Mechanical Behaviour of Materials
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Lecture - 29
Strengthening Mechanisms in Crystalline Materials - II

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Hello, I am Professor S. Sankaran in the Department of Metallurgical and Materials Engineering. Now, we will come to solid solution strengthening with a specific idea.We just looked at it in a general formulation about obstacle in a matrix in the initial slides, but now we will talk about specific systems. So, here is the schematic which has the lattice and then and some of the lattice positions are substituted by the foreign atoms. So, called you know substituting substitutional solid solutions.

And then you see that the black ones the open circle they are all of similar size. But you are here you also having solute atom which is smaller in size as compared to the rest. So, what you see here is the slip plane and then you know this kind of this is a void and this could be an edge dislocation something like that and the direction of the dislocation motion is this way and then this direction all this you understand now. So now, the question is having the small solute atom in this position what are all the consequences? This is what we have to understand.

So, now, you know what kind of stress field surrounding an edge dislocation we have sufficient idea and when the solute atom is small as compared to the solvent atom then what are all the consequences? An edge dislocation moving on a slip plane containing a solute atom of atomic size less than the solvent.When the dislocation core reaches the solute the compressive strain energy that is somewhat relieved.

So, what is that we have seen in the dislocation core the above the extra half planes, especially the hydrostatic compression that is what we have seen. So, the compressive strain energy is somewhat relieved when the small solute atom goes and get locked inside the dislocation. This leads to an attractive interaction energy between the solute and the dislocation. This we already seen. If the solute atom were positioned below the glide plane here repulsive energy would result. So, this scenario is quite interesting now, a small solute atom we are putting the dislocation core above the glide plane then it becomes you know kind of attractive forces, attractive interaction energy, the same solute where question below this it is a repulsive because you know the stress field is quite different it is tension hydrostatic tension it a repels. Thus a small solute atom can depending on its position relative to the glide plane attract or repel an edge dislocation.

A similar result is obtained when the solute atom has this size larger than the solvent. So, we are now generally talking about size effect here. On the average both relatively larger and smaller solute atoms interact attractively with an edge dislocation and an increase in the flow stress results. So, whether it is a larger or smaller. The net result is the increase in the flow stress that is important.

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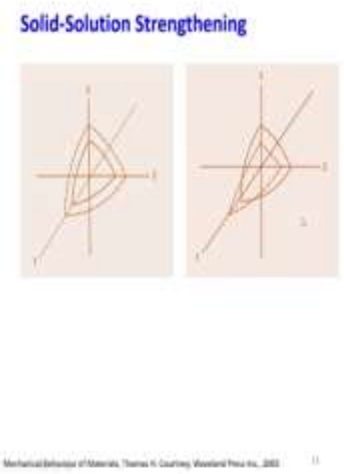

Now, we are going to look at a little more closely these two plots exhibit a comparison of this train associated with spherical our tetragonal distortions. What is spherical distortions, what is tetragonal distortion? We can spend some time on this. I said that if you bring a 14 atom to matrix, especially in this case we are talking about a substitutional solid solution. Suppose the atoms of similar size for example, in this case the open circle and the black circles they are of the same diameter.

So, what you have to understand is the diameter of the solute atom even though it is comparable in size they will not be exactly the same, they will produce some kind of distortion. But if it is of a similar size then the stress field around is going to be symmetrical. It is going to produce symmetrical stress field. On the other hand if it is a small and it is not going to produce a symmetrical stress field around. This is what we are going to see.

So, that is what shown in this plot, a spherical distortion produces a dilation for which ε_1, ε_2, ε_3 they are all same, what is there are strain components strain components of three all the three strain components will be equal if it is a spherical distortion. For the tetragonal distortion, an octant of an ellipsoid of revolution is formed. So, this is what is shown, an octant of ellipsoid of a revelation is formed here.

At what condition that could be epsilon 1 is greater than 0, ε_2, ε_3 is less than 0 or epsilon 1 can be less than 0 and $\varepsilon_2 = \varepsilon_3$ which is greater than 0 that means, 1 strain will be having a different magnitude than the other two, but the other two will have equal magnitude, that is what it means the tetragonal distortion. So now, I said that is spherical distortion comes when you have the substitutional solid solution.

