replace this L / L - 2r we are replacing L / L – 2r where the mean spacing between particles is replaced by this to account for the finite particle sizes. For a fixed volume fraction of particles L increases concurrently with r.

That is (L - 2r) increases as the dispersion becomes closer and thus τ_B is greatest are the finer or fine dispersion and this was shown in the figure what we have just seen where τ_B is plotted versus r of the two different values of f, as indicated by the equation particle strength per se does not influence τ_B. That is once a particle is hard enough that is bowing rather than cutting is the slip mechanism.

Further increases in resistance of the particle to dislocation penetration do not affect τ_B. So, the moment you see that particle is hard bowing is the slip mechanism rather than cutting that is a message on the other hand the maximum possible particle hardening is frequently related to the particle strength for this dictates both particle size and the stress at which the transition from transition from dislocation cutting to bowing occurs.

This is another important point we are going to look at now. So, when we look at the maximum possible particle hardening which is related to the strength of the particle and it is not just strength of the particle both particle size and the stress at which the transition from dislocation cutting to bowing. So, we are now talking about the transition from dislocation cutting to bowing occurs so how this transition is realised.

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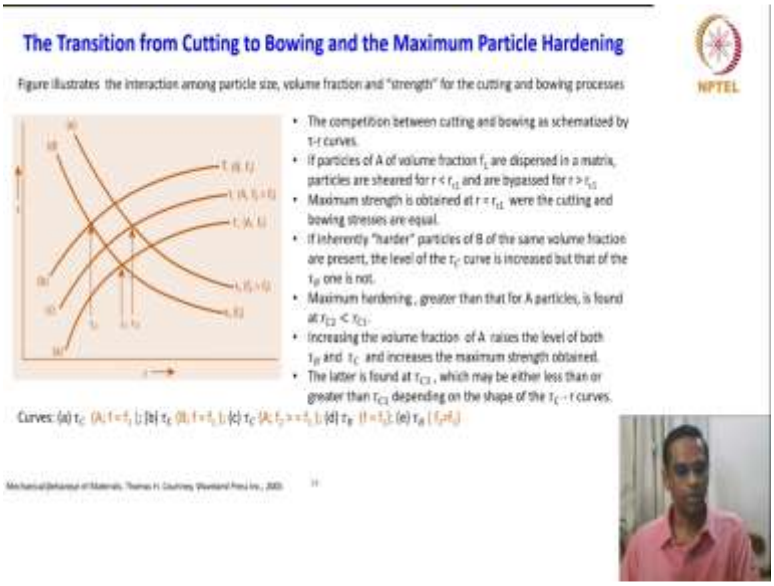

This is what we are going to look at now, the transition from cutting to bowing and the maximum particles and we are going to have a figure which is which is going to be like this basically a very clumsy figure to start with, but we will go through one by one the figure illustrates the interaction among the particle size volume fraction and strength for the cutting and bowing processes.

What is this figure shows this is τ - r and another description for this figure is the competition between cutting and bowing is schematize in the τ or curves, let us now go through one by one what is curve a curve a is showing τ_c that is cutting stress for particle A.τ_c for a particle A with the volume fraction f_1. So, the τ_c varies with respect to r like this that is A.

What is B? B is again τ c for a particle B with a similar volume fraction like A that goes like this, this is a cutting stress versus r for the B that means B is much harder than the A that is what you are seeing this. So, what is c? c again cutting stress against r for particle A, but this is for a different volume fraction the volume fraction is f_2 now which is greater than f_1. So, interesting and d is the τ_B bowing stress.

Bowing stress for a volume fraction f_1 and e is a τ_B variation with respect to r for the particle of volume fraction f_2 ,where $f_2 > f_1$. So, it is quite interesting plot in fact, if you look at very carefully, so, now, what are all the critical parameters we have to look at we will see one by one if particles of A of volume fraction f_1 are dispersed in a matrix particles are sheared for $r < r_{c1}$ and are bypassed for $r > r_{c1}$.

So, what does it mean, we are not talking about particle A. So, this is cutting stress going up to this and then here it you know intersects with the curve d. So, that particular point the intersection point the r s, r_{c1} so, it is as long as the particle radius is less than this r_{c1} this particle a is going to get sheared the moment the radius becomes greater than this r_{c1} then it is going to bypassed. So, this is cutting up to this r_{c1} and then after that it is bypass the maximum strength is obtained at $r = r_{c1}$ where the cutting and the bowing stress are equal. So, at this particular point r c1 the stress required to cut and bypass the particle r equal. So, this is quite interesting discussion if inherently harder particle of B of the same volume fraction or present, the level of the τ_c curve is increased but that of the τ_B one is not.

