Structure of Materials

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Lecture - 27
Defects in Crystals

The next topic we consider is intersection of dislocations with point defects, as we know the dislocations have long range elastic stress fields and point defects are associated also with certain kind of stress field, because typically any point defect. Even, if you consider substitutional atom will be different in size as compare to the host atom, and will therefore result in as stress field. In these cases of course, we have to differentiate the stress field of a substitutional atom, from that of the interstitial atom, typically substitutional atom has a spherical distortion field.

Why interstitial atom, which is interstitial wides have apart from a spherical component, sudden shear component also associated with them. This implies that point defects can actually interact with the elastic stress fields of a dislocations, and this interaction can live to certain kind of segregation or sudden kind of attraction to start with.

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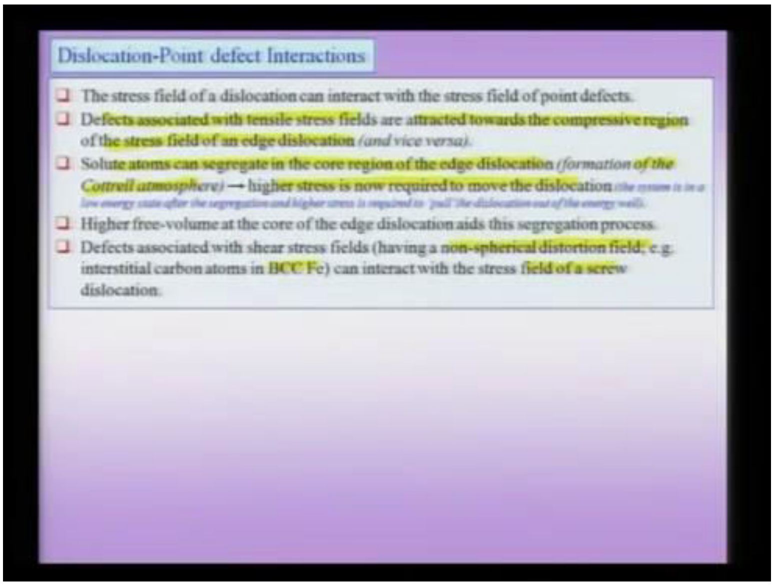

So, defects associated with tensile stress or a attracted towards the compressive region of the stress field of an edge dislocation, and as a point out screw locations have only as shear stresses field. And therefore, if a defect has a as shear stress field it can interact with the shear stress field of a screw dislocation, otherwise if the stress field of the defect is purely dilatational or hydro static, then it cannot interact with the screw dislocations.

The solid atoms therefore, can actually segregate to the core region of an edge dislocation, and can be to the formation of an cottrell atmosphere, so this kind of an higher concentration of the salute elements, in the region of the core of the dislocation is called a cottrell atmosphere. And this cottrell atmosphere as important implications to the behavior of the material when you loaded in tensile stress; that means, if you plot a stress strain diagram, in the absent of the solid, and in the presence of this solid elements.

Then there will be considerable difference, and we will take up the difference very soon, the region that we need to that the main important difference, you will see that we actually require higher stress to more the dislocation. Once, there is a segregation of the dislocation to the core of the dislocation, because now the segregation would mean to the system has gone into lower state of energy.

And if I have to pull the system out this energy well, then I have to apply a higher stress, and this case as we know to dislocation we need to apply shear stresses at the atomic level. Also, we know that the dislocation core is associated, especially they are talking about an edge dislocation and the region just below the half plane, then that region are region of extra volume or free volume.

And therefore, that region can nicely accommodates certain small interstitial atom as compare to the normal lattice, where in which is you require a certain higher energy to accommodate the interstitial atoms. And important example of this case of this interstitial elements, is the non spherical distortion field of the bcc carbon atom in bcc ion, and this can interact with screw dislocations. And as we shall see that this kind of a segregation of this carbon atoms in bcc ion, which to an alteration of the shape of the stress strain diagram.

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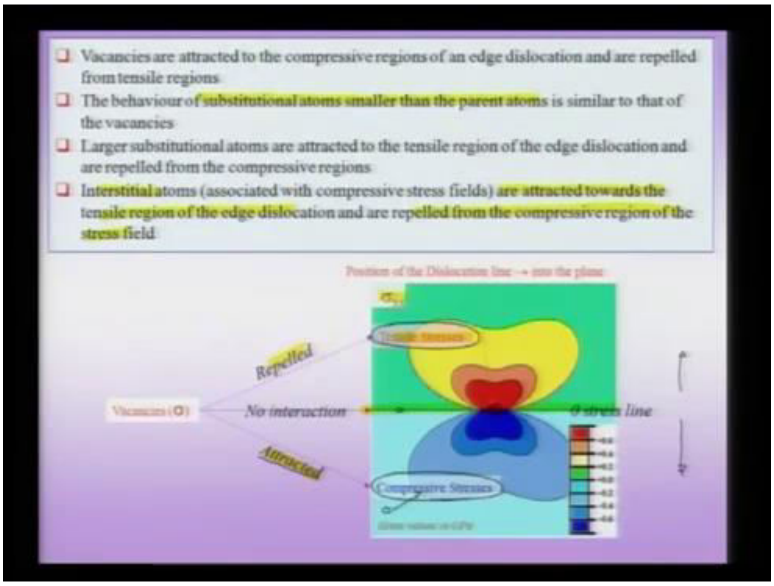

Now, let us start with an interaction of vacancies with the stress field of the edge dislocation, so in the figure below you can see that, actually I am showing the sigma x stress field around an edge dislocation, that dislocation line is into the plane other board right of the center here. And so, let me mark that, so this my edge location is right of the center, and you can see that the entire half space about is tensile in nature, and entire half space below is compressive in nature.

So, this my compressive stresses below, and my tensile stresses are above, and we know that this complete half space being tensile or compressive is in the case of edge dislocations, in an infinite media. If your finite medium or certain other possibilities, then this kind of a beautiful picture, which is very symmetrical there is a top down inverse symmetry; that means, a symmetry.

That top half space has compressive, the bottom spaces is or this case tensile in compressive, and you also have the left right symmetry would be broken in certain other cases. Now, what happens to vacancies, when they are present very near or nearer edge dislocation, the actually as you can see that the vacancies are associate tensile stresses, and they are therefore, attracted to the compressive region of the edge dislocation.

That means, that suppose I have vacancy this thing here, then it will tent to move towards the compressive region; that means, related motions, because there is gradient in the stresses. And it can lower its energy, as it go move towards the core of the dislocation or towards the dislocation line, the behavior of sub smaller substitutional atoms is also similar to that, we are talking about substitutional atom smaller the parent atom is also similar to that of vacancies.

Largest substitutional atoms will associated with compressive stress fields and actually they will be attracted towards the tensile region of the dislocation, and if you are talking about interstitial atoms. And they are typically interstitial atoms as you know are largest in the wides, in which they say typically, we are seen that in a FCC crystals for this in the wides are the tetrahedral, and octahedral wide. And this interstitial atoms are typically larger than those wides, and therefore they are associates with compressive stress field apart from as t told you that also some shear stress field.

