Mechanical Behavior of Materials-1

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Lecture - 34
Precipitation Strengthening: Mechanisms

So now we know that the characteristics like size and interface between the precipitate and matrix, they change with aging times, okay. So now what we are going to do, we are going to try to understand how these changes in the characteristic are going to affect the way dislocations interact with the precipitate, okay. So let us try to understand that.

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So dislocations can interact with the precipitate in two ways, okay. The first one is dislocations can cut or say shear the precipitates, okay. And the second one is it can bypass the precipitate, okay or we call it say bowing around of dislocations, okay. We also call sometimes as bypassing. I am going to explain each of these okay one by one.

And depending upon whether the dislocations are cutting or shearing the precipitate or bowing around of dislocations the interactions the strength of the material or say in this case we are talking about focusing on aluminum alloys, the strength of aluminum alloys is going to change okay. So let us talk about the first one, the shearing or cutting of the precipitate, okay. Shearing of precipitates, okay.

So the name itself suggests that you have a precipitate okay and the dislocation is coming okay and it cuts or shears the precipitate, okay. It is like you have a watermelon and you have a knife and you are cutting it. So you can imagine something like that, okay. So suppose you have a dislocation. So this is your dislocation line and you have a precipitate. Let me change the color.

Okay, so you have this precipitate here and you have dislocation, so this is your precipitate and this is your dislocation, okay. So dislocation is moving on a slip plane. It finds a precipitate there, okay. Now I have already mentioned. Now it can do two things. It can either cut it or it can bypass it okay, the dislocation can bypass it. Right now we are talking about cutting of the precipitate, okay.

So when it interacts when it cuts it, the precipitate is going to be something like this, okay something like this. So it is going to create two new surfaces okay, so it is going to cut. So this is cutting, after cutting. So it has cut the precipitate, okay. So I have the schematic also.

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So this is how the schematic looks like. So you have a slip plane here. So this is your slip plane for that particular dislocation and this is your half plane and this particular line, the blue line here is your dislocation line and Burger vector is also shown in red, right? And the circle here, the sphere here is your precipitate. So this one is your precipitate, this guy here okay.

So now the dislocation is moving on its slip plane, we can see in the bottom one here, dislocation is moving the slip plane. As soon as it reaches to the precipitate it cuts it, okay. This is after cutting, okay. And this I have taken from Professor Anand Subramanyam's lecture note. He is a professor at IIT Kanpur, okay. So this is how dislocation is going to cut the precipitate.

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Now, so there are six properties of the particle which can affect the way a dislocation interact or in this case precipitates can be sheared, okay. Let us try to understand those. So six properties of the particle or precipitate affect the ease at which it can be sheared okay. So what are those six properties? The first one is coherency strain. And this one we have already studied before, is it not?

So in the coherency strain as I mentioned before that whenever you have a coherent interface you are going to have some amount of strain associated with it, right? Now a dislocation moves on a slip plane, it comes near to the precipitate, dislocation already have a strain field associated with it. Now you have coherency strain associated with the precipitate, is it not?

So these strain fields are going to interact, okay. So coherency strain is there. Second one is stacking fault energy. So there is a significant difference between the stacking fault of particle or precipitate and the matrix, right? So the local variation of the fault weight will affect the interaction between the dislocation in the precipitate. So that is the second factor. Now the third is order structure, okay.

So the if the precipitate has a order structure and typically most of the precipitates are going to have some sort of order structures, especially Al2Cu and other precipitates, right. They are going to have order structures. So if they have order structures and dislocation, you know shear them then you are going to introduce anti-phase boundaries, okay. And that will also try to enhance the strength.

Now the fourth one is modulus effect. Now if the precipitate and the matrix both have different modulus right and remember the dislocation energy is also associated with the modulus, right? So if dislocation moves from the matrix to the precipitate and it shears it, it is going to change the energy of the dislocation, is it not? So that will also require some amount of energy.

It might decrease or increase, okay. But they will be changing the energy of the dislocation, is it not? So that is the fourth effect. The fifth is interfacial energy. Now if you see what I showed before, so you are going to create new interfaces here, right. Now the creation of these new interfaces will also require some amount of strain energy. So it will also enhance the strength, okay.