For example, if you take chromium in ion or nickel in ion or chromium nickel these are all some of the classical examples where the substitutional solid solution will experience spherical stress field. And then when will you have a tetragonal distortion. So, before even going to the solute if you compare the dislocation itself. The screw dislocation is completely associated with shear stress alone. So, shear stress will be associated with some distorted bonds which is also creates a tetragonal distortions.

On the other hand in edge dislocation we know, both it has got distortions as well as dilatation or dilation operates. The shear stress as well as harvesters. But, as well as two dislocations are concerned it has got only shear stress that means it is only a distorted I would say distorted energy or a distorted bonds you can see the distortion tetragonal distortions. Tetragonal distortions in the lattice will significantly interact with screw dislocations because of this, because of the shear stress.

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Some examples we are going to see now one by one. The first one shows the BCC lattice which is going to exhibit a tetragonal distortion. So, an interstitial atom in the BCC lattice and b is a divalent ion plus positive ion vacancy in a monovalent ionic solid. So, the matrix is monovalent and you have a divalent substitution under vacancy here. So, this kind of imbalance charge distribution is going to cause tetragonal distortion.

And here we are talking about the interstitial atom which is going to sit in octahedral widen a BCC lattice is also going to cause tetragonal distortion. So, we were talking about the dislocation and it is a stress field and distortion. And then now we are talking about lattice which is having tetragonal distortions. So, you have to be clear about this. So, only you know wherever you are whichever the interaction is going to make a significant effect is all depending upon what kind of distortion or what kind of a stress field in both sides.

So, in the first one that is the interstitial atom does not fit without a distortion in the structure and these results in displacement of solvent atoms along the z axis that is the tetragonal distortion results. In the example b, the divalent ion and associated vacancies relax by approaching each other, this also produces the tetragonal distortion. The arrows indicate the direction in which the atoms or ions move in response to the presence of the distorting agent.

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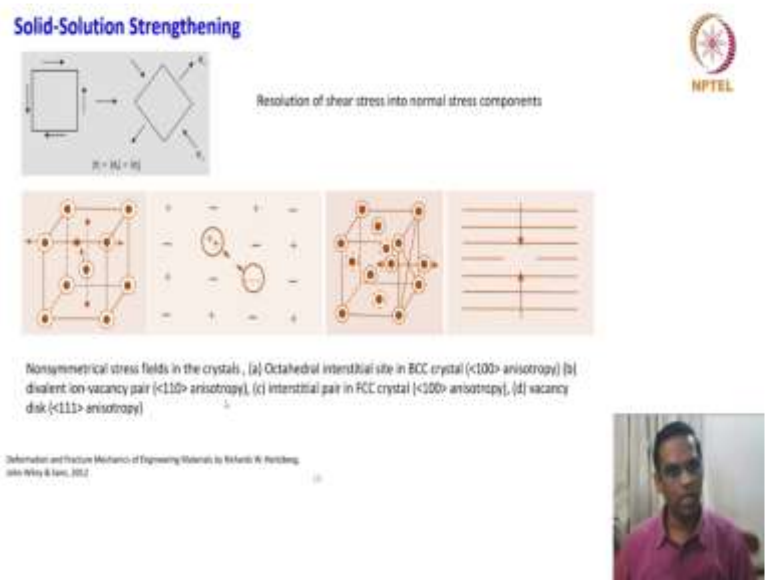

So, this is one simple demonstration about this distortion. Now, I will show a little more explanation on this with a few more examples, what is shown in the slide is first of all the top image shows the resolution of shear stress into normal stress components. Since we are going to talk about the stress field atom this locations and other solute atoms stress field this is quite significant. So, you know this shear stress can be resolved into in terms of normal stress remember the magnitude of both shear and normal stress is going to be same.

Whether it is tension and compression, so the magnitude of the all the three stresses are going to be same. So, when you have this shear stress for example in a screw dislocations and there we can consider this is getting decomposed into these kind of normal stress components and this will have that interaction with the lattice energy level, lattice stress fields. So, now, we look at the first one in non symmetrical stress fields in the crystals, first one is octahedral interstitial site in BCC crystal, they will have anisotropy in <100> direction.

So, here we are going to this arrow direction you can see and what is shown here is the interstitial site there are two possibilities one is in the edge center the other is in the face center in a BCC lattice both of them are octahedral sites. The question is whether these octahedral sites are of similar size or not they are not the one which is in the edge is typically in the order of 0.038 nanometer, the one which is there in the face center is the order of 0.156 nanometer and they have the anisotropy in <100> direction as well as <110> direction respectively.

We are not shown the other one, but there is an anisotropy in this two octahedral voids itself. So, when you have these kind of anisotropy in the void size itself, when the interstitials, I mean solute like carbon which is, when it approaches here their attraction will be very strong because the tetragonal distortion. Which is getting generated in this BCC lattice is quite large and that stress field are going to attract this interstitial carbon atom into this octahedral voids.

And if you look at the carbon atom size which is about 0.154 nanometers and they are going to try to occupy into this octahedral site which is not very convenient to fill in right. So, that is why the solubility of carbon in BCC iron is very low 0.02%. On the other hand, if you look at the solubility in a FCC iron, it is enormous. So, if you look at the void size which is there in the FCC it is equal to 0.1 to 0.102 nanometers which is much larger than this octahedral void where the carbon dissolves.

Because the stress field there it is not like a distorted one or asymmetric it is a spherical stress field there. So, the carbon dissolution is more when compared to the BCC lattice. So, that it does not know enormous technological important that is why steel is becoming very popular and still an important material all of you know this and it is a very classical example of you know, having a distorted lattice but still forming a very strong solid solution. So, non symmetric stress field in this is a lattice a carbon as an interstitial is a classical example.

So, they exhibit anisotropy in <100> and <110> also and if you take the second one the divalent ion, vacancy there, so this is again showed in the previous slide and it shows the anisotropy in <110. directions. And here again interstitial pair in FCC crystal exhibits anisotropy in <100> that also will produce some kind of for distortion and the finally, the vacancy disk exhibits anisotropy, in <111> direction also we will create non symmetrical stress fields. So, these are all some of the classical examples of how the crystal system will have non symmetrical stress fields and how they are going to interact with the stress field of the dislocation as they perform in drawers.

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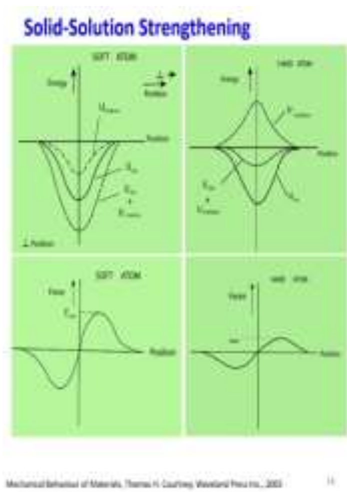

So, what we are now seeing here is energy versus position plot where the dislocation is approaching a soft atom as a solid solute atom in as solvent matrix. So, what you are seeing here is this is a dislocation and this is a position and it moves this direction and what you are seeing here is the energy of modulus how it various with the dislocation position the energy variation. We were just looking at the modulus. And suppose, if you look at the size and if you look at the size plus modulus how they are going to compare in terms of energy.

So, how do we, what do we say? Why do we say soft because if you consider the modulus of the solute atom is you know is less than the solvent atom. So, then it is considered as soft and then that energy is going to vary at this respect to the position of the edge dislocation. So, the soft atom of a given size suppose it small size and they are going to reinforce each other and there force versus position. So, this kind of energy and force plots are quite familiar to us. We looked at in condon morse curve.

So, energy versus position and then force it is the same idea here. So, if you have the you know soft atom and a small size, they are going to vary the energy is going to vary like this and they are going to reinforce the energy and then this is simply a derivative of this reinforced or so, it is going to have attractive and repulsive or positive or negative force depending upon the positions for the soft atom. On the other hand, if you plot it for a hard atom that is the solute atom has got higher modulus than the solvent.

Then it is going to be the energy variation is going to be like this with respect to the dislocation position and the size is the same it is just that the modulus is higher than the solvent for a given size, but if you look at the net that is energy of size plus modulus is becoming smaller, but in this previous case it was a softer atom and a smaller size, the energy is reinforcing but in the higher modulus and smaller size then the net forces vary smallest compared to the software, in terms of attraction as well as repulsion.

So, that means a soft item with the smaller size will have a strong interaction energy or a strong force with a dislocation that is how you should look at it. So, the interaction energy versus relative slip plane position of an edge dislocation is shown as a soft solute and hard solute. But soft solute this is an interaction and this reinforce, this is not for the hard atom. So, it is quite different. So, the size interaction is taken as the more important one and this results in that net attraction between the dislocation and the solute.