So what does it say we are now talking about B so, the strength is increased for only cutting τ_c is increased but τ_B is not increased. The maximum hardening greater than the top for A particles is found that r_{c2} is less than r_{c1}. So, this is a maximum hardening for B which is greater than the particle A, we are talking about particle B which occurs at r_{c2} which is less than r_{c1}.This is r_{c1} this is r_{c2}. Increasing the volume fraction of A raises the level of both τ_B and τ_c and increases the maximum strength obtained. So, now A volume fraction is increased in the seeker so, we are talking about this point the maximum strength is also increased and τ_B and τ_C also increased so, the increasing the volume fraction the particles gives most you know possible our maximum particle hardening effect.

It is perceive the latter is formed at τ r_{c3}. So, this is τ r_{c3} which may be either less than or greater than τ_{c1} this could be greater than or τ_{c1} depending upon the shape of the τ_c-r. So, this could be so each τ_c curve has a different shape. So, depending upon the shape the τ values also is going to be different. So, by looking at all this interaction term what you are realising is.

The τ-r, curve keep on increasing it reaches a maximum point and it comes down and this kind of behaviour mostly observed in I mean are commonly observed in most of the presentation hardened systems. But there are some systems which checks which initial increase in the τ and then it shows a plateau and then it decreases that is also how people have found and reported. But in general this kind of reaching maximum and it is come down is normally supported by most of the precipitation hardened alloys.

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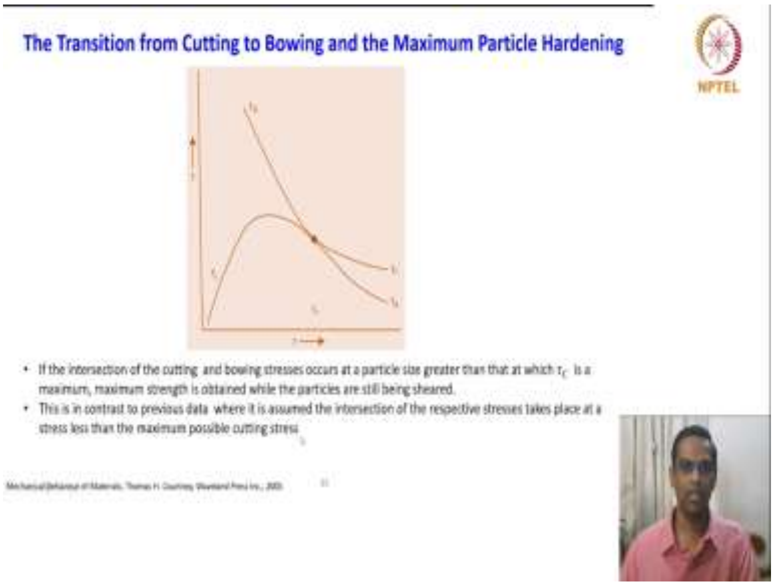

There are some systems, where you are going to see the you know the maximum, the τ_C is maximum. That occurs still in the shearing of the particle rather than intersection of the bowing stress in the previous system, the maximum was found in the intersection of the τ_B and τ_C, but some of the materials exhibits this kind of behaviour that is the intersection of the cutting and bowing stresses are occurs at a particle size greater than that at which τ_C is the maximum strength is obtained while the particles are still being sheared.

So, that is what it is. So, here the maximum strength is obtained for the alloy, but still the mechanism is particle shaped this is in contrast to previous data where it is assumed the interaction or intersection of the respective stresses takes place at a stress less than the maximum possible cutting stress. So, what we have now seen is you know we have looked at quite a bit of mechanisms for the strengthening the alloy.

Especially the detail idea about you know particle hardening, we looked at different mechanisms and different possibilities and which are all very technologically important you know systems. So, with this background, we will now go to the actual material properties we now start looking at the material properties, we look at mechanical testing and then how the each material will behave.

Now we have enough background to look at the mechanical property, whatever the, you know, the material system could be now we have the enough background to look at the mechanic data and then interpret them based on the knowledge we have upgraded so far. So, we will stop here and then we will start from the mechanical testing in the next lecture.