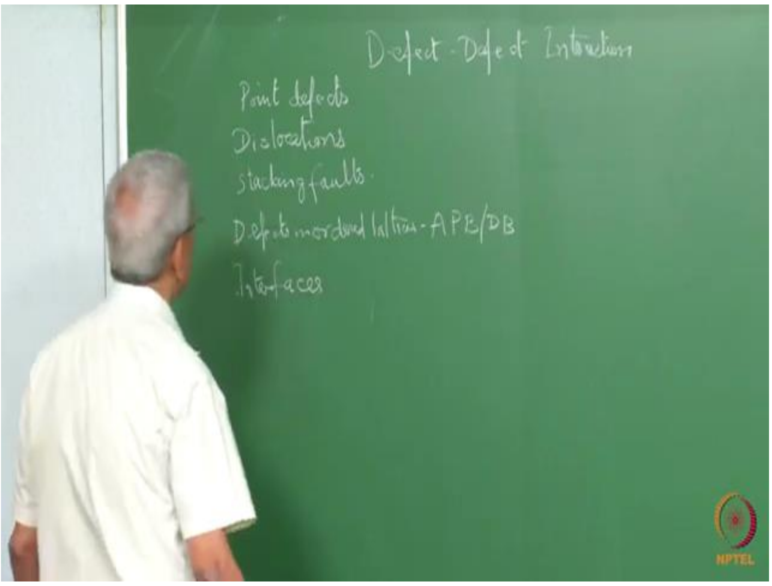
Defects in Materials
Prof. M Sundararaman
Department of Metallurgical and Materials Engineering
Indian Institute of Technology, Madras

Lecture – 35
Defect Interaction and Strength

Welcome you all to this course on defects in material. Today we will have the class on defect interaction.

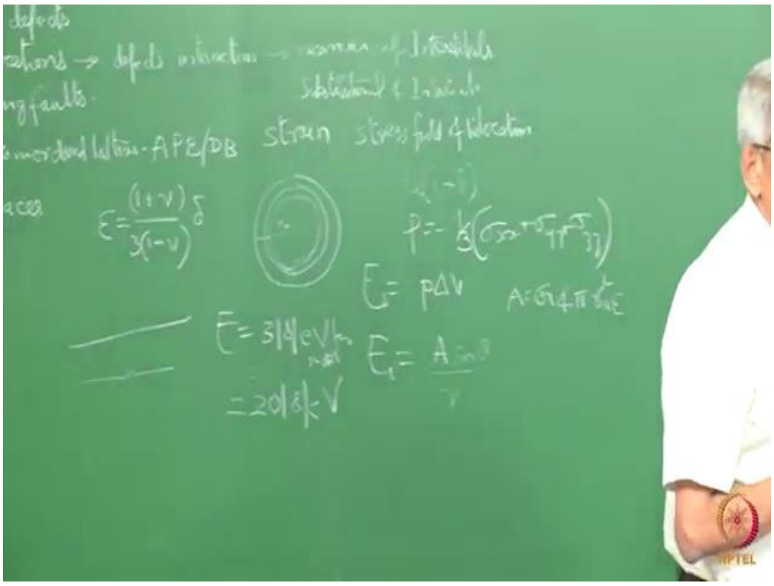
(Refer Slide Time: 00:37)



So, for we have considered today's class is an defect interaction. What are the defects which we have considered? Essentially point defects dislocations, stacking faults, then defects in ordered lattices, like a anti-phase boundaries and domain boundaries. And then this have considered interfaces, and this defect interaction controls the quite a bit of a proper almost all the properties of this material. Electrical property, optical property, magnetic property, mechanical property all these properties are controlled by defect interaction, but what we will do is that since this course is essentially on a mechanical side of you just mainly for metallurgist we will concentrate mainly on the defect interaction on mechanical properties.

Essentially we will consider some of these interactions one. So, we know that the deformation of the material is essentially controlled by movement of dislocation and this dislocation can interact with this various types of defects which are present.

(Refer Slide Time: 02:13)



So, essentially what we will be looking at in today's class is dislocation defects interaction, when we talk about this what all the defects which we have considered, one vacancies self-interstitials, substitutional in interstitials impurities in both in substitutional and interstitial size. These are all the ones which will consider.

All these point defects when we consider. We have earlier looked at that various types of point defects in ordered as well as disordered lattices. How to I in identify the various point defects their concentration all these aspects we have looked at it, but what does point defects to like a vacancy if it is present are an interstitial is there, it is going to distort the lattice. There could be a contraction are it could be an expansion which can happen the same thing will happen with either substitutional interstitial impurities also which are added. Then they will generate when they distort the lattice essentially it is generating a strain in the lattice correct.

So, they generate a strain and how this strain is going to interact with the stress field due to the dislocation. That is this will give us if we take the stress multiplied by the strain that will give what is the energy change which is going to take place in the lattice that is the information which is necessary. That will tell you whether that is a repulsive type of an whether it is an increase in energy are decrease in energy depending upon that we can decide whether it is attractive or repulsive type of an interaction which is taking place. That is what essentially is was required. Suppose we assume that the simplest way a vacancy or a defects is that assume that some area of that sample is there into which we are putting a defect maybe the radius of it is you assume it be r a, into this region we are introducing a defect which has a r a into 1 plus delta, I will write it delta is the misfit parameter; that means, that it has a which is slightly larger lattice parameter. So, this is the misfit.