So, even though the energy of you know high modulus solute timed size varies like this, but the net is still an attractive, the interaction force position relationship for these respective cases is shown in (c) and (d) that we already seen. The force proportional to the derivative of the energy position curve is a negative or attractive as the dislocation approaches the solute atom for both situations. The force necessary to continue dislocation motion that is max is that required to tear the dislocation away from the solute.

So, we are now talking about the interaction energy of solute with respective dislocation position that means, their interaction they are interacting they are holding together. Whatever happens, but if you look at the force necessary to continue the dislocation that dislocation has to continue to move surpassing these obstacles then, that force has to tear the dislocation away from the solute. So, that is F_{max} is should be high enough whether it is a soft or a harder, whatever may be the case.

If the dislocation has to move from this obstacle that max should be higher, as a result of the adding of the size and modulus effect, this force is greater for the soft atom very important idea. So, we are talking about strengthening mechanism. So, that means, you this gives a clear idea if you add a soft atom to the solvent that is going to result in a F_{max} is higher. You are going to require higher F_{max}, higher force to move the dislocation. Both size and modulus effects produce a dislocation solute atom interaction energy that is elastic in nature.

Please one second understands we are still talking about elastic energy. We are talking about elastic the all the forces are still in elastic in nature.

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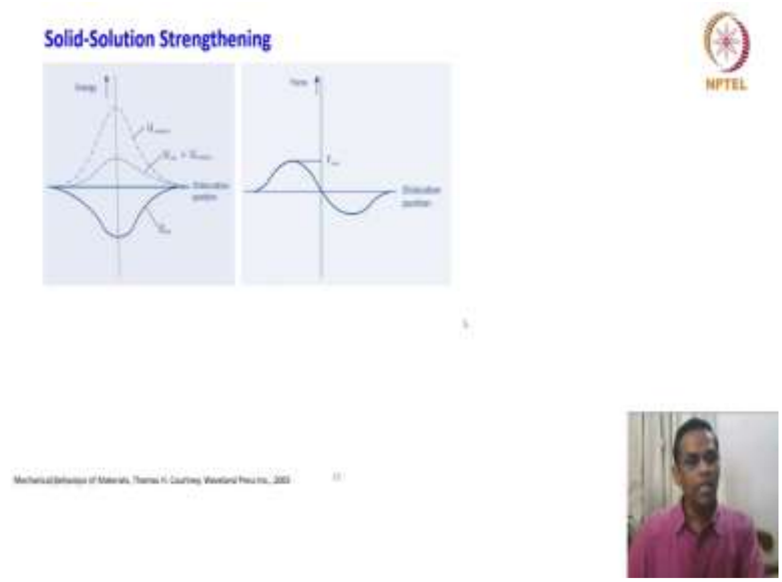

So, we will compare the similar situation that is the dislocation solute atom interaction energy versus position for hard atom for which the modulus interaction energy is greater magnitude than the size interaction energy. Now, earlier we have looked at a moderate modulus interaction in energy. Now it is significantly hard significantly higher modulus interaction energy with the hard particle. So, this is higher interaction energy but keep the size same and then what kind of the force position plot will come as shown here.

So, the net positive energy results in the forceposition curve shown in. So, this is a net positive energy, here the force F_{max} required to continue the dislocation motion is that necessary to push the dislocation by rather than the as the case of the negative interaction energy. The force required to pull the dislocation away from the solute atom. Here is slightly different there he said that tear away here it is tight of a push we require a little slightly in opposite sense, the dislocation motion to be continued and the necessary forces to push the dislocation.

By the solute atom, the solute atoms supposed to push this dislocation to move away from this or keep the dislocation motion in continuation. Strengthening results, regardless of whether the solute atom dislocation interaction is attractive or repulsive. Very important point we are looking at very closely whether it is attractive or repulsive depending upon the dislocation configuration as well as the type of solute and its size and its modulus.

Ultimately it is going to produce whether it is going to get attracted towards dislocation or it is going to repel the dislocation. So, the net energy whatever is going to result out of this interaction is going to be beneficial for the strengthening the material, that is the information. We will stop here we will continue the lecture in the next class.