And therefore, this interstitial atoms are attracted towards the tensile region of the edge dislocation, so and they are repelled form the compressive region of these edge dislocation stress field. So, let us look at the complete picture for the vacancies, revising it, so vacancies are attracted towards the compressive regions are repelled from the tensile regions, and you know there is a 0 line as stress field right at the middle. For instance, and there is only one single 0 line when we are talking about an edge dislocation and finite medium, so if vacancies sits on the this dislocation line.

Suppose, I am talking about vacancies seating the right at this point, then it will not interact with the dislocation stress field in other words it will remain unaltered, it will not feel the force of the dislocation. So, in essence this elastic interaction between a point defect, and a dislocation stress field a can lead to attraction or repulsion or in re-specially cases no interaction also, and this interaction or repulsion can actually lead to and assist a diffusion of these point defects two words or away from the dislocation.

And the most important case of this is a case, where in there is an attractive interaction of the solids atoms of carbon towards the edge dislocations in BCC ions, so that is a very important example.

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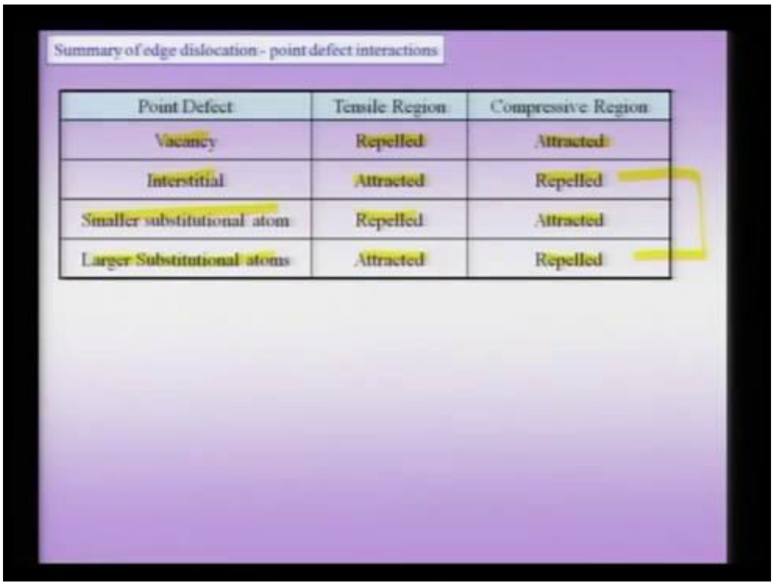

So, if I write down the character table of the kind of point defect left hand side, and the kind of interaction within, so we can see that a vacancy is repelled from the tensile region, and attracted towards the compressive region. And interstitial atom we has write in the opposite way, it is attracted towards the tensile region and repelled from the compressive region, a smallest substitutional atom behaves similar to the vacancy, and is repelled from the tensile regional attracted towards the compressive region.

A point defect which is larger then, which consider of largest substitutional atoms then the host atom is attracted towards the tensile region, and repelled from the compressive region, and in this sense it is similar to a interstitial atom. But, as I told you there is a fundamental difference between interstitial and substitutional atoms, that they distortion field of an interstitial atom might have a shear component, and hence it can also interact with screw dislocations to be.

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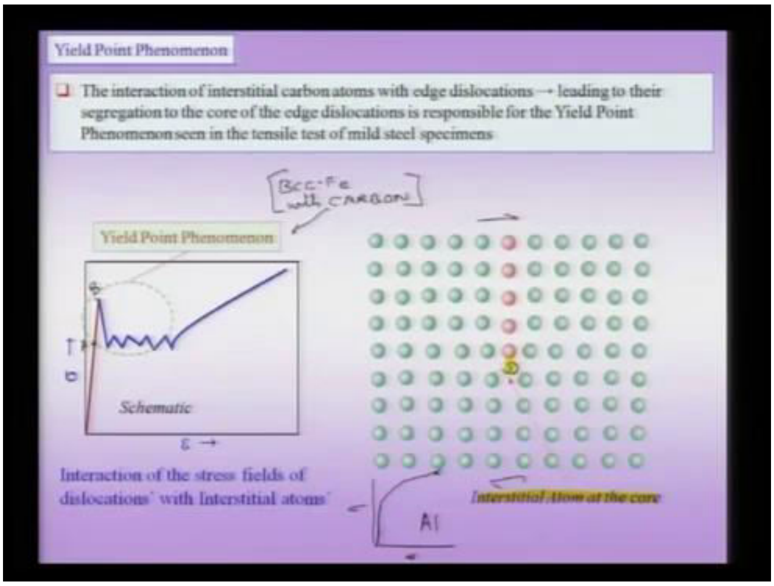

So, what happens, when I have for instance a carbon atoms solid solution in a BCC ion, so what can happen is that these interstitial atom the carbon can actually segregate to the core region of the dislocation, and perpentionally come and sit in this region. Of course, we are seeing one atoms here, but what we mean is that along this direction into the plane of the slide, lot of atoms can come and sit any other core of the dislocation. And this is what, which I pointed out is called the cottrell atmosphere.

So, there is atmosphere these atoms around the core region of the dislocation, and overall this results in the lowering of the energy of the system, because now the tensile stress field, so go back to the character table ((Refer Slide Time: 07:25)). It compressive stress field of the interstitial atom will cancel the tensile stress field of the dislocation, and therefore you have a lowering of the energy, and now if I what is the designator of this on the stress strain diagram.

Now, suppose I do a stress strain diagram for instance an aluminum, so let me draw for instance the typical stress strain diagram of aluminum, you notice that pure aluminum for instance or commercially available aluminum. Then you would notice that the curve will go up straight, and then will keep going up and this is a 2 stress, 2 strain diagram, but if you look carefully at this diagram, which is for now for the example of material like this BCC ion with carbon. And the clear cut signature is seen in a phenomenon was the point phenomena, in the case of aluminum for instance which I draw here, the material will be I show an elastic region.

And then it will slowly the curve will bend and; that means, the dislocation are moving and continue to cost plasticity, in this case what happens even though if you look at this overall curve, you will see you can look guess that the material starts yielding somewhere here, because of this cottrell atmosphere. You need to apply an extra stress, which is up and above this stress from here to here, suppose I call this point a, and I call this point b, I need to or this point b actually the upper yield point.

I can i have to apply this extras stress, so that and this stress, of course in the microscopic level can be drawn like this on this diagram, so this extra stress has to be applies, so that is dislocation can break free from the cottrell atmosphere. And of course, repeated locking in this atmosphere can lead to phenomena known as serrated yielding, so there is serrated yielding, and once the dislocation of the free of this cottrell atmosphere, then they can this stress strain diagrams looks rather smoother.

So, the entire presence of this yield point phenomena is because of this interaction of dislocation with the point defects in this case, carbon and bcc ion, so to summarize to this slide if I have to take a pure ions material and shear it. Then typically it will lead at stresses, which are somewhere round the; that means, the elastic to elastic plus, plus transitions would take place at lower stresses.

Now, because the intersection presence of carbon, the carbon is attracted to towards the lower half of the edge of the extra half plane, other words regions of high free volume right here, which is now in the tensile region of the edge dislocation. And this segregation by actually by diffusion can live to the cottrell atmosphere, which implies that now I need to apply extra stresses then above what are would expect normally for a pure material, and therefore this leads yield point phenomena which is nothing but, the locking of the dislocation by the carbon atoms.