If I introduce this into this area, that is going to be a change in volume which we can find out how much it is going to be. The misfit volume change, but once it has been introduced into the lattice, the lattice has got it is own elastic constants associated with it. So, what is essentially is going to happen is that, some part of the strain will be accommodated in the matrix some into this vacant site. So, it reaches size that is with the misfit if I take it if this is the size, r a plus delta it comes. What it will reach is that finally, a size which will be somewhere in between so; that means, that the strain which is introduced into the lattice is not the same as the misfit correct.

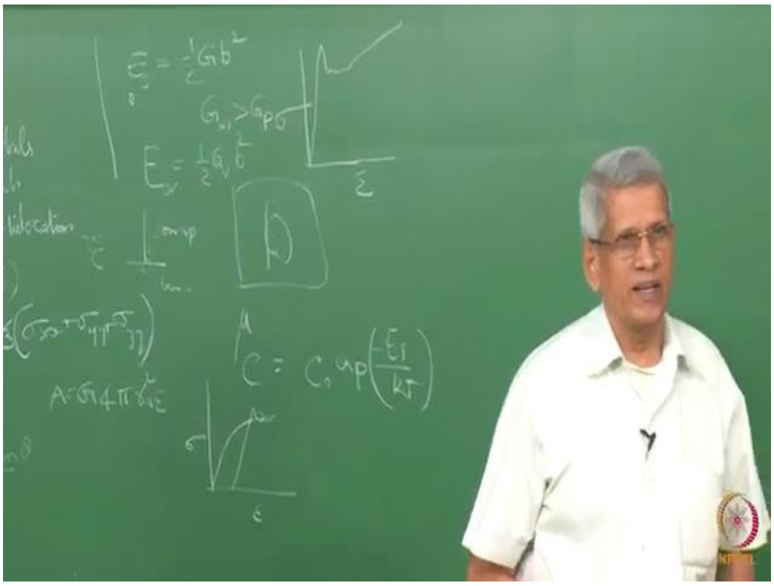
This one can find out and it is essentially given by this relationship, that epsilon will be equal to into delta. This relationship from elasticity theory linear elasticity theory we can derive it I am only just giving this expression. Essentially what it is that strain and the misfit are related. We mention that we can find out the product of strain and the stress filed of the dislocation will give. This defect we are considering it as a volume defect. We can find out what is the volume change, and the what is the volume strain. That will volume strain nothing, but some delta v divided by some volume will be there. Plus, the stress could be preferentially around the whole volume if you take it can be taken, to be the stress p can be taken to be one by 3 into correct. Then if you take that then the energy will be p into delta v we can write it this is also in energy term.

So this energy is the interaction energy. If you do a substitution and find out what is the net change. This will turn out to be some terms will be there a constants I will put it sin theta will come. What essentially it is going to happen is that this constant will consist of shear modulus then the volume term some part 4 pi r a squared will come. And the strain also will come into the picture. What is essentially important if we look at it is if that the interaction energy or the change in energy which is taking place is inversely proportional to r. Depending upon the sin of that epsilon the strain will depend upon whether it is a contraction or an expansion that will also decide whether it is positive or negative correct. Immediately one can understand that suppose it is a vacancy which is going to be here then there is going to be small contraction. So, interaction energy is negative; that means that whenever we consider an edge dislocation, this vacancy if it comes in that interaction it will be on the side where compressive stresses are going to be there.

If it comes there it will relieve and if it is going to be on the other side it will be the interstitial atoms which will be coming there. The sin of interactions will change depending upon that not only that, this interaction energy also tells that that is a sort of a binding which takes place, between the defect this one if the energy is negative then what is going to be it is getting attracted towards the dislocation. The consequence of here we have calculated the energy, but the other aspect of this interaction of vacancy with a dislocation we have already considered earlier, where what is going to happen is that when a vacancy interacts with a dislocation it introduces a jog into the material right. And a dislocation is here it comes and gets attached it will be shifting in locally and jog will be created in this the region where it has come. This jog what it is going to happen and then we looked at how this dislocation will move. We have seen that that jog is essentially where is not in the slip plane because of it, it is not able to move as fast as the dislocation. So, it has to be dragged that itself give raise to hardening of the material that is one consequence of it.

Here we are looking at the other part of it. When they are even further away, there is an interaction the maximum, when that come has closed and joins with it then then that the maximum energy can right. If you look at what is going to be this interaction energy essentially this value I think is about 3 thinks that delta, which turns out to be into e v for metals most of the metals. And in the case of like semiconductors it is from 20 times delta, electron volt this is what the energy of it is which has been some values, which calculations have shown. Here what we have considered is only one aspect of the interaction energy. That is an another aspect also which we can there are many aspects which we can consider. Suppose we assume that the point defect is there what will be the modulus of the point defect it is almost 0. What is a modulus of the dislocation it is going to be high that of them matrix modulus of the matrix is there? When they interact there is going to be a modulus effect where when it reaches dislocation that region segment if it is lying there. It has not modulus which is small these going to be there in even in a material where a second phase.

