Mechanical Behavior of Materials-1

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Lecture - 35
Effect of Temperature: Dispersion Strengthening

So till now we have discussed about you know criteria for precipitation, then how microstructure and interface between the matrix and precipitate be changed during aging treatment. And then how dislocations interact with precipitates and how the interaction changes during aging, right? We have discussed all these and also we have discussed about how the strength and hardness changes with aging with respect to radius and aging time, we have discussed that right?

So today what we are going to discuss is the effect of temperature first. So what is the effect of temperature on the aging curve and then we will talk about the dispersion strengthening, okay. So let us talk about first effect of temperature. So to understand that let me first draw the phase diagram, okay.

(Refer Slide Time: 01:07)

So we have temperature here, then weight percent of say B, right? So we are talking about A and B and we have discussed about the alloy, A aluminum 4% copper alloy, okay. So here we are talking about A and B. So this is alpha which is single phase, then we have alpha plus L and then alpha plus beta, okay. So now let us take two temperatures here, say we are aging the alloy.

We are taking say this particular composition, okay having the concentration of C naught and so this will be something like this right, this particular composition. Now let us take two alloys here. One is at temperature T 1 and another one at temperature T 2, okay. And here T 2 is greater than T 1, okay. Now since we are aging it, beta will come out from the alpha matrix and this beta is actually precipitate, okay.

So if we age it at T 1 we are going to have this much of beta volume fraction eventually at equilibrium condition. And at temperature T 2 this is the beta fraction, right? If you use Lever rule you are going to get the volume fraction of beta and alpha respectively, right. So here this much at T 1 and this much at T 2 is your fraction of beta in the microstructure, okay.

So let us talk about it. So at high temperature, so in this case T 2, what you are going to see is smaller volume fraction of precipitates, okay. So you can see here at T 2 you have very small volume fraction, right compared to at temperature T 1. So T 1 here you have higher volume fraction. So at lower temperature T 1 you have higher volume fraction of precipitates, okay.

So now you already know depending upon the volume fraction, your hardness is going to change, is it not? So the higher the volume fraction of the precipitate, you are going to observe higher hardness of the alloy, right. So this also means that at lower temperature which is T 1 here, you are going to have higher hardness of the alloy compared to a temperature T 2 which is higher than T 1, okay.

So as you increase the temperature, since the volume fraction of the precipitate decreases, the hardness of the alloy is also going to decrease, that is point number one. Now the second is at higher temperature you have more driving force right, diffusion is faster. That means you have higher kinetics. What does it mean? It means that the precipitates can form much earlier right if you are at higher temperature because your diffusion is more here is it not?

And at lower temperature you have lower kinetics. So as you increase the temperature in this case from T 1 to T 2, the kinetics also increases. That also means that the precipitate formation is going to be faster when the temperature, aging temperature is increased, okay. This also means that the time to reach the peak hardness is going to be lower at higher temperature, okay.

So suppose we have a peak-aged hardness for lower temperature is H 1 okay and that high temperature is H 2, the peak hardness I am talking about then the time to reach H 1 will be higher than the time to reach H 2, okay. So these are the two things we need to know.

(Refer Slide Time: 06:50)

So the first point is as temperature increases what is going to happen? Your hardness is going to decrease. That is point number one because the volume fraction of the precipitate is going to decrease. Now second point as temperature increases time to reach peak hardness is also going to decrease, okay. So when you increase the aging temperature both hardness as well as time to reach peak hardness will also decrease, okay.

So these are the two things you are going to observe with respect to aging temperature. So now if I plot the aging curve, we have discussed aging curve, right? So let us now plot and whatever we discussed before was for a particular temperature. Now we are changing the temperature. So let us look at it how it is going to change with aging temperature. So we have hardness. Then aging time here, okay.

So you are going to have some hardness even if you do not age it because of solid solution strengthening and that will be our next topic, okay. So we are going to see something like this okay, say temperature T 1. Now if I increase it, increase the temperature you are going to see something like this. Then if I increase furthermore, it is going to be something like this, okay. So T 1, T 2 and T 3 where T 3 is higher than T 2 and then T 1, okay.

So let me, so this is your peak hardness at temperature T 1 and time to reach the peak hardness which is small t 1 okay at temperature T 1. And then this is your peak hardness at temperature T 2 and the corresponding time let us denote it using t 2 and then at temperature T 3 the time to reach the peak hardness, so let me also write, so okay. So this is your t 3 here.

And let me write the peak hardness value H 1, H 2, H 3, okay. So the sequence will be H 3 is going to be lower than H 2 and then H 1. And similarly t 3 is going to be lower than t 2 than t 1, okay. So as you increase the aging temperature which is here okay, your both hardness and time to reach the peak hardness is going to decrease and that is what is observed in the aging curve I have drawn here, okay.

So now you know how the precipitate size etc., changes with respect to time and how the aging curve changes with respect to time at a particular temperature. Then we just learned how the aging curve changes when you change the aging temperature, okay. So now let me go to another important point.

(Refer Slide Time: 11:20)

So if you remember when we are talking about the steps for aging treatment, steps for precipitation right, the first step was solution treatment. Then we quenched it and then we aged the alloy, right? So the now question comes why do you want to quench it, right? Why do you not slow cool it and form beta, right? Anyway the equilibrium structure based on the phase diagram.

So if you see here, based on the phase diagram, the equilibrium structure is alpha plus beta, is it not? So if you go to alpha region, single phase region, and do solution treatment, you could have slowly cooled it and formed alpha plus beta. Why do you want to quench it first and then age it again right, and wasting some amount of energy by heating it again, is it not, right?

So what is the necessity of quenching it rather than slowly cooling it after you have solution treated the alloy, okay? So let us understand that concept. So the question is why do we need to quench the alloy after solution treatment we are talking about and not slowly cool it, okay. Because based on the phase diagram we are going to get alpha plus beta even if we slowly cool it, okay. So let us understand that.

So suppose you are going to a high temperature, so you are in this particular region okay and I have phase diagram here now. So you are here, okay. Then we are quenching it rather than slowly cooling it. So what is happening, right? If you slowly cool it the process is very slow and consider it that you are doing everything at high temperature and then you are slowly cooling it to room temperature.

So you are spending sufficient amount of time at high temperature so that the diffusion is faster there, okay. Because you are spending sufficient amount of time at high temperature okay, while your are slowly cooling it. So what will happen? If you see your microstructure after slowly cooling it, you have say these grain boundaries, okay.

So since you are slowly cooling it, you are giving sufficient amount of time for B atoms to come out from the alpha matrix if this is alpha here okay and we have alpha plus beta. So B atoms will come out from the alpha matrix and they are going to form beta phase, right? And since you are giving sufficient amount of time and the temperature is also higher, you have lots of diffusion going on.

There is a possibility that the atoms here they will diffuse to grain boundaries and they are going to form precipitates at the grain boundary itself, something like this, okay. Because the diffusion is faster you are giving sufficient amount of time also. So atoms have sufficient driving force to move from interior of the grain at the grain boundary and form beta phase. Now these beta phase are what?

They are intermetallic in nature, right. So there are brittle in nature. Now if you start doing tensile test of this particular alloy, this beta phase is going to fail right away, okay. So you are going to get intergranular fracture. So this beta phase here they are going to fail all this, right? And you are going to observe fracture through the grain boundary. So we call it intergranular fracture, okay.

And you do not want that, is it not? The whole purpose of doing aging treatment is to increase the strength, but you do not want to lose ductility completely, okay. There should be sufficient ductility as well if you want to, if you are increasing the strength, okay. So what do we do? Instead of slowly cooling it, so this is the case of slowly cooling. So instead of slowly cooling it we are going to quench it.

So if you quench it, you are going to form supersaturated solid solution. We have discussed that okay. And now you are heating it again. But remember, you are not heating it to a very high temperature right and but your B atoms they want to come out because that is not the equilibrium condition. The supersaturated solid solution is not at equilibrium still, okay.

So B atoms will want to come out. So if you remember we had discussed this before. So if I am aging it at this particular temperature, so this much of super saturation, right? Equilibrium suggest, this phase diagram suggest that the solubility is only here, right?

But we have extra B atoms, this much. So this much B atoms will try to come out as soon as possible so that the whole system is in equilibrium, okay.

But you are not at very high temperature when you age it, right? But you are giving some driving force so that atoms can move. But again atoms want to come out quickly and then form beta phase because they want to achieve equilibrium, right? So what will happen, they will start forming precipitate inside itself.

Obviously you are going to observe some precipitates also at the grain boundaries, no one is denying that. But apart from the grain boundaries you are also going to observe precipitates interior, inside the grain, okay. Now if you compare the one microstructure where we have slowly cooled it, there you had a continuous film of Al2Cu if we are talking about aluminum copper or say beta phase.

Now if you compare you do not have a continuous film of beta phase. They are distributed inside the grain as well as grain boundary and this is what we want. So you have sufficient ductility also. So this is the structure of quenching plus aging, okay. So you are doing both here. So that is the reason why we first quench the alloy and then age it, we do not slowly cool it okay so that we can avoid the formation of beta phase at the grain boundary, continuous film of beta phase at the grain boundary.

Got it? Okay. So this is much I wanted to discuss in precipitation strengthening. So what I am going to do now is to talk about something called dispersion strengthening, okay.

(Refer Slide Time: 19:30)

So we will discuss about dispersion strengthening, okay. The name suggest you know you have dispersed something and because of that, you are getting some strengthening in the alloy, okay. So now the question is, what do you disperse? So let us understand that. So in this mechanism the strength is enhanced by the addition of dispersoids, okay.

So you are adding dispersoids and these dispersoids are actually hindering or say restricting the movement of dislocations. Remember, when I started talking about strengthening mechanism, the first thing I mentioned that the whole mechanism, all these mechanisms are based on the restriction of movement of dislocations, okay.

So previously we talked about precipitation strengthening where precipitates were responsible for the restriction in the movement of dislocations. Here dispersoids are restricting the movement of dislocations and thereby increasing the strength of a given alloy, okay. So what are dispersoids? So they are hard and insoluble second phase, okay. So I will tell you what do I mean by insoluble second phase, okay.

So now let us consider the difference between precipitates and dispersoids, right? So if you remember the precipitates they are forming from the matrix itself. So when you quench it and then age it, this beta phase were coming from the alpha matrix, right? So these precipitates were forming in situ, they were coming out from the matrix itself. In dispersant strengthening this dispersoids are added from outside.

So you are adding say oxides, nitrides. So some you know hard particle okay, you are adding it from outside. So that is one of the differences between precipitates and dispersoids. Now second difference is that if you talk about precipitation strengthened alloys, if you go to high temperature right, those precipitates which you have formed during aging treatment can again dissolve back, right?

And that was the first treatment if you remember the solution treatment itself, right? So the precipitation hardenable alloys, they are not very suitable if you want to work at very high temperature. Because the precipitates will dissolve back and then the strengthening will be lost, okay. If we compare that to dispersion strengthened alloy, the dispersoids on the other hand they are insoluble at high temperature, we are not talking about the melting point, okay.

We are talking about a temperature like in precipitation hardenable alloys, we are talking about say solution treatment temperature. So in the same range if you talk about for dispersion strengthening alloy, these dispersoids they are not going to dissolve okay, they will be stable there, okay. That this also means that these type of alloys where we are adding dispersoids they are suitable for applications at higher temperature as compared to precipitation hardenable alloys, okay.

So these are the two main differences you have between dispersoids and precipitates and correspondingly dispersion strengthened alloy and precipitation strengthened alloy, okay. So let us write it down very quickly.

(Refer Slide Time: 24:34)

So dispersoids you add it from outside, okay. And if you remember precipitates they formed from the matrix, okay like beta phase form from the alpha matrix, okay. But here we are adding from outside, dispersoids okay. Now the second difference is dispersion hardened systems maintain strength at high temperatures, okay.

And if I talk about precipitates, so in the bracket when I am writing there is a contrast right between dispersion hardened system and precipitation hardenable alloys. So in precipitation hardenable systems, precipitates will dissolve back in the matrix, okay. And this also means not very suitable for high temperature in solution treatment temperature, something like that, okay.

Why because you are dissolving the precipitates back into the matrix. So if precipitate have dissolved there is you know no one to restrict the movement of dislocations, right? Obviously, there will be some lattice resistance there, but you are going to lose the strength you had achieved by aging, okay.

So these are the two main differences between precipitation hardenable system and dispersion hardenable system. So 1 and 2 okay. Now what are the examples?

(Refer Slide Time: 28:01)

So if I talk about examples for dispersion hardenable system, you have aluminum and then say $Al2O3$ okay or say copper $Al2O3$ and then one of the famous is you ODS steels, which are being used in nuclear power plants. So ODS means oxide dispersion strengthening steels, okay. So these are ferritic steels with high chromium okay and then you are adding yttria so $Y2O3$.

So you are adding yttria, they act as a dispersoids in the matrix and thereby they provide strength at higher temperature. So these are being used, this ODS steels are being used in nuclear power plant also, okay. So now we know that the strength is coming from the dispersoids because they are restricting the movement of dislocations. Now what is the mechanism?

So if you remember previously, when we were talking about precipitation hardenable alloys we discussed about two mechanisms. So dislocations can either bypass the precipitates or dislocations then cut the precipitates, right. Now that will depend upon whether it is coherent, incoherent, also the size, right. And we discussed also that if the size is small and the precipitate is coherent right, then it is going to shear.