So, this important effect pears seen, the yield point phenomena coming purely the interaction of an edge dislocation with point effect, which is the interstitial atom of carbon. Dislocation can interact with as a pointed out before can interact with any one this long ranges fields, and one important interaction is the dislocation precipitate interaction.

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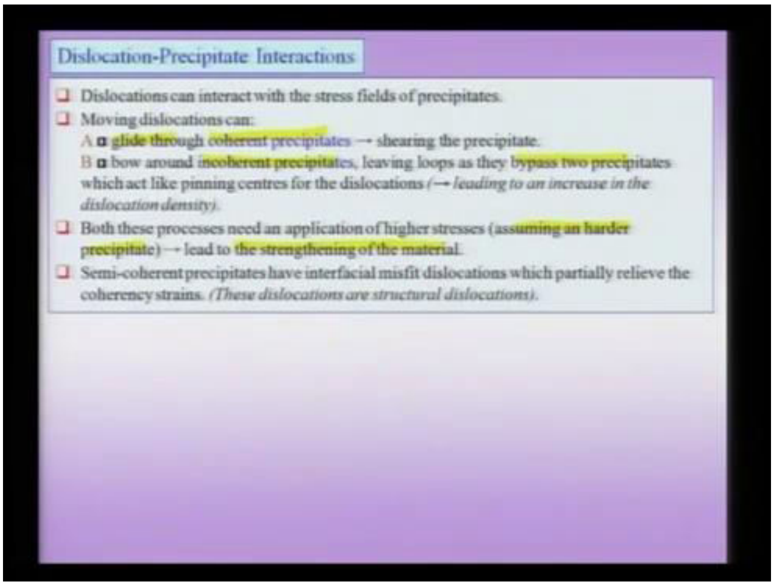

So, some of this interactions are very, very important, because we start off with the material. If we say take a pure material a whisker would 100 percent free of dislocations, we know that we can expect a yield stresses of the order of theoretical stresses, presence of dislocation weekends the crystals, and therefore we have two find mechanism by which we can strength on the crystal.

One of the mechanism, is actually add substutional long elements, which can actually raise your lattice fraction, and therefore in other words give your strengthening effect which is called the solid solutions strengthening. Interstitial atoms will also give you this kind of solid solution strengthening, the other mechanism which is very popular is the participation hardening mechanism, in which you produce precipitates in its materials, and these precipitates can give you a hardening effect.

So, let us try to understand how the hardening effect of precipitates comes about, and more importantly what is the dislocation precipitate interaction that we are talking about, so precipitate are 3 types.

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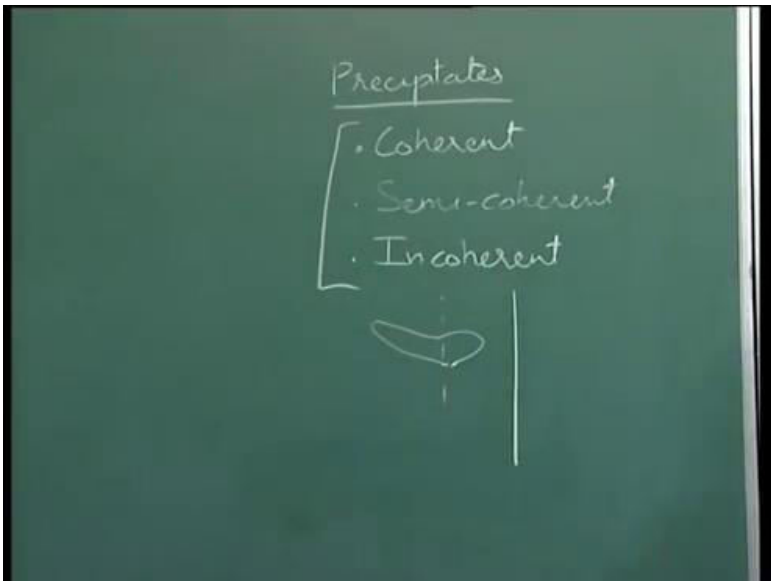

So, here three types of precipitates out here, and the coherent precipitate is a precipitate in which the atomic planes are continuous from the matrix into the precipitates, in a semi coherent precipitate there are regions in which the atomic planes are continuance. And there are regions with atomic planes ends at the interface, and that they can be interpreted as the presence of an dislocation.

And if we are talking about the precipitate which has dilatationally or which has lattice parameters larger than the or larger smaller than the matrix, then typically this would be edge dislocation or edge dislocation loops in the around the interface between the precipitate and the matrix. Therefore, there are coherent precipitate there planes are continues, semi coherent precipitate which are associate with region of continues planes and also with a the presence of interstitial dislocations.

And there are incoherent precipitate, where in the atomic planes do not continue from the matrix to the precipitate. So, the mechanism by which a dislocation interact with these kind of precipitates, defers depending on the kind of precipitates of talking about. And one important point about co coherent states, they are also associated with long range stress filled; that means, because there is miss feet in lattice parameters between the matrix in the precipitate.

There is a stress field, and therefore you have as stress field of the dislocation can interact with the stress field of the coherent precipitate. And as for as the normal stress interaction they remain identical as for as the coherent precipitate like, if we have tensile region give attract to the compressive region, if we have compressive region, it will be attractive tensile region. And therefore, there is no difference in that aspect, but as far as the dislocation interaction with a coherent precipitate goes, it is a it could be very different from that the way dislocation interact with the incoherent precipitate.

And we will take up these two examples by the kind of mechanism by which they would interacts, and important point to be noted is here. Even, though I said that there is an interfacial miss feet dislocation presence in the case of semi coherent precipitate, we are not dealing with the interaction of that dislocation with the precipitate.

What we are talking about is a dislocation which is present in the matrix far away from the interface, which is now moving towards a dislocation, and try to interact with the this precipitate, but in this set of lectures we will only consider the interaction of a dislocation with the coherent precipitates and within an incoherent precipitate. So, what is the essential difference between a dislocation interacting with these two kind of precipitate, in case of coherent precipitate the dislocation actually can glide through the coherent precipitate, and which will actually share the precipitate.

Now, again guide through because atomic plane it has set continues from the matrix to the precipitate even though they are distorted, in case of incoherent precipitate the dislocation cannot be glide through the precipitate. It has to bow or by pass the precipitate living a certain loops in the wake of the moving dislocations, so we will take up the graphically, so that we can understand these two interactions in a better fraction.

The important point to be noted is at both these processes lead to an need an higher application was typically, and of course I am receiving the harder than the matrix and this lead to the strengthening of the material. So, precipitation hardening or precipitation strengthening is a very important mechanisms by which a material can be hardened, and therefore you can sort of increase the strength of the material, as compare to the we can state, because of the presence of dislocation.