(Refer Slide Time: 13:20)



Particle is there that is if a dislocation moves in a material, we know that the self-energy of a material is given by it is formula roughly half G b squared correct.

Suppose the modulus of the matrix is a G m which is greater than that of a modulus of the precipitate. Then the segment of the dislocation which is going to be in there or in the frequency if it is going to be I will put it equals half into that is this modulus and this self-energy is small compared to that of the one in the matrix. So, when it enters we require higher stress to be applied to take the dislocation out from that; that means, the that also shows that there is an interaction correct. This interaction is also an attractive one. Suppose we assume that consider the case when the second phase this region which we are considering it is that sample the sample. This region has got a modulus which is much higher than the self-energy of the dislocation within that region is going to be very high.

So, it would always try to prefer to be away from it. So, there is a sort of a repulsive force which will be acting when they come close by correct. So, here what is going to happen is a that the dislocation tries to enter here, there will be a repulsive force it will try to keep away whereas, in the other case it is attracted towards it. So, the interaction energies are. So, modulus also gives one more interaction. So, all the interaction energies will be acting at different line scales. In the sense at different positions that is, suppose this is where we have the defects which is present. Depending upon this distance the interaction energy will change. That is what essentially is going to be only this this interaction energy is essentially the stress and strain field interaction is going to be registered.

The other one is that the modulus effect will come into the picture only when it just enters. Because it is not going to act correct. Then an another effect which can happen is that which normally is ignored, is that whenever we look like an look at an edge dislocation. The edge dislocation that is a compressive stress here this is compressive and concile is going to be there. So, closer towards this core if you look at it, in this region that is going to be less of atoms means that atom is not going to be there that region has to be replaced with some electrons which have to come correct. And here it will be the other way around positively this one will be there; that means, some dipole interaction will take place these dipoles can also interact with whenever defects is being present there also if you look at it there is going to be a variation in the electron density correct. So, that interaction also will take place. In cases like ionic materials and all where these interactions may be stronger in most of the metallic cases we just ignore them.

Then there is an another type of an interaction which can happen is that in many materials the dislocation can split into partials. Whenever the dislocation split is into a partial the region between them we call that a stacking fault is created. The stacking fault is nothing, but a different phase correct. Is a nuclei of a different phase? When a nuclei of a different phase is there the compositional affects how much the defect can be dissolved in it is going to be different.

Not only that for that phase there is since a chemical composition also can be different the chemical potential between the faulted region and the unfaulted region will also be different right. This chemical what will be the effect of this change in chemical potential more solutes can come into the stacking faults and segregate to them. So, that is another way in which they are attracted to it this effect is called as the Suzuki effect. This is an another type of effect with which solutes segregation will occur. So, these are all the various types of interactions which point defects can have with dislocation is it clear. This sort of interaction what is the consequence of it here we have considered vacancies

Now let us take the case of a substitutional or an interstitial solute also which we can consider it. Suppose the defect is a present the substitutional defect is present or a industrial defect is also represent this defect can have a positive misfit or a negative misfit. This change in misfit will make the defects segregate preferentially to the above the slip plane or below the slip plane in the case of an edge dislocation, because if the misfit is negative, that is then what will it will segregate to the compressive region correct.

If the misfit is large positive, it will segregate to the tensile portion of the dislocation. These gives a bias also and more than that what we have considered. So, far is essentially a defect which is isotropic. Quite often defect could be an isotropic also like in iron, when a carbon goes to an interstitial position it occupies a position which is an isotropic, where the defect essentially is the defect has a site symmetry which is essentially tetragonal; that means, that in some directions if you look at it the misfit will be small, when the carbon atom sit is on to cage in another direction that is in the along the c axis it is going to be a large though strain will be large in those direction.

So finally, it does not matter whatever is that when we have to find out the total interaction energy, we have to take the misfit is in each of the direction into account and then calculate the total energy, but this interaction energy what it brings out is the fact that there will be a preference for defects. If they come close to the core of the dislocation there is an energy minimization is going to be take place; that means, that suppose we consider an alloy which contains small concentration of defects which could be either interstitial or vacancies. A interstitial or substitutional a impurities are present there, very small concentration, when we what we mean by small concentration essentially is that the defect that between the interstitial interaction is very smart. That is, so, isolated that there is no interaction between them that is the way we look at it.

These defects generally we assume that the concentration is uniform correct. But if the defect is able to migrate; what it will happen is that there is the temperature is such that these defects are able to diffuse. If they diffuse as they go along when they come very close to the defect which is being present to a dislocation, it will get attached to this region because their interaction energy becomes negative. Then like that so many defects will come they will be drifting towards it. So, the concentration of the defect itself if you look at it, if it is z 0 is the initial concentration into exponential k t. This way the concentration we will find that is going to increase the defect; that means, there will be atmosphere which will be formed around the defects work.