Now this dispersoids since you are adding from outside, in most of the cases the interface between the precipitate or sorry dispersoids and the matrix is going to be incoherent in nature, okay. This also means that in most of the cases, dislocations are going to bypass the dispersoids. They are not going to cut it because the interface is incoherent in nature, okay. So that is the mechanism.

So mechanism if you see the interface between the matrix and dispersoids is incoherent okay. And if it is incoherent it is going to bowing around of dislocations, around dispersoids okay. So they are not able to cut, dislocations are going to bypass the dispersoids and thereby increasing the strength of that particular dispersion strengthening alloy, okay. So we have completed precipitation strengthening mechanism.

We have also completed dispersion strengthening mechanism. See the concept remains same, both dispersion strengthening mechanism and the precipitation strengthening mechanism. Only thing is there is a difference between dispersoids and precipitates which we have already discussed. So let me quickly give you very two basic problems okay based on the distance between the precipitates and the size of the precipitates and rest you will do in the assignment also, okay.

(Refer Slide Time: 32:12)

$$\frac{\tau_1}{\tau_2} = \frac{r_2}{r_1}$$

So suppose, I have an alloy okay aluminum alloy and we are aging it okay. So we aged it and after aging we have two conditions. So in first condition the precipitate size was say suppose 30 nanometer, okay. And the strength, you measured strength the tau value and that you got say 100 mPa okay. Now the question is if you change the say aging condition and the precipitate size is now say 60 nanometer then what is the strength, okay.

So you are talking about same alloy system. So G remain same, B will remain same, means material properties are going to remain same, okay. So you are changing the aging condition and because of the change in aging condition, precipitate size is changing. So strength is 100 mPa when precipitate size is 30 nanometer. And if precipitate size is 60 nanometer what is the strength and you are assuming that you have cutting of precipitates, okay.

This means it is on the left side from the peak-aged condition, okay. So it is very simple, right? We discussed before that tau is directly proportional to root r. So you know what is the size here, right? So say if size, if you consider size to be d diameter which is 30 nanometer, so you know d 1. And remember r is the radius here, right? So d 1 is known and d 2 is known.

And d 1 corresponding strength say tau 1 that is known 100 mPa. So you have to figure out what is tau 2. So if you have this particular equation right, you can write it down as tau 1 by tau 2 equal to root over r 1 by root over r 2, okay. So now you know diameter is known d 1 and d 2. So you know what is r 1, is 15 and r 2 is 30 nanometer, okay.

So you can now use this particular equation. You can find out what is tau 2. That is given by tau 1 root over r 2 divided by root over r 1. Now you have all the values. You know what is tau 1, you know what is r 2, you know what is r 1. So you can calculate what is tau 2, okay. So this is one simple problem. Another one is related to the distance between the precipitate.

(Refer Slide Time: 35:42)

$$\boldsymbol{\frac{\tau_1}{\tau_2} = \frac{\lambda_2}{\lambda_1}}$$

That means, we are talking about now bowing around the precipitate okay or bowing around of dislocations. So say again aluminium alloy we are talking about and you have aged it okay. So size is now larger because we are talking about bypassing, okay. So say the size is, size is larger. So let us talk about distance.

So previously say you had distance of lambda 1 as 1 micron meter and then the distance, average distance has increased to say lambda 2 as 2.5 micrometer, okay. So you have aged it and the distance, average distance between the particles, precipitates, it has increased from 1 micrometer to 2.5 micrometer and the strength corresponding to this was suppose tau 1 as again 100 mPa.

So you have to figure out what is going to be tau 2, okay. And here you are assuming that dislocations are going to bypass the precipitates, okay. The previous one was related to cutting. This problem is related to bypassing, okay. So here also we have discussed the formula, right. So stress required to bow a dislocation that is given by Gb by lambda you remember, right?

So we can write it here again tau 1 is equal to Gb by lambda 1. Now Gb will remain same because the material is same. So tau 2 here is Gb by lambda 2, okay. So we can write tau 1 by tau 2 as lambda 2 by lambda 1. Gb, Gb will cancel out, okay. Now you know all the values. You see here tau 1 is known, sorry tau 1 here. Tau 1 is known, lambda 1 is known, lambda 2 is known.

So you have to calculate what is tau 2. So tau 2 from this equation is given as tau 1 lambda 1 by lambda 2. So you can calculate. You know all the values is it not? So these are the two simplest problems related to precipitation strengthening and you will know more in the assignments, okay. So next we are going to discuss about solid solution strengthening.