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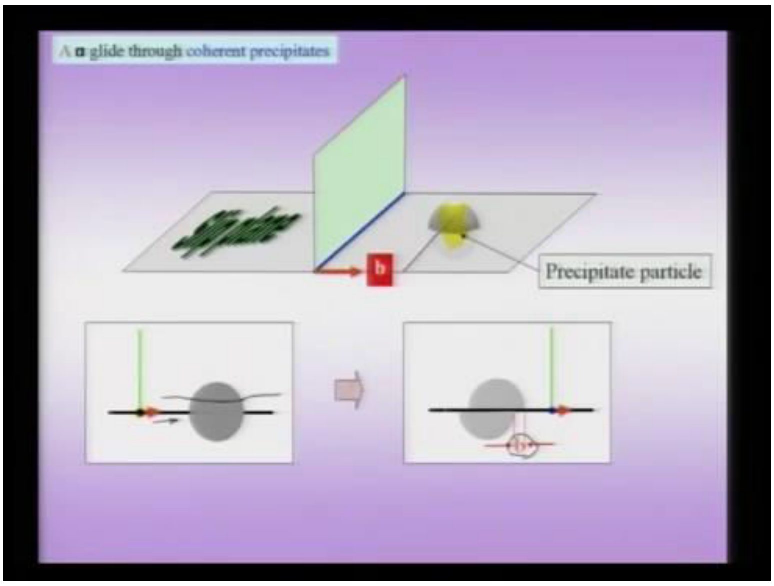

Now, suppose I have a precipitate line on this slip plane, and now this is a coherent precipitate right here, sitting on the slip plane, and now I have dislocation line which is shown in blue moving on this slip plane, try coming to this precipitate. Now, I can actually see this precipitate on the side view, where in I have dislocation line here, and the dislocation is moving towards may right into the grey color precipitate.

So, what is going to happen, is insets it is a coherent precipitate the planes are continues from the matrix to the precipitate, even though function this where atomic plane for instance, this could get distorted in the and it could this will continuous. So, typical kind of atomic plan within from going from the precipitate to the matrix, so when this dislocations moves to the precipitate. The section of the dislocation for instance suppose now it is reach the stage, where in I have section in this location line in the matrix, and there is section line within the precipitate.

The section of the dislocation which slides and the matrix would feel a different resistance to motion, as compare to that would which lies within the precipitate particle. Because, now the precipitate particles is could be elastic harder, and would there could be difficult and would a different pulse stress, and therefore difficult to more location within the precipitated.

Now, what happens when this location yield a precipitate is it creates a small step of burgus vector b, so within the adman's a particle is not been shear, and therefore at least the burgus vectors in each wakes. Now, this means that the surface area of or interface area of this precipitate as increased, and therefore that would require a little extra energy, and there which would in term another words show extra stress, which we need to apply to more dislocation.

But, any case the section lying within the receipted would face a higher, what you call pulse stress to move the dislocation, and therefore you see hardening effect even the presence of the, even though the fact that the dislocation is actually gliding through the precipitate. Now, of course, this is now, so far ignoring the long range of effects, but there also be interaction stresses of the dislocation with the precipitate.

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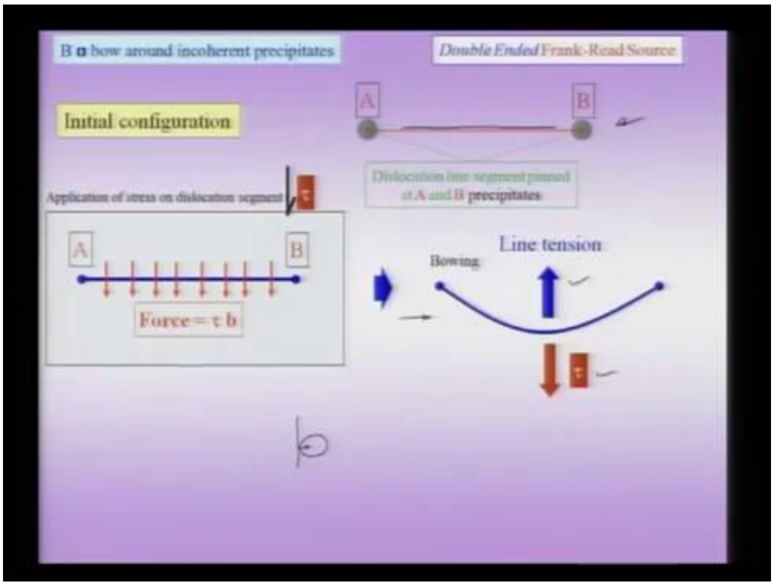

Now, suppose I am talking about incoherent precipitate. And therefore, I come to a different kind of mechanism by which dislocation can actually interact with the in coherent precipitate, so now, suppose I considering coherent precipitate. And let me start with this diagram on the right hand side here, where and I can see that these 2 grab sphere are always circle the incoherent precipitate.

And this is my dislocation line shown in red coal, and this dislocation line is now for instance this is my location here, and right here, and this is now pinned up at this 2 point, because if I am talking about a precipitate here for instance. And my dislocation line moving, it cannot move into the precipitate, as it is in coherent there is no continuous plane, so in other words is as is a different crystals setting across the interface.

Therefore, the dislocation gets actually pinned at these 2 points, and therefore it cannot move at those 2 points, now suppose I am applying an external shear stress, the stress would fail at all the points along the dislocation line. And this stresses would tent to bow the dislocation as shown in the figure on the right hand side, but if I bow the dislocation, then the length of the dislocation line is increasing; that means, the energy of associated with this location at unit length is also this increasing.

Of course, if I started off with pure edge dislocation, now this dislocation would have a certain screw component to it; that means, only one point would remain in generate the remaining would becomes screw. If I am starting with the pure screw to this dislocation, then I can simple the argue the disturb dislocation has a mixed character, now applying this external stress. The external stress suppose has a value tau, it will try to balance the line tension, the original line tension being the increasing energy associated with the dislocation line, which goes has g b square per unit length of the dislocation.

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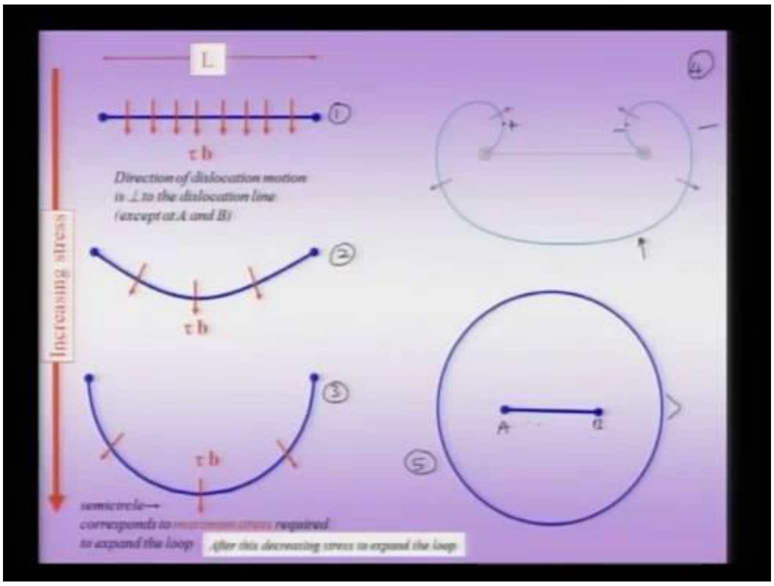

Now, suppose I keep increasing the stress, then what would happen is that the dislocation line would bow more and more, this segment which is unpinned, the segment which is free to move, would in an increasing stress lead to larger larger bowing. The upper limit for this radius would be the radius, where in this becomes semi circle and entire process starting from figure. For instance, this point 1 to 2 to 3 will take place appealing stress, because now I am increasing that this locations line and therefore, I have to counteract with my applied stress.