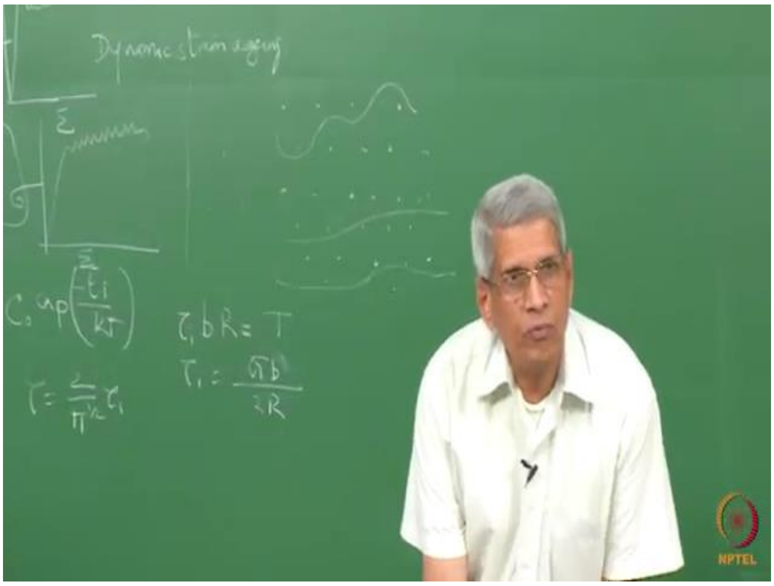
This happens because the temperature is such that defects is able to diffuse, but at the same thing when the temperature is high and the dislocation is able to diffuse there is an another process which can happen is that as the thermal vibration also will increase it is temperature. So, that can make the atom vibrate and come out of that phase. So, if the temperature is very high, the thermal vibration also is going to play a role it may. So, happen that at very high temperature atoms come close to it, but they move away from it also because of the thermal vibration. That is generally this happens at temperatures less than 0.5 t m their diffusivity is sufficient for impurities to migrate, but at the same thing the thermal vibration is not sufficient for the atoms console; that means, that there is a net concentration increase of the solute is going to take place around the dislocation.

If this sort of impurities atmosphere form this is what is called as the catrole atmosphere. What will be the consequence of it? Now once an atmosphere has been formed dislocation and the point defect is there where it is in a low energy configuration. Now if we apply an external stress in this direction suppose an atmosphere has formed around this dislocation. If we apply an external stress to move it has to the stress which is required for the dislocation to move in the absence of the atmosphere is some value, but when an atmosphere has formed it requires higher stress to move; that means, a suddenly you find that the yield stress is going up this effect is in metallurgy parlors it is called as static strain aging effect.

What is static strain aging effect is quite simple. If I am doing a mechanical testing of a sample, an alloy; I do a test. Try to look at the stress strain plot it has reached at some particular point. I unload it and bring it there room temperature. If I load it again immediately and bring it then what I will observe is that at the same point again the yield stress will come it will try to the stresses point will be starting from here. Suppose I leave it for some time at that temperature, then that is I am giving sufficient time for the defects to diffuse to a lot of dislocations, which are there when they form an atmosphere around it now the stress which will be required becomes rather high. Then the stress will go up like this and at this then once it breaks away from the dislocation from the quarter atmosphere the stress will come down and it will come like this.

This is what essentially we see in the case of iron in interstitial elements. What happens in the case of interstitial elements is that, even at room temperature the defects are sufficiently mobile interstitial defects. So, they can form an atmosphere around the dislocation that is why in pure iron if BCC iron when we test it we find that it always there is a yield phenomenon which occurs goes up then it goes like this correct. This is because at this higher stress is required for the dislocation to be freed from the atmosphere this phenomenon is occurring because of this dislocation defect interaction. That is what I wanted to tell. This we call it as a static strain aging.

(Refer Slide Time: 27:40)



Suppose this process itself occurs during the test. Then this phenomenon we call it as dynamic strain aging or DSA. There are many manifestations of DSA. The whole talk is not on that aspect of it, but what I wanted to understand is that out of the many manifestation phone which is normally prominently seen in many of the materials is what is called as a serrated yielding. Serrated yielding is a phenomenon in which there are low drops like this it goes. This is occurring because of one of the reason is that when the dislocations are moving in the material the lot of farest dislocations are there. The dislocations get stopped at the farest dislocation. When the dislocation is stopped at the farest dislocation the defects can come and form an atmosphere around it. The applied stress is also increasing the internal stress also is increasing because an atmosphere is forming. At some particular point if the applied stress become sufficiently high to overcome this atmosphere. Then the dislocation will move out of it then there will be a drop which will be seen.

Again next obstacle it goes there it will be stopped like this this is what is going to happen. Then there is some negative strain rate sensitivity effect and this phenomenon is very important in mechanical behavior of material. Because this can alter the total elongation wheel stress ultimate tensile stress there are lots of properties have been affected, especially when the material has to be formed at different temperatures. The amount of energy which has to be put to process the material to different shapes will depend upon what all the phenomena which occur dynamic strain aging is one important phenomena which has to be considered. This phenomenon the way I look at it is that many people report this phenomena, but the basic understanding of it especially the manifestations of this phenomena is still I feel that on the theoretical side a lot of work has to be done to get a very clear picture of it. So, what we have considered is the solute dislocation defect interaction either point defects are impurities and what is the consequence of it one of the effect correct.

Let us now consider the other effects another important effect of this point defects is if you take a material and irradiate it then when we irradiate it either it is with the self-ions or different type of ions which are accelerated to high energy. Or with an neutrons in a reactor atoms are displaced from the lattice site when these atoms are displaced from the lots of defects are introduced. These point defects and these vacancies they can elaborate to form different types of clusters defect clusters as well as some loops can be formed. Naturally when we deform this sample the dislocation has to overcome all these obstacles and this also gives raise to hardening this is called as an irradiation hardening this has an effect on creeps so many other properties of the material.

There are some cases which has been observed that like in stainless steel sometimes this itself gives rise to what is called as dislocation channeling there is a softening of the material is noticed. When you do a subsequent mechanical testing that is thought to be that this defects interact with the dislocation which has been generated they annihilate and create a channel, which is free of defects within which the subsequent deformation could be propagated. This is one of the things.

So far we have looked at it essentially a dislocation defects interaction looking at only individual one. Now suppose let us consider a case these defects are distributed uniformly in the material or in materials which contain a second element as an alloy in element at a temperature at which we are doing the heat treatment the solute super saturation is here that can come out and form a second phase particle precipitation can occur. So, this precipitates are nothing, but their volume defects in the material.

So, far in this course the initially I mentioned that volume defects are 2 types the 3 types of volume defects, elements in striking fault tetrahedral precipitation and voids. Voids can form during irradiation. Striking fault tetrahedral can also form in some materials because of materials with low striking fault energy because of some specific type of dislocation interaction precipitation can occur when super saturation is there. That aspect I did not go into a detail just mentioned it, but essentially this part of a transformation that is why I had not gone into a detail, but what we will look at it is that is also a defect volume defect what will be the interaction of dislocation with these defects that is what we will discuss in this class.

Suppose these solutes are distributed uniformly in the lattice then the interaction with the dislocation can take place with 2 different ways. One is the interaction could be very local unless the dislocation comes in core close to the defect that is suppose a dislocation is here some defects are distributed their like this. Unless the dislocation is very close to the defect there is no effect. Then it is called as a local interaction. In some cases, the interaction itself could be the diffuse interaction means that, the long range interaction takes place between the solute atoms and the dislocation. Both the types of interactions can take place like in the case of a matrix, whenever an interaction is going to take place where the defects are distributed uniformly. Then that interaction is going to be essentially a diffuse type of an interaction with respect to a second phase particle when an interaction is going to take place it will be a short range interaction when the dislocation comes very close to it correct.

What is going to be the effect of this interaction? Let us assume that in one element we have put an another element where the misfit is large it could be a positive or a negative misfit if we introduce that that misfit will the atom which has been introduced. One it can appear as a strain because the lattice parameter change is going to take place correct. That we can say it in an another way, that this interaction energy which we consider what we have looked at dislocation useful that interaction energy itself is if you take the rate of change of interaction energy that will be giving a force. Some stress is being generated internal stress is being generated initially a dislocation at a is able to move at a lower stress. Now we find that the higher stress is there that is some internal stress which is opposing it is created because of introduction of these impurities into the material.

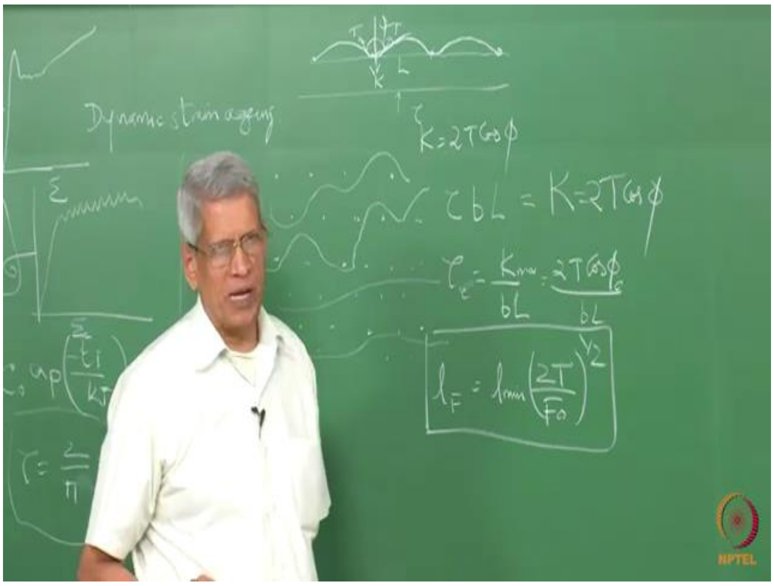
Suppose this interaction itself is a very diffuse one in the sense that the defects are present at various region. How do we consider interaction as defect is diffuse, that is suppose defects are present like this? Suppose the dislocation moves like this this means essentially it is a locally that is a variation which is going to be there. Other way in which it can happen is that the dislocations are present.

That is here it is not interacting particularly with any this one, but the effect of that defect has a long range interaction which is going to be there correct. That is interaction is essentially a long range elastic interaction which is taking place when such long range elastic interaction takes place. One of the thing is that over all there will be a bending of this dislocation correct. When a bending of a dislocation takes place then what is the radius to which they are bent, but that is tau I is the b is the burgers vector. This is the force, this should be equal to some t the line tension of the dislocation from this we can find out the tau, I will be equal to half G b squared. So, this will G b by 2 r from which we can find out what will be the r correct. So, essentially this tells if this is with respect to a particular defect or some concentration of defects which are being present.

