Mechanical Behavior of Materials-1

Prof. Sudhanshu Shekhar Singh
Department of Materials Science and Engineering
Indian Institute of Technology-Kanpur

Lecture - 36
Solid Solution Strengthening: Basics

Welcome back class to our course Mechanical Behavior of Materials. So in the last lecture, we completed the topic of precipitation strengthening and dispersion hardening. So today we will start talking about solid solution strengthening, which is one of the another type of mechanisms, okay. So we will talk about solid solution strengthening, okay.

So now if you remember when we were talking about aluminum 4% copper system in precipitation strengthening right, so we had this alpha phase.

(Refer Slide Time: 00:59)

If you remember the phase diagram we had this alpha phase which was single phase, right? Okay. And if you talk about aluminum 4% copper this alpha phase is actually a solid solution of copper in aluminum, okay. We had discussed this, okay. So you have copper which is solute and aluminum is solvent here, okay. So alpha phase is a solid solution.

Now because of the presence of copper which is solute the dislocation movement is going to be restricted, okay. And because of that you are going to see some amount of strengthening and since it is happening because of the formation of solid solution, the whole phenomena is called solid solution strengthening. Again remember alpha is a solid solution okay of copper in aluminum.

Now copper is restricting the movement of dislocation and that is why this whole phenomena, the whole concept is called solid solution strengthening, okay. So strengthening due to the addition of solute atoms right, this is called solid solution strengthening, okay.

(Refer Slide Time: 03:29)

Now if you remember the aging curve of aluminum 4 weight percent copper, I am using this example because we have discussed this before, okay. And if I draw the aging curve, so you have hardness here and then aging time on the x axis, right? And if you remember the curve load like something like this, okay.

And at that time, I mentioned that this particular point which corresponds to time t = 0, the strengthening you are getting from the alloy, the contribution is coming from solid solution strengthening. Obviously, you are going to have some lattice resistance right in the matrix, but main contribution will be coming from solid solution strengthening.

So whatever hardness here, say if I say hardness as H naught, the contribution towards H naught will be coming from solid solution strengthening. So some contribution of solid solution strengthening towards H naught, okay. And as you increase the aging time here, so all these hardness in this range you have a contribution also from precipitates, is it not?

So at time t = 0 if you remember the condition was H quench condition. So you had supersaturated solid solution, right. So there you have a contribution from solid solution strengthening because you have lots of solutes because you have quenched it is it not? And as soon as you start aging it precipitates form and then they will contribute towards precipitation strengthening, okay.

So realize the difference between solid solution strengthening and precipitation strengthening. In precipitation strengthening you have contribution from precipitates, okay and in solid solution strengthening you have contribution from the solutes present in the solid solution. Now again realize that the solid solution the crystal structure of the solvent remain same.

So it does not change, right. Like in aluminum 4% copper the alpha phase is also FCC like aluminum, okay. But in precipitates whenever we form precipitates like beta phase can have a different crystal structure than alpha, okay. So Al2Cu the precipitate is forming aluminum 4% copper, the equilibrium precipitate, the crystal structure is not FCC, okay. So crystal structure of the precipitates can change.

That is the difference, one of the differences between the solute and the precipitate. Solute is atom, okay and precipitate is phase. So there is a difference, okay. And remember in aging curve at time t = 0 you see a contribution from solid solution strengthening because you have not formed any precipitate yet and after that you start seeing the contribution from precipitation strengthening one, okay.

(Refer Slide Time: 07:34)

Now some of the examples, common examples for solid solution. You know these example already. So brass, right? Then you have copper, nickel, then steel also, right? Carbon, carbon atom is a solute atom in iron, so steel. So you have lots of example, where you can see solid solution strengthening, okay. So this is the difference between solid solution strengthening and precipitation strengthening.

So let us understand how the properties of the material changes when we add more number of solutes, okay. So if I plot stress versus strain, okay. So let us say we have three plots. First one is for pure metal. So this is for say pure metal, okay. Now we are adding solute. So you can have another plot going to look something like this, okay. So this is a solute of concentration c 1, okay.

Now let us draw another one, okay. So you have solute of concentration of c 2, okay. So you can clearly see the difference between pure metal solute of concentration c 1 and c 2 where say concentration is increasing in this direction, okay. So c 2 is higher than c 1 concentration. And what you see here that as you increase the solute concentration the strength increases and ductility slightly decreases.

Okay, you can clearly see it. So this is your tensile strength here, somewhere here say, okay. So strength of the pure metal is the lowest and as you start adding solute you are going to get contribution from solid solution strengthening, this solute atoms are going to restrict the movement of dislocations okay and thereby you are going to see the increment in the strength, okay.

So what you can write here is that solid solution offers greater resistance to the dislocation motion than pure crystals, okay. You can see a pure crystal, right. So this is your pure crystal in the red color here. So pure metal. It has lower strength than the other two solute solutions where one contain solute of c 1 and other one c 2.

(Refer Slide Time: 12:24)

Now if I plot another plot where you are varying the concentration, so let us see something like this. So all these are qualitative. Qualitative means schematic I am drawing. And for different metals for different alloy system you are going to see different strength of, or magnitude of strengthening. So you have say A was your pure metal and then you are adding B. So weight percent of B here, okay.

And here say I am drawing tensile strength and here we have elongation. So if I see the above plot here, we can conclude that if you increase the concentration, if you go from c 1 to c 2 here in this direction, you are going to decrease the elongation and increase the strength right, and pure metal is the lowest in terms of strength. So if I draw now, so this becomes your pure metal here, pure A.

Now we are adding B, so your strength is going to increase something like, okay. The trend line can be different for different alloy system but it is going to increase. So say for different concentration of B you are going to obtain different tensile strength, something like this. Similarly, for pure A, you are going to have a higher elongation and it is going to decrease as you increase the concentration of solute, okay.

So overall what you see here that there is a change in tensile strength as well as elongation and this is happening because of solid solution strengthening, okay. So your strength is going to enhance because of the presence of solute atoms because they are going to restrict the movement of dislocations.

Again, I am reiterating the whole crux of this strengthening mechanism is that you have to somehow restrict the movement of the dislocation, okay. Now let us talk about solid solution very quickly. You already know about solid solution.

(Refer Slide Time: 14:58)

So solid solution. So there are two types. One is your substitutional solid solution and another one is interstitial solid solution, okay. So in substitutional solid solution you are going to replace the solvent items by solute atoms, right? So solute atoms replace solvent atoms. And in interstitial solute atoms are going to occupy the interstitial positions or voids. Solute atoms will occupy interstitial positions or say voids, okay.

So this is the difference between substitutional solid solution and interstitial solid solution. And if you again, let us talk about aluminum 4% copper, that is your substitutional solid solution but if we talk about steel that becomes interstitial solid solution of carbon in iron because carbon goes in the interstitials okay, in the iron lattice. And if you just draw a very quick diagram of these two.

So if I have say atom A, okay so I am drawing by hand so you know the size of all these atoms are not similar. But again just learn the concepts. Suppose you have, let me draw another one for interstitial. Okay, so these are your say lattice of A. So you have A atoms here. So the black one here is A atom, so A atom, okay. Now if it is substitutional what we are going to do?

We are going to replace some of the A atoms with say B atoms, something like this, right? So this becomes your B atom. So this is the case of substitutional solid solution where B atoms which is a solute is going to replace the A atoms.

(Refer Slide Time: 19:08)

So here this is your solute and this is your, A is your solvent. Now if the same situation is there with the interstitial, let A atom is same color and B atom is same color. So I can place here B atom something like this, okay. So what is happening here? B atoms as a solute they are going to sit into the interstitials, okay. They are voids, interstitial voids. So they are going to sit there. So this is the case of interstitial solid solution, okay.

And here this one is your substitutional solid solution. And the example I already mentioned for substitutional solid solution, you have say copper in nickel, okay. And interstitial solid solution the example steel. That is carbon in iron. So carbon is your solute atom, iron is your solvent. And copper here is your solute atom and nickel is your solvent, okay.

So here I have not shown you any strain in the lattice and we are going to learn eventually that whenever you add solute atoms you are going to see strain in the lattice, okay. So depending upon the size you are going to see strain in the lattice, we are discussing. For now I have just unejected the strains see. So you are not going to see any strain in the lattice, okay.

(Refer Slide Time: 21:18)

Now let us talk about something called distortion. So if you see here depending upon the size of the B atoms you can imagine right that there will be distortion in the lattice, okay. So if the size of this B atoms here right, is large then you are going to see expansion in the lattice. You can force it, is it not?

Similarly, the size atom here in the substitutional case okay, if it is smaller and larger there is going to be distortion in the lattice. So let us talk about distortion in the lattice due to solute atoms, okay. So now let me again draw a nice lattice with no distortion. Again all these atoms should be of same size. I will just draw one more line, one more row of atoms, okay.

So this is a solvent and now let us put interstitial atoms at say this position here, let me mark it, is in black. So at this position we are going to put say interstitial atom. And now since because of the interstitial atom you are going to see distortion in the lattice, okay. So I have now interstitial atom here. And now let us draw the same atoms what we had before. So you are going to see something like this okay, something like this.

So what do you see that there is a distortion in the lattice okay around this region, right? If you see here I can draw a straight line like this, right? But here you are seeing a distortion as soon as you reach around the interstitial atom, right? So there is expansion in the lattice, okay. Now this is interstitial. So I have shown here in the schematic here at the bottom you can see unit cells, right?

So this is FCC, face-centered cubic, you know this and then this is BCC, okay. And you can see in FCC both tetrahedral as well as octahedral voids. So let me change the color. Okay, so here this one this blue one is your octahedral voids, okay and then you can see the tetrahedron in the red color here is it not, this guy in the red color. So this one, okay. So this is a tetrahedron.

So there is a void in the tetrahedron, we call it tetrahedral void. So this is for FCC, right? So imagine that you have this blue atom. So this blue atoms if I mark on the top A right, and we are talking about this black atoms which is a solute say black atom is here B okay and blue atom is A. So imagine that in FCC lattice the face-centered atoms are also A as well as the corners are A. That is how FCC is made, right?

So the B atoms which is in black color they are going to sit either in tetrahedral void or octahedral void. So this is, either it is going to sit in octahedral here or in the tetrahedral void, okay. Now in BCC also you can see one tetrahedron here. See the dotted line, so you will see a tetrahedron. So there is a void in BCC also, okay.

So the interstitial atom which is B this case can go and sit in the interstitial void which is tetrahedron void here also, okay. So whether it is BCC or FCC you are going to have some void, some interstitial positions okay and the solute atoms are going to sit in those octahedral or tetrahedral voids.

And since this is sitting in octahedral or tetrahedral voids, the distortion what you see here on the top, so this type of distortion is going to be non-symmetrical in nature, okay. That means interstitial solute atoms have a non-spherical distortion field okay, tetragonal or octahedral, okay. So the distortion you see is non-spherical type, okay. Because it is sitting in either tetragonal position or octahedral position, okay.

So this is the case of interstitial solid solution, okay. So we have interstitial solute atom. So take me write here. So this is the case of interstitial solid solution. Now if we come to substitutional solid solution let us see what happens.

(Refer Slide Time: 29:30)

Substitutional solid solution. So let me quickly draw the atoms for understanding. So I will have A atoms. Okay, so I am not drawing again the perfect lattice. So let us quickly draw if you have a substitutional atom which is smaller in size and substitutional atom which is larger in size, okay. So what happens if the substitutional atoms is smaller in size. So we are going to see something like this the structure.

Then this line of atoms will be sitting here, something like this, okay. Okay, something like this. So what you see that this is, here in this region, you have somewhat compressed the lattice is it not? So you have somewhat compressed compared to your previous lattice okay, if you have no solute atom present, okay.

Now if I add a larger substitutional atoms, if you see here if I start adding you know larger substitutional atoms anywhere in this A here right, you are going to see expansion in the lattice. So you can imagine, right? If you have a smaller substitutional atom you are going to have contraction in the lattice and if you have larger solute atom you are going to span the lattice is it not?

So here we are going to see expansion. So it is going to be something like this, okay. And then you are going to have another set of atoms here and then, actually I have to make much larger in size. So let me change, make it much larger, okay. Now this guy here will move up. It will be something like this, okay. And this atom will also move down, okay. And then you have this situation, okay.

So what you see here that there is a expansion in the lattice here, okay. So this is your larger solute atom, larger substitutional atom and this is smaller substitutional atom, okay. So in both the cases you see strain in the lattice, but in one case there is a contraction, in another one there is expansion of the lattice, right.

So and if you see if you imagine it, this is going to be completely spherical distortion right, compared to the interstitial solid solution where it was non-spherical because the solute atoms were sitting in the tetrahedral or octahedral voids, okay. So in substitutional solid solution substitutional atoms have spherical distortion field, okay. So it will lead to spherical distortion.

And if you see here it is non-spherical, interstitial. So this is the difference between the strain associated with substitutional atoms and interstitial atom. In substitutional atom you have a spherical distortion, in interstitial atom you have non-spherical distortion.

And you know you are going to learn later that since the nature of distortion is different in interstitial and substitutional atoms the interaction with dislocations, the way they are interacting with dislocations, they are also going to be different for substitutional solid solution and interstitial solid solutions, okay. So I will stop now and we will learn more about substitutional solution in the next lecture. Thank you.