So that is what when I wrote interfacial energy, that is what I mean, okay. So creation of new interfaces will require extra amount of energy. And the last one is lattice friction stress. So both matrix and the precipitate both are going to have the internal frictional stresses right, like your Peierls stress, okay. So when a dislocation moves from the matrix to the precipitate and tries to shear it right.

So you are going to, dislocation is going to observe different friction stresses, okay. So these are the six points or six properties of the precipitate which can affect by the way a dislocation is shearing the precipitate, okay.

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Now I have listed the formula related to all these effects. This is taken by the book of Dieter, from the book of Dieter, okay. So like coherency strain, you have a factor of epsilon here. So this is your coherency strain and if you see all of these properties are depending upon the radius, radius of the precipitate, okay. So overall if you see, you can go through these formula.

It is standard and it is given in all the books, but you know there might be some variations in terms of the constant etc. Otherwise the concept remains the same, okay.

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So overall cutting or shearing of the precipitates will be preferred when the precipitate is coherent and small in size. So dislocation will try to cut the precipitate when it is smaller in size and the interface is coherent, okay. So overall dislocation will prefer to shear or cut the precipitate when it is small in size and the interface between precipitate and matrix is coherent. So it has to be smaller in size and coherent interface, okay.

So if a dislocation is moving on the slip plane it finds a precipitate, right? The dislocation will prefer to cut it or shear it if the precipitate size is small and the interface is coherent, okay. Now if the precipitate size becomes larger and larger and that is what we also discussed before is it not that with respect to time the precipitate size is going to increase. So after certain amount of time the precipitate size will be larger.

And now the dislocation will find it very difficult to cut because the stress required to cut the precipitate will be higher if the radius is higher, okay. So typically the stress required to shear the precipitate varies proportional to root r, okay. So if this radius is higher, stresses for cutting the precipitate is also going to be higher. So after you know some amount of time your precipitate size is large enough that dislocation will find it to cut it.

Now what to do? Now the second option is there. The instead of cutting dislocation we will try to bypass the precipitate or there will be bowing of the dislocation, okay. So the second option is bypassing, right? Bypassing the precipitates or bowing off dislocations, okay.

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So when precipitate size is too large to be sheared then dislocations find a way to move around, move around the precipitates, okay. So if the size is very large, dislocation will find it difficult to cut it because the stress is proportional to root r. So it is going to bypass the precipitate and how does it do it? So let us see it. So suppose you have two precipitate, something like this and then you have a dislocation which is moving under the applied stress of tau, okay.

This is your dislocation, okay. Now after some time it is going to close near to the precipitate and then it has to bypass it, right? So it is, what it will do? Since it cannot cut it, it will bow around the precipitate, okay. So let me first draw the precipitates so that I can show the sequence, okay. So all these are your precipitates. Now let me move the dislocations. So as soon as it reaches to it, it is going to bow, going to be something like this, okay.

So this is say situation number one, situation number two where dislocation is bowing, okay. Now what will happen? After some time it will bow more. So situation is going to be something like this, okay. Now if you see the dislocation line vector direction is going to be this way, is it not? So see the direction of arrow, okay. So now at these two points this point here, this point here.

Similarly this point here and this point here, okay. The direction of dislocation line vector is opposite, is it not it? So what is going to happen? They are going to annihilate, okay. So finally what you are going to have, a loop of dislocation because these two sections here, so these two sections right, this point, let me change the color now. So this particular point and this point they are going to annihilate.

Similarly, these two points of the dislocation vector they are going to annihilate, okay. And finally, they are going to leave a loop around the precipitate and then this dislocation will move forward, okay. So you have now generated two loops, one this one here and another one here, okay. So see you have now learned a way of generating more number of dislocations also.

So you had one dislocation, which was moving on the slip plane and then it observes two precipitates which are of larger size. It cannot cut them, so it bows around the precipitate and by doing that, it also generates new number of dislocations, more number of dislocations, okay. So you have learned a new method of generation of dislocations, okay.

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$$\Delta\tau = \frac{2\alpha Gb}{\lambda}$$

So overall if I write, under applied stress tau okay, the dislocation bows in between the particle, right. You can see it, number two here, sequence number two, between the precipitates, okay. And after that what is going to happen? The segment of dislocations with opposite direction they are going to annihilate, right? So the segments of dislocation with opposite direction right, or opposite line vector cancel each other, right?

And by doing that they form a new loop right, so dislocation loops, okay. So if the particle size, precipitate size is larger, dislocations are going to bow around the precipitate. And if it is smaller, then the dislocation is going to cut through the precipitate, right? Now as far as the stress is concerned, stress can be given as 2 alpha Gb by say lambda where lambda is the distance between the two particle or precipitates.

So if you have one and second precipitate here, so this distance, okay. So if this is lambda, so this. The stress, incrementing the stress for bowing the dislocation will be given as 2 alpha Gb by lambda where lambda is the inter particle distance or spacing, okay.

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$$\Delta\tau = \frac{2\alpha Gb}{\lambda}$$

So overall here if I want to write similar to what I wrote in the cutting of the precipitate. So overall I can write that bowing around of dislocations will be preferred when the dislocation, sorry not the dislocation, when the precipitate size is large, okay. So if the precipitate size is small dislocation is going to cut. If it is large it is going to bypass, dissociation is going to bypass.

So now let us combine both of them and try to understand how the shear stress, this delta tau right or tau is going to vary with respect to size of the precipitate, which is somewhat related to the aging time also right, because if we increase the aging time the size of the precipitate is going to increase, okay.

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So let me draw. So here we have tau okay shear stress and then on the x axis we have particle radius or precipitate radius, say r okay. Now we know that if we increase the precipitate size, particle size, your stress required to share the precipitate is going to increase okay. So let me draw it. So something like this, okay. So this black dotted curve will belong to cutting of precipitates, okay.

Now let me draw another one corresponding to the bowing of dislocation, bypassing the precipitate, right. So that is going to vary something like this, okay. Because the bowing of dislocation around the precipitate is inversely proportional to r because as we increase the r the distance between the particle or precipitate is going to reduce, okay, sorry it is going to increase okay.

So overall the strength, the stress required to bowing the dislocation around the precipitate is also going to reduce, okay. So now if I combine these two my net curve is going to look something like this, okay. So the blue one here is for bowing of dislocations and the final red one is the net curve, okay. And the maximum here will correspond to a radius, let us say we call this radius as r c or critical radius, okay.

So below the critical radius now if you see this curve, overall curve is now the red one, okay. So below the critical radius we have cutting of precipitates, okay. And above the critical radius the bowing of dislocation is going to be dominant mechanism, okay. So the mechanism changes with respect to radius. So with aging time the radius of the precipitate or precipitate size is increasing.

As soon as it reaches to a particular radius say here in this critical radius your mechanism is going to change from cutting of the precipitate to bowing around the precipitate, okay. And at the critical radius both mechanisms are going to be active together, is it not? Okay? So this is how the strength of a material is dependent upon the particle radius or precipitate size, okay.

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So we can write here that as precipitate size increases you know there will be increment in the shearing stress, okay. Now second we can write a critical radius r c is reached when both right, both are comparable for cutting as well as bowing, when bowing is comparable to that of shearing. This means both will be active, both mechanisms will be active. And after this, after it reaches to critical radius you have only bowing right, bowing of dislocation is dominant, okay?

So this is how the characteristics of precipitate size and interface will determine the shear stress required, okay. So it changes with respect to size of the precipitate, okay? So now let us come to something called aging curve, which typically you know all experiments, we will try to find out when we talk about the aging behavior of aluminum alloy or precipitation strengthening in aluminum alloy, okay.

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So let us understand what is aging curve, okay? So what we do here we plot hardness versus aging time, okay? Now we know that with respect to aging time the size of the precipitate is going to change and that will also lead to the changing in the shear stress required, okay. So here we are going to plot the hardness of the sample with respect to time, okay. And how do we do the experiment?

So what we do? We take number of samples. Suppose I want to do the same experiment for aluminum 4% copper and want to generate the curve. So let us say aluminum 4 weight percent copper. We are taking this particular alloy, and I want to generate the aging curve for this alloy. So what I am going to do, I am going to turn the alloy in small samples, number of samples.

And I am going to put all the samples together in the furnace okay, artificial aging we are doing, okay. So the first step is solution treatment. So we will go to high temperature, make it single phase, put all the samples together and then we will quench it, okay. All the samples we are going to quench one by one.

And then we are going to place all the samples together in another furnace, which will be maintained at a lower temperature say T 2. We have discussed what T 2 is right, to perform the aging treatment, okay. Now we have kept all the samples. Now after some amount of time we will take out one sample say T 1, then another sample at T 2, another sample at T 3 and so on.

And then for each sample we are going to measure the hardness of that particular sample. In that way what we are going to get is something like this. So we are going to plot time on the x axis, then here we are going to have hardness on the y axis and this is aging time here, okay? So we are going to have one hardness at time t equal to 0. That means, after quenching we have not started aging yet for that particular sample, okay.

Now another sample we have taken out from the furnace say at T 1 and we obtain one hardness value which will be say here. Then at T 2 we have obtained another hardness value here. Then T 3 here and so on we are going to get number of data points, is it not? Something like this, okay. Now if I join this particular line, the curve is going to look similar to what we just learned about the variation of shear stress with respect to particle size.

And this particular curve is known as aging curve, okay. And now why do we call it aging curve, right? Because we are keeping the sample at a particular temperature for long time, okay. So it is like aging okay, with age. We also age. The sample is also going to age, okay. That is why this whole phenomena is also called age hardening, with respect to age the material is hardened, okay.

So we call it age hardening and this particular curve here is called aging curve, okay. So this hardness, so remember the curve is similar to what we just saw for shear stress versus the particle size okay. So now let me draw it again and then I will mark these regions separately.

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So aging time, hardness and then your curve is going to look something like this, okay. Now this particular point where it is 0, the only contribution towards the hardness will be from the lattice stress as well as solid solution strengthening and we will discuss it eventually, solid solution strengthening, because we have not formed any precipitate. But this is a condition if you remember it is supersaturated solid solution.

So you have lots of solutes present in the matrix, okay. So if I talk about aluminum 4% copper, you have lots of copper in aluminum matrix, and because of those solutes you are going to have some amount of hardness, right and that will be called solid solution strengthening. So we will come to that particular point.

And after this particular point, your stress hardness is going to increase because of the formation of precipitates and at some time here your hardness is maximum, okay. And this particular condition if I take this any alloy and age it to this particular time here, okay this particular time, that particular condition of the alloy is called peak-aged condition. So the highest hardness corresponds to peak-aged condition, okay.

So this particular condition is peak-aged. And name itself suggest, is it not? Peak-aged. Peak, peak of, so see it as a valley okay, mountain, not valley, mountain right? So the peak of the mountain. So this is called peak-aged condition. Now below peak-aged we have under-aged. So this whole region here will be called under-aged. You have a condition which is under-aged.

It has not reached to peak age level yet. Above peak-aged if we age the sample to time which is more than the peak-aged condition time we call it over-aged, okay. So you have aged more than what is required in that sense if I imagine, right? So it is more than the peak aged. So you have over-aged the sample, okay. So we have three conditions, over-aged, peak-aged and under-aged.

And the highest hardness will correspond to the peak-aged condition. Now if I take aluminum 4% copper, I already mentioned before the sequence of the precipitation is going to be alpha, will be then GP zones. Then you have theta double prime to theta prime to theta. And if I try to mark all these precipitates in the aging curve, where these precipitates are forming, I can say that the GP zones will be somewhere here.

Then theta double prime will be in this regime. Theta prime here and then over-aged will be mostly theta equilibrium condition. And theta will be much larger in size, okay. So the shape is again similar to the, what we just discussed about the shear stress versus precipitate size, okay. And remember there is a correlation between aging time and precipitate size also.

So as aging time increases precipitate size also increases. So your stress is going to increase, so hardness is also going to increase. That means in this particular region here, up to this point, you are going to have shearing of the precipitate will be dominant, okay. And after that, after it has reached to peak age, both shearing and bowing will be comparable okay, both will be active.

And after that in the over-aged condition your bowing of the dislocation will be dominant mechanism, okay. So this is how the aging curve looks like. Now we have discussed about the temperature right, effect of aging time. But what is the effect of temperature, we also need to know about it, right? So till now whatever we have discussed is for a particular temperature.

So the plot what I have just shown the aging curve is for a particular temperature. So what happens when we change the temperature? If we increase the temperature what will happen to peak-aged hardness? Whether it will move left side or whether it will decrease or increase? Or similarly what will be the effect on the time okay, time to reach the peak hardness. Whether it will also decrease or increase? So next we are going to talk about that concept.