So this if we average it out some statistical value which will give that gives the total this one tau to be equal to I think, 2 by half, tau I this will be an average value because in all these calculations when lot of particles are involved, we have to take an average. Is it clear? Think here it is 2 by pi only. This also we can calculate what is it going to be another, this tells you about what will be the then some more factors which we have to consider it is this interaction.

Suppose different particles are present at different places, there is an inter particle spacing which is going to be there. How do we take out the inter particle spacing? One is we can assume this is a random distributed particle, then the average in the particle spacing will be square root of if the number of particles per unit volume is n a unit area is n then one by root n, that is will give that value that is the way we can do it. Let us now look at the interaction which is going to be a strong interaction; that means that unless the dislocation features very close to the particle there is no interaction takes place.

(Refer Slide Time: 40:50)



Let us take a case such here like this. Let say dislocation line which is there and as this dislocation line under the action of a stress moves and reaches here comes here under the action of the applied stress; these obstacles will put a resistive force. Because of the resistive force the dislocation will bend like this. This is how it is going to take place.

So essentially the interaction is only at this point, essentially if we look at it here that is going to be a t is the line tension with respect to this. This angle we can calculate this is going to be the resistive force which it is going to what will be this resistive force k that will be equal to 2 t. If this angle is phi cos phi correct, that is what the resistive force which is essentially going to be. And suppose this separation is L from here to here. It bends into a radius correct. Is it not when it bends into a radius what will be the force which will be applied force which is going to act that is going to be tau into b into L the separation between them it is going to be equal to the force k.

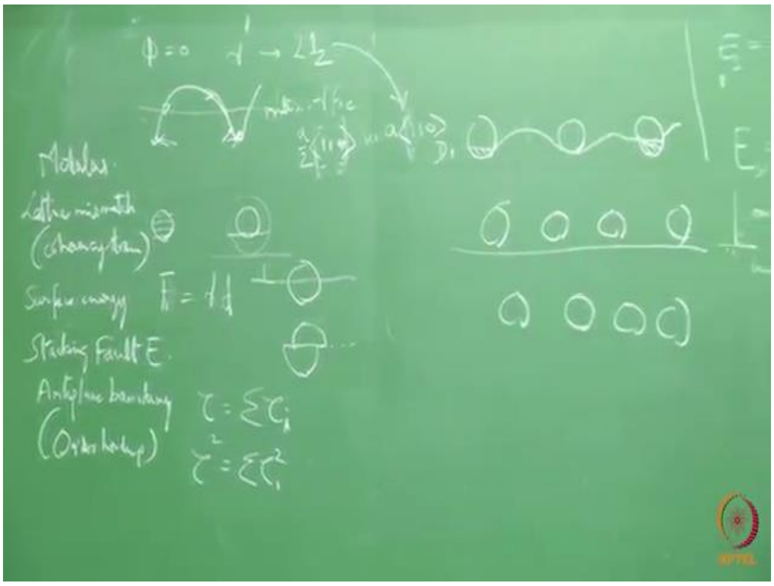
And this is a very critical one. And k can be written as 2 t cos phi, what is the critical stress which is required for this to be that is tau max what is the stress or critical stress which will be equal to, this will be k by b L k max, this will be 2 t into cos phi a critical value will be their maximum value divided by b l, we can put it this is essentially what is the stress which is required. Suppose now the most critical crucial point of it is that, at some value of the line tension corresponding to some particular angle the k max reaches where their dislocation is able to shear through the particle. Because the dislocation has got a the line tension depends upon half G b squared the modulus of the material it has nothing to do with that particles.

It is able to reach that value then it will just cut through the particle right. And suppose it is not able to cut through the particle there is another critical value at which you can do from this particle. That will decide whether, it is going to be shearing or looping, which is the mechanism which is going to operate in this interaction dislocation precipitate interaction. And another factor also which has taken it that there we have taken L to be this particle are like this, but normally what happens is that whenever a deformation takes place, quite often in these regions as you can see it the dislocations may be like this like this it may be going; that means, that the dislocation line if it is a straight line, then we can calculate and tell that the line spacing is pro equal to one by root n.

But that will not be possible when the dislocation line is not a straight line; that means, there is some statistical averaging has to be done. That is statistical averaging which has being done that is called as a friddle spacing. The friddle spacing essentially the formula is, this is the spacing which it is going to have is L minimum, which is given by when the it is a dislocation is a straight line the minimum spacing into 2 t by f 0. What is f 0 f 0 is the different type of interaction which it can have the dislocation can have with the particle like it could be an order hardening there are. So, many types of mechanisms which can happen that will have some maximum value which is required. That is what essentially this f 0 represents the force corresponding to that.

In this case we can consider 2 cases. Suppose this this phi becomes 90 degrees. Then k max will be equal to 2 t. Then the dislocation is essentially a straight line which just cuts and goes with whatever is the stress which is being applied. Let us take an intermediate case where it is a critical angle is there, when it is bent like this, it has reached the value where it is able to cut and go through it correct. And when this value of phi becomes 0 conserve that case at that point it is not able to cut then what is the consequence which will happen at that particular point when phi equals I will just.

(Refer Slide Time: 47:43)



Essentially the dislocation has bent like this correct. The tangent essentially angle becomes 0. This has become a semicircle when it has become a semicircle from the peach coiler force equation we have understood that the force is always going to act in this line direction perpendicularity. So, here the force will be in this direction here the force will be in this direction this will make the dislocation move like this, here it will move like this, will move like this finally, both of them will come and join together and this dislocation will just come out of it as a straight way. So, that is the critical condition when phi equals 0 where the looping will take place that is what one looping.

So when phi equals a 90 degree, we will call this as a peak obstacle look at the strength of the particle changes in between is this clear. Now here we mentioned that this phi is determined by the strength what is the strength, which we will consider here there are many parameters which can be considered. One supposes these are 2 different phases both are disordered and assume that both have got the same crystal structure. Then what will happen is that and for the movement we consider that the lattice parameter remains the same suppose. The modulus is different between these 2 then what will happen. The modulus will determine what is the stress which is required suppose this has a modulus which is higher. So, to account for the modulus if it bends a little bit the line tension becomes sufficient. It can make the particle cut through it. So, modulus also plays a role to decide correct.

Another is that is suppose there is a lattice parameter misfit is there. We have seen that interaction which can happen as parameter, is not only that in that particular case which you are considered there is going to be a strain which is accommodated around it this strain we call it as a coherency strain which you have talked about in the last class. So, with the coherency strain the dislocation can interact and depending upon the sin of the strain positive or negative, it can be an attractive or repulsive interaction. That also puts an effect on what is their stress which is necessary critical stress which is necessary for the dislocation to overcome the particle stacking fault energy in the matrix and in the precipitate could be different then if a variation strike fault energy is here that much energy difference also may be necessary the force necessary to generate that much of striking fault energy also has to be provided for the dislocation to pass through it correct.

That is one which will occur then another is order hardening suppose this particle itself is, suppose these are all we consider it as a large particle, and they are ordered. Then the dislocation as it comes and touches here. Further even if the crystal structure remains the same lattice parameter remains that same as the dislocation moves first dislocation it moves atom from the right. Position to the wrong position; that means, that anti-phase boundary is created that much energy is also necessary for the dislocating.

So in that case the force which we consider f will be equal to gamma into d. This is what it will turn out to be where gamma is the stacking fault energy. These are all the various types of, then one more if the dislocation passes through the sample that is you assume that a dislocation is there which is the precipitate a dislocate, this is the slip plane as the dislocation has come out of it, what will happen is that it has created a surface on the through the so extra energy is required to them create the surface that energy. So, surface energy can be different for different type of particles.

So, these are all the various types of mechanisms. So, essentially what we have looked at it is modulus, lattice mismatch and which is called as coherency strain and surface energy because extra surface is created stacking fault energy. Then comes anti-phase boundary or this is called as some times order hardening that when the discriminate has to disorders the ordered lattice. So, all these effects are going to contribute to strain. As I mentioned earlier depending upon where it is, where the dislocation is of x location enters different type of interactions will start. So, if it is a coherency strain around these particles there is going to be a strain around it. So, as the dislocation reaches here itself, the coherency strain part will be acting order, hardening part will act only when the dislocation tries to enter into the particle that will be.

So all these effects are going to act at different instants of time at different positions with respect to the particles that some of the effect at each point it will be changing now, that will reach a maximum value at some particular point. That maximum value is the stress which is required for the dislocation to overcome the particle. If that stress turns out to be much higher, then what the line tension can provide by bending it. Then what will happen is that the looping will take place in that case right. This is what essentially which happens is it clear.

Depending upon this the average distance between the particle, some expressions could be derived for the modulus each of this hardening effect, one can calculate what is going to be the critical stress which is required. Generally, the various stresses acting together there are many ways in which this is being taken. One if they are all assembled this could be sigma into i, I can write it because of radius efforts that is one way, is an another way in which it is done is that, i square because this depending upon the type nature of the forces in some cases where the stresses are vastly different then it is a simple addition which is taken when they are all of the same magnitude. Essentially they are squared added and the square root of the mean is taken. These are standard procedures which is followed in other branches of science also. This essentially tells about the hardening.

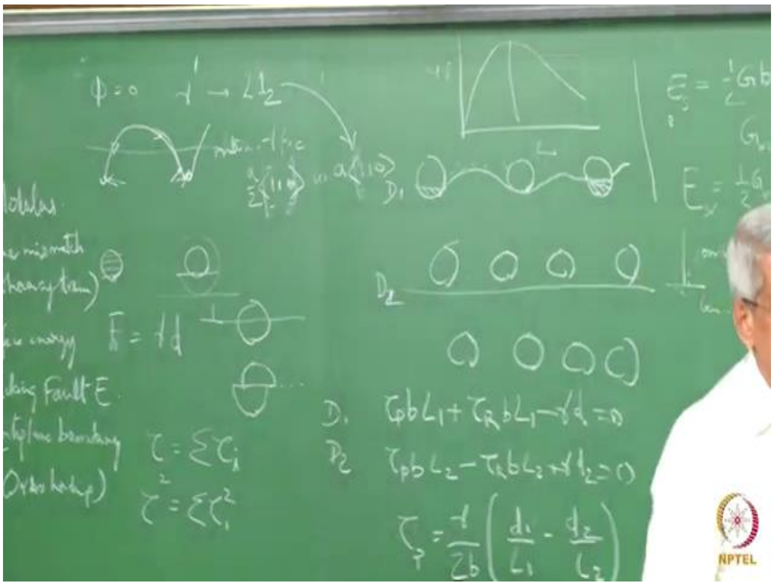
Now let us just consider one particular case which I just wanted to tell is that whenever these precipitates are or these particles are not decided because we considered 2 cases. This particle has a finite radius, but they are disordered, and another is order hardening comes in the case where the particles have a particles are ordered. Suppose ordered particles are there. Then what happens when the first dislocation passes through the particle, it disorders it. Depending upon the crystal structure difference between the matrix and the precipitate or the crystal structures of the matrix and the precipitate groups of dislocations have to pass through.

In the case of gamma precipitation, in many of the nickel base super alloys essentially the crystal structure of the ordered phase the gamma prime is L 1 2 and the matrix essentially is gamma, here 2 dislocations that is in FCC matrix essentially a by 2 1 1 is the burgers vector of the perfect dislocation. Burgers vector perfect dislocation in L 1 2 is essentially a 1 1 0, but what is essentially is going to happen is that, this since the burgers the magnitude of a burgers vector is large the self-energy is high. So, in because of that it will try to split into super partial all these aspects we have considered earlier.

If a super partial is passing that is nothing, but burgers vector of the first dislocation what it happens is that it will come. This is the way it will be happening because it has just entered here also it has entered here it is about to enter. When the second dislocation comes this is n the first dislocation generates a p b's (Refer Time: 59:20). The next dislocation which follows suppose we said this is D 1. The next dislocation which it comes it is nearly straight because it is seeing only a ordered lattice. It is seeing a not align itself it is in a disordered lattice. In a disordered lattice if it does not see any obstacle it will be a straight dislocation.

And as this dislocation comes very close to it since the burgers vectors are the same. And they are lying in the same slip plane. They will repel each other correct. And as it passes restores order that is a gain in energy is also going to be there corresponding to the order the energy correct. This will lead to yeah sort of a situation, where we can write a force balance equation for these 2 dislocations.

(Refer Slide Time: 60:14)



What are these 2 equations? This equation is for the first dislocation the applied stress the force which is acting on this. This is this dislocation puts a repulsive force on to it that also adds to it together. These 2 should be managed by equal to the order the anti-phase boundary energy which has to be generated that, then they are in equilibrium this should be equal to 0 correct. For the second dislocation what it happens is that, this is the applied stress this is the inter particle spacing. Then this will put a force which is negative of it on to this one, plus some gain in this going to be there, if we solve these 2 equations then we will be able to get these the sort of an expression will come. This is gamma is the anti-phase boundary energy this is the burgers vector of the dislocation this is D 1 by L 1 is the D 1 is the average distance which the dislocation has cut in the particle this dislocation one and L 1 is the average spacing.

Similarly, L 2 remains that and D 2 has the same meaning. These one can there are some formulas with which one can find out. This gives the expression to find out what is the critical stress which is necessary this will be the increase in yield stress which it will occur when we deform a material. In all these things here you can see the dislocation has been already bent into this one. Suppose even before the dislocation has entered it has already reached the semicircular one. Then what will happen is that that it will not be able to enter into the particle, instead a looping will take place. That will occur when the particle spacing is large for the same size of the particle the spacing is large then it can occur.

If the spacing is small; that means, that the volume fraction remains the same. And the number density is getting reduced. Then what is the consequence of this as the volume fraction and the number density changes, is that when we do the work hardening plot the y s versus particle size, if we plot it or versus the distance if you try to plot it. You will see that it goes to a maximum and comes correct. There is a maximum hardening region is this and then it is starts decreasing. I do not want to go into any of these aspects of it because I am containing myself here only to a defect interaction. This is the sort of an interaction and the stress at which it will introduce.

So from this region it is essentially going to be a looping which is going to be the predominant mechanism. Suppose it is not a second phase particle which is produced, it is dispersion hardening we have put an oxide particle into it. No way the dislocation can enter and cut the packages.

In such cases only a looping will take place will be the main mechanism of information. More information about how this affects the mechanical properties especially the instant and all flows stress that unmechanical behavior most of you will be studying. That is not the objective of this course.

Now, we will stop here. So, essentially what I had given is an overall view of the point defect dislocation interaction. And this, the point defects the dislocation volume defect interaction. Dislocation-dislocation interaction has already been covered earlier, so almost all the types of interactions which are required in a single crystal which I have covered. The other aspect of it is that the dislocations can interact with the grain boundaries that part of it is level I do not want to bring it at this particular level. That is also one thing which has to become, because that also gives raise to hardening that is what the all pitch relationship which corresponds to.