And therefore, I need to apply an additional stress to cross this semi circle, but beyond the semi circle, now if I look at figure 4 this happens from beyond from point 3, figure 3 would take place in a down yielding stress. And what would happen is that, this dislocation line will take shape as shown by this right of blue line on this figure, this figure here, so this figure here. And you can see that it takes a shape like this, and if this segment has a certain sign of the dislocation about this is positive, then obviously this segment would have negative sign.

And therefore, they would be attracted towards each other, at each point at remember to the line tension and applied stress or opposing each other. Of course, this is now going downhill stresses and finally, if the final picture would be, this picture 5 as shown here, in which case you will have a original line segment retained, but additionally this two segments are opposite negative come an cancel each other. And this dislocation would take a circular shape which you would give it the equilibrium configurations.

So, because that would be the for a given length of segment, this would be the what if I increase or cause any dense in this, that will increase an length of the dislocation line. And therefore, this is the configuration would up the lowest energy and so at the end of this whole posses of shearing, I would notice that, I have a dislocation line segment which a origin start of each, so you can see this my original line segments, which is pin between a and b.

So, I have this my a and b penned segments remaining, but I have additionally created at dislocation loop, this mechanism as I pointed out this call the frank read mechanism. Or the frank read double source as it is called a double inter frankly source, and this is creating an additional loop that means, as the same set of same dislocation pinned segment, can keep on operating again and again creating such kind of loops.

So, again apply shear stress, then this whole process of going of the dislocation line, but now we have to remember this both segment has to interact with the stress field of the additional loop, which has been created. That means the second time operate to same pinned segment to operate a double frankly, so I would have to apply an additional stress as compare to the first time raw. But, nevertheless I can keep on operating this frankly source and therefore, create more and more loops.

So, we seen that, so this is just an example of an interaction of dislocation with incoherent precipitate,((Refer Slide Time: 12:17)) there may be other important ways in which taken interact. But, now in constant two examples, one for coherent precipitate and one for in coherent precipitate. So, let me summarize this dislocation precipitate interaction briefly, that in case of coherent precipitates, the dislocation can shear to the other state, and even in this case we would observe some amount of hardening.

But, suppose you talk about incoherent precipitate, not only can the dislocation not shear to the precipitate, but would remain pinned at these two points of the state, but nevertheless it can bypass the pinned segments by creation of loops. But, never the less the virginal segments still remains which can be operated further and further, and some point of time if this a b segment, the stressed operate a b segments becomes too much.

Then there will be other segments, for instance suppose you would start with the longest segment which can be operated first, then the shorter and the shorter. So, let me now go to smaller and smaller pinch segments, which requires higher and higher stresses to operate. And therefore, this also would lead to a hardening in the material now, because now you have not allowing the free motion of dislocation. So, both these mechanism would lead to hardening of the material and therefore, would constitute important from the materials behavior perspective.

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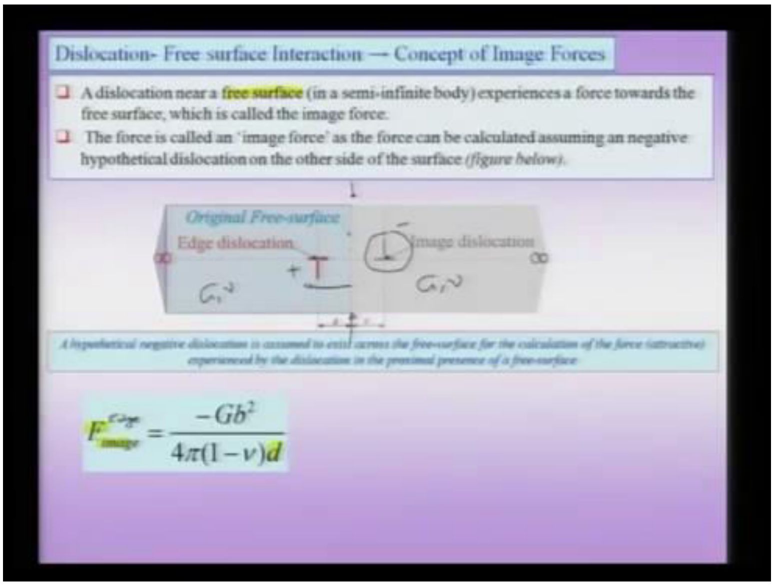

Next, we consider the dislocation frees surface interaction, the so far what we consider the dislocation stress filled as may be if we consider the figure here,((Refer Slide Time: 04:04)) you see the figure here. This is a dislocation stress field in an infinite body, but now suppose I have a dislocation sitting in a finite media, so now you can see that this is my body on the left hand side, so this is my inter surface, free surface here. And to the left of this free surface is my body, the entire gray shaded area is the, what you might call the vacuum issue like, now are hire for that matter.

At dislocation near a free surface gets actually attracted towards the free surface, and this can happen because now, the dislocation stress filed; and in the presence of a free surface the dislocation stress field which have this left right symmetry ((Refer Slide Time: 04:04)), on this broken down it no longer has the left right symmetry. So, in other words you have dislocation infinite medium, now this is my symmetry line, the line at the middle. But, this kind of a symmetry is broken down in the presence of an free surface, now I can proximately draw my stress field in the presence of free surface.

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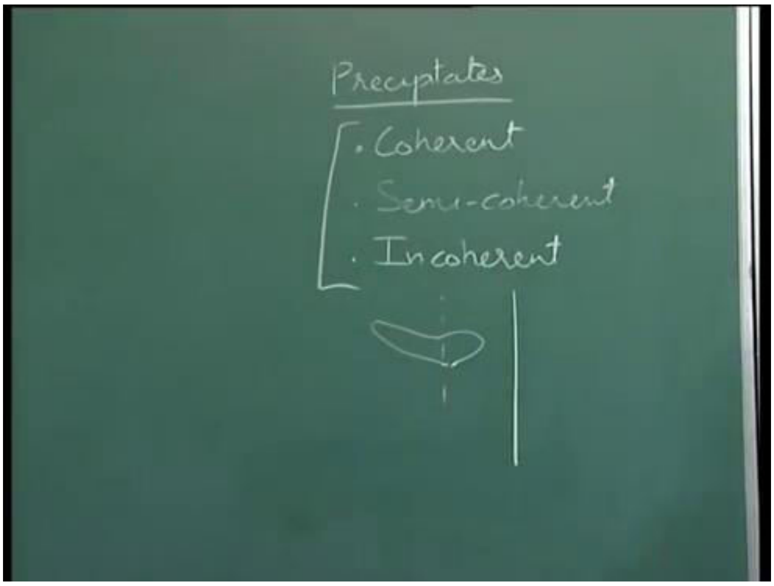

So, now I would have this is my free surface, and I have dislocation presents here, so now, my butterflies would have a certain kind of distraction in the presence of the free surface. In other words, now it does not have that left right symmetry which originally had around the dislocation line. Now, the dislocation is attracted towards the free surface, because the free surface is attraction free surfaces.

In another words, there no attractions on the free surface, the force with which dislocation attracted towards and edge free surface, is given by this formula right here the F image. And it is called the image force and it goes as 1 by d, where d is the distance from of the dislocation from the free surface, so this is for an image force experience by an edge dislocation. So, this an image force for an experiment by an edge dislocation, similarly is grew dislocation also in experiment in attractions towards the free surface.

So, what is the reason that this dislocation gets attracted towards the free surface this, the reason is that actually if I dislocation moves to the free surface, it can relieve all stresses and the energy system would be relieved, except for the small step which is created. So, therefore, as a dislocation move towards a surface, it is a energy reduces and this is the reason that the dislocation is attracted towards the free surface. So, now of the other hands suppose why this called the images force, is because this is a kind of force which made call configurational force.

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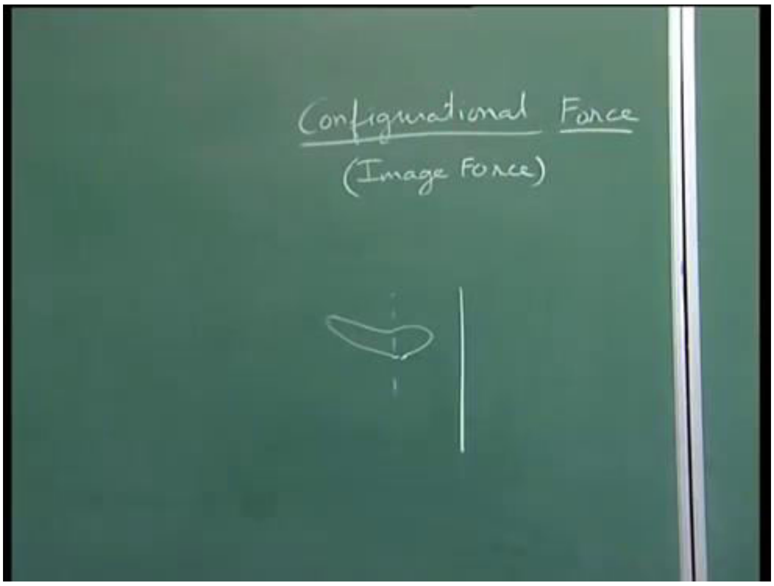

So, let me write down this name for you, so this image force kind of configurations force, the image force is a kind of configuration force which attracts dislocations, towards free surfaces. Now, as I said the region for the attraction is the lowering of the energy of the dislocation, as it most to others free surface and finally, when it reaches the free surface, it creates a small step, and all this stress fields are relieved.

On the other hand, suppose I have a interface with the harder material, then that will be a repulse that means, having the free surface, suppose I have the harder material on the other side of this inter face.

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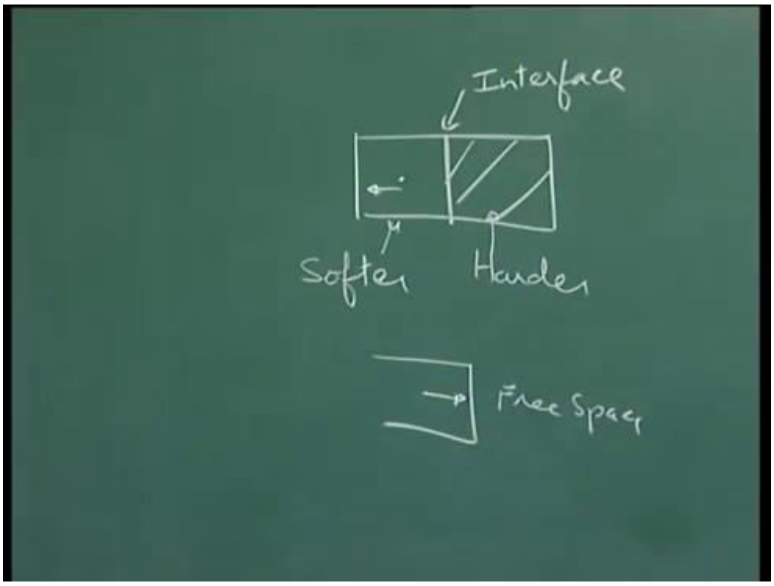

So, I have dislocation here and now this is my harder material, and I would dislocation here, so this is harder, this is my softer material, then the dislocation would actually be repelled from this interface. So, I have my softer material on the left hand side, and harder material and dislocation sitting here, going into the plane of the board. Then this location would be repelled from this interface, well another hand suppose you had a softer material or a free space here, then the dislocation will be attracted towards the free space, free surface.

Now, the reason this is called an image forces that, that suppose you want to calculate the value this force, which is shown here below, you would actually construct an hypothetical negative dislocation, located at distance d. And now what I will do, I artificially not only constructed dislocation of the opposite the sign, but I will assume the material properties, which are for instance g and u on the left hand side, is also maintain for this materials g and u.

So, the hypothetical dislocation which I have constructed of the opposite signs, suppose this is normal customs dislocation to the negative dislocation, they will be force of attractions and between the positive and an negative dislocation. And that is why this is called the image force, because now I have constructed an hypothetical dislocation at the same distance from the interface. And now I calculate the force between these two, and dislocation is called the imaged dislocation and hence, this force is called the imaged force.

So, a dislocation can also interact with three surfaces and interfaces with harder or softer materials, so this is an important point to be noted. And if this force of attraction can exceed the pulse stress, then the dislocation would automatically leave the crystal and go tense it on the surface. So, we actually make a calculation later of the value of this image force and the kind of interaction, and kind of motion it can lead to. And important point to be noted here is that, as a dislocation goes to the free surface, it can actually distorted the free surface as well.

So, if I dislocation here ((Refer Time: 30:50)) for instance get closer and closer for the free surface, and now assume that extra half plane is dislocated at the bottom, this is my extra half plane. So, I have extra half plane here dislocation, it is going towards the free surface, then as a goes to suppose to a very close to free surface, so this is my the free surface would be distorted. Presence of dislocation distort my free surface, this is my extra half plane, so this can lead to a distortion of the free surface.

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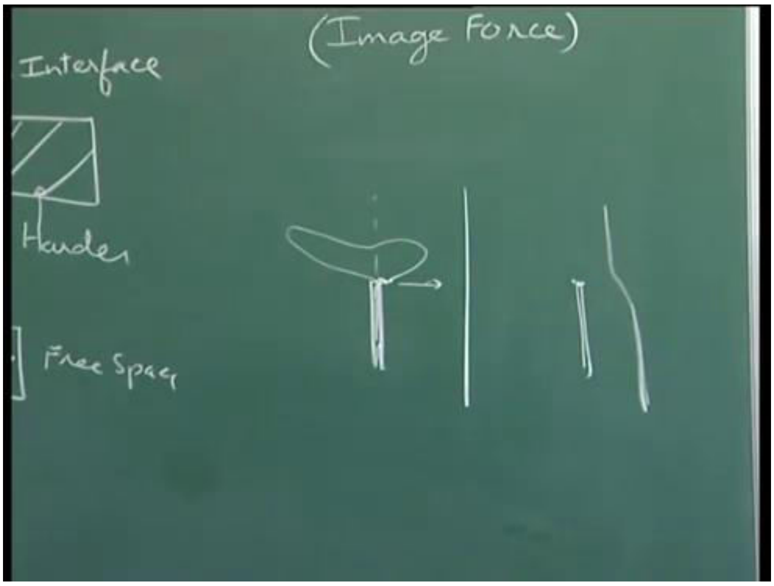

So, this is something which is to be noted, so the image force goes as 1 by d that means, it grows asymptotically as you approach the free surface. Now, dislocations can also as I told you, this is small motion which we talking about in this case, but presence of dislocation thin plates or thin cylinder, can actually lead to a larger kind of deformation. And that kind of deformation often cannot be ignore, as compare to the small deformation the surface changes pointed out.

Now, suppose I have a thin plate, now I am talking about dimension plate of the order nanometers, and I have an edge dislocations setting here. And suppose, I have flat plate originally and then, I introduce my edge dislocation going into the plane of the plates, so my plate could be thin plate like this. What would happen is that, very mere presence of this dislocations, because now this dislocation is ((Refer Time: 32:15)) extra half plane, would lead to the bending of the plate. So, the plate would bend, because I have exaggerated the picture here, but typically if I had a plate of few nanometer, it could even bend of few degrees.

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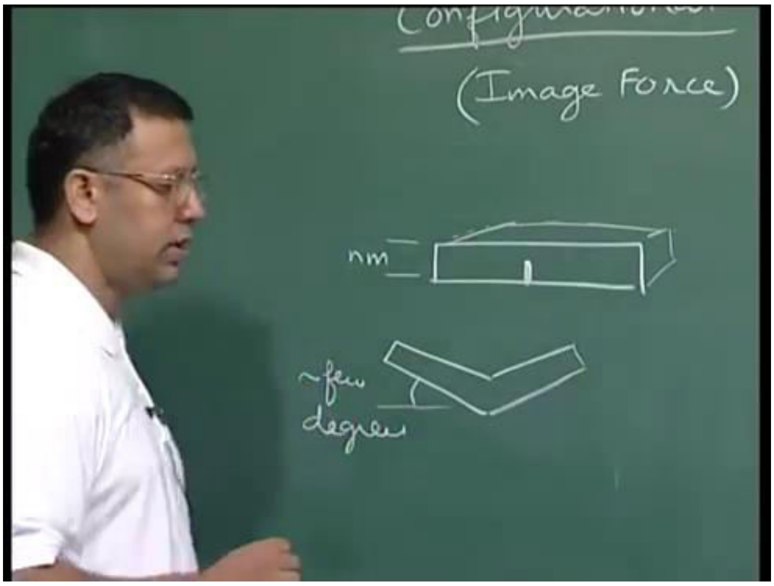

But, you have to remember now, this bending is a coming, because now introducing at dislocation into a flat place, which originally was completely defect. So, you can have what you might call deformation of this type, which are purely elastic deformation coming from the presence of dislocation, so this is something which again is important to noted.

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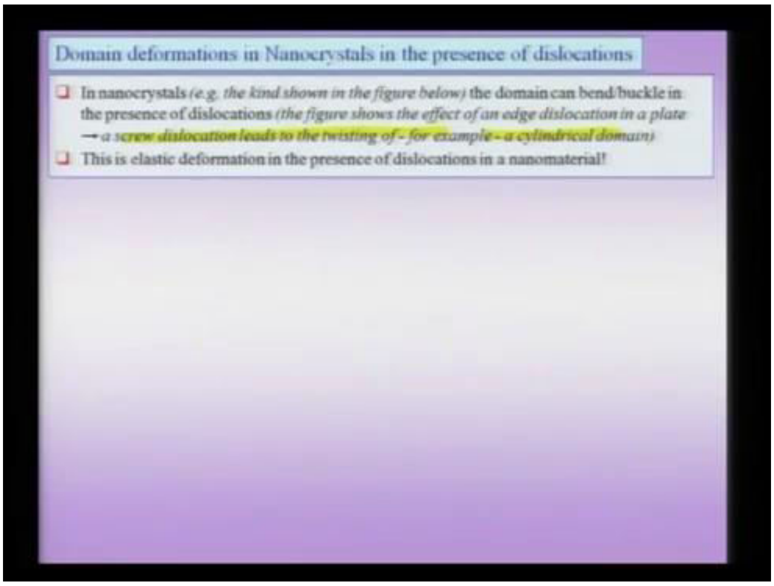

A screw dislocation on like edge dislocation each to this twisting of the materials, suppose you had a cylindrical domain and introduce dislocation at the center of the cylinder. Then it will actually lead to a twist in the a cylinder is coming from the presence of the dislocations, and so this kind of deformation is not the plastic deformation we should talk about.

Even, though you can see that this is large microscopic deformation the shape of the object, but this is an elastic deformation which is coming from presence of the dislocation. Now, so, far we are considering dislocation in some sense negative line, because now dislocation is a agent which breaks the complete beautiful symmetry the translation symmetry of the crystal.

And therefore, it is an agent responsible for a what might a call breaking the symmetry it is a defect, so often it is it seems to us that it is the anti thesis of a crystal. So, presence of a crystal and it is defect is the opposite sense or on the opposite directions, but now let us consider a very interesting example, which is the constructive role of dislocations.

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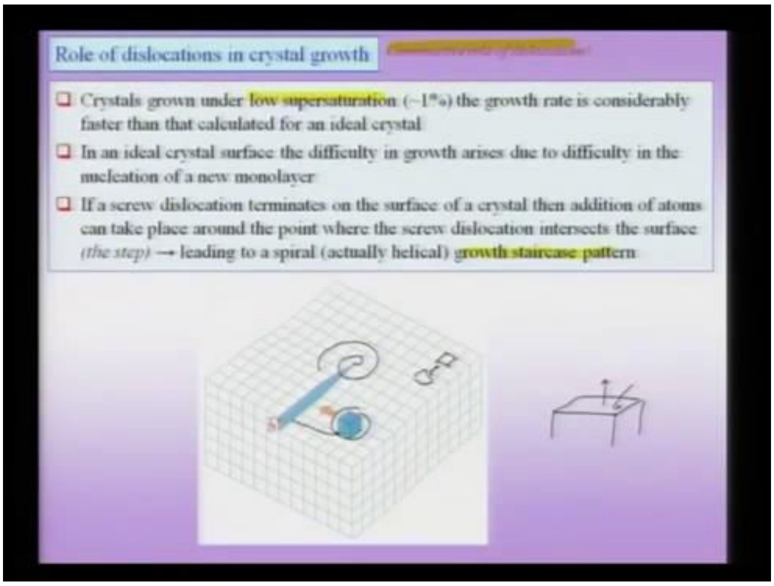

And this role of dislocation comes in crystal growth, often when you grow a crystal from low super saturation, it is formed that the growth rate is considerably faster than that calculated for ideal crystal. So, the original calculation was made by a sub frank and it was found that this, what we call disparity between the actual growth rate. And the growth rate assuming that of flat surface, from which the crystal is going; that means, suppose I have flat crystal surface like this and a crystal flat crystal like this.

And now, as I calculate theoretically that should be the growth rate of this crystal by atoms coming and sitting on this surface, then this model would lead a disparity with respect to the actual growth rate found experimental by huge amount, the exponential of the order of hundreds. So, therefore, there was a there was a need for different kind of mechanism, which actually can lead to a growth rate which is compensation to the experimental values, and the model propose before frank was this model shown in the figure.

Wherein, you assume that screw dislocation is terminating on the surface, and we just tilting the picture around which we saw before, and now if an add atom one an atom shown in the picture in blue, try to common stick to the surface. Then it has professionals sides for instance suppose it wants to shape here, then it sides is for instance no different from the sides, and little free bit diffuse from this side to that side.

And so, you face the problem of ultimate we called the two dimensions log of the three dimensions nucleation problems, so you have to nuclear the surface step on the surface, but or a this foreign matter, but here the nucleation problem is gotten of. And now you this ad atom is shown blue here, can actually common attached to the core of the dislocation, somewhere here on the, along the dislocation h. And the important point is that actually, that this if it is come in attached this here this atoms, this will not lead to the exhaustion of the spider the dislocation.

So, it will keep on rotating; that means, in more at atoms come here, there is location keep on rotating and this is create a spiral around this central step, so actually you can have a spiral coming out from here. And at during this whole growth is this step created by the termination of the screw dislocation of the surface exactly, so many, many case they are actually seen this experimentally observed this presence of the helical steps and leading to faster growth rate.

So, we can see that the presence of the surface step created by screw dislocation terminating on the free surface can help the growth of crystal, and this sense it is actually constructive role of the a screw dislocation in case of growth of a crystal. So, in this case the very growth of crystal of formation of crystal is being held by dislocation, and the important point is that this can actually lead to a beautiful growths spirals, which never terminates and continued to operate itself, leading to actually growth of the crystal.

So, this is the spiral staircases, which is created and looks extremely beautiful, and this kind of spinal star cases, where discovered in the 1950 using interference optical microscopic.

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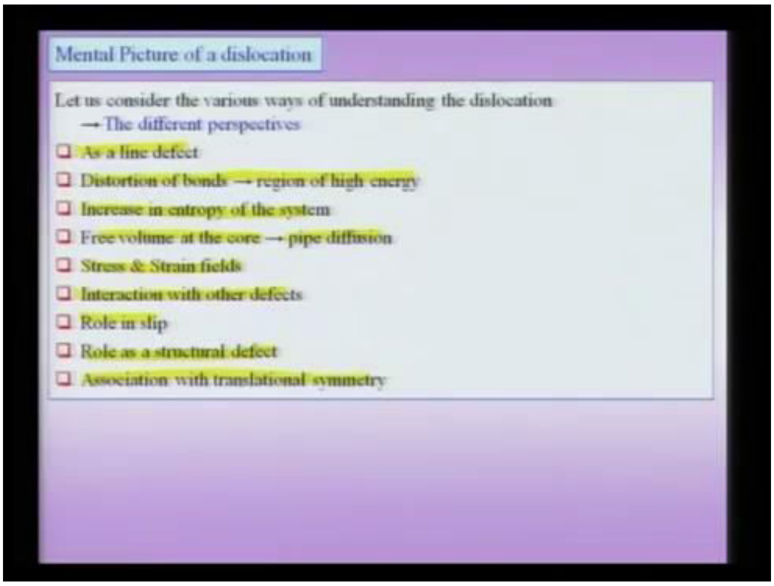

Now, we are close to the end of the chapter on dislocations, and what is the kind of mental picture that we should leave in, when we talking about dislocations, and there are many assets to understanding dislocation. And there are very many ways to need to understand dislocation, but the composite picture, which we need to develop putting together. This into usual pieces or the this individual collapse items is what we have to carry at all points, when we turn to understand the dislocation, we need to understand; obviously, that is a line different.

We need to understand that it locally cost distortion of bonds, and it is result in the state of high energy for the crystal it also leads to increase the entropy of the system, because now there is a single perfect crystal. For instance exist in a single configuration state, but now in the presence of the dislocation there is dislocation can exist many, many positions to the crystal. And therefore, it will be a increase in the configurational entropy of the system, it is associated the free volume and the core we already notice, that can lead to the formation of the cottrell atmosphere.

And it can lead to the diffusion of this interstitial speeches along the dislocation line which is called pipe diffusion, and this pipe diffusion can have diffuse into value, which are orders some magnitude away from the diffusive through the lattice. We already seen that is a this strength and stress field, which are long range strains in fields and stress fields, and this long stress fields can interact with the stress field other defects frees surfaces, and as you can see that cause bending of the crystals themselves.

And, if you are talking about nano crystals and this bending can be very dramitical, and actually can lead to when alter shape of the crystal, which is purely and elastic bending and not a plastic bending, even though the bending volume is very large. Now, we need to worry about the interaction of this dislocation other defects, and that leads to very interesting effects like another yield point phenomena.

You had understand the role of dislocation role in slip which is perhaps very, very important role of dislocation, we need to understand it has a structural defect apart from a the fact that. And this role of understanding the structural defect will take up a little more, when we take up two dimensional or low angle green model. For instance now so, for we are talking about what I might call random dislocation, which can be present anywhere in the crystal, but it can also take up a structural role, and that will consider when we talk about two dimensions surface.

And more important and the starting point for all this was association of dislocation to the translation symmetry of the crystal, so we have many, many mental picture of a dislocation. And when we put up this all this individual faces together, we get a complete picture of dislocation and then of course, we can worry about the motion of dislocation and interaction of this dislocation etcetera, which we consider at the beginning of the chapter.

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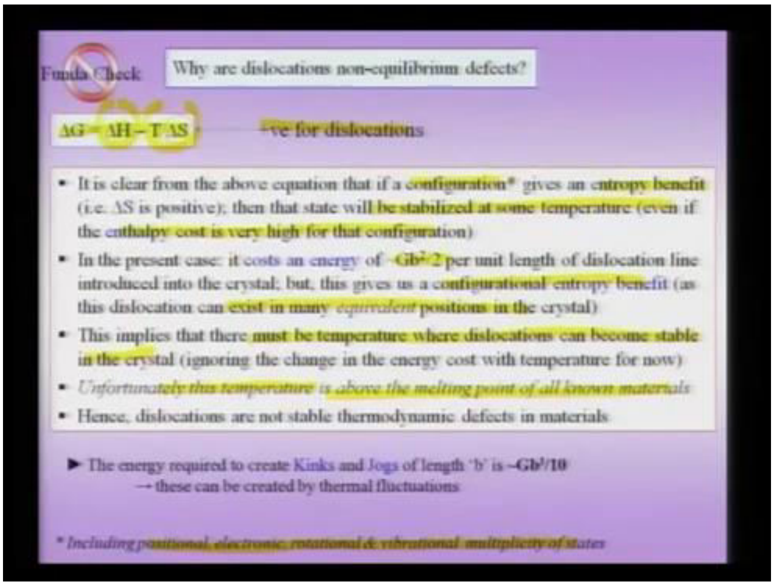

So, now, let us ask us a few questions which are very, very important, the first questions we can ask why are dislocation non equilibrium defects, I just now pointed out that like vacancies presence of dislocation increases the configurationally entropy of the system. If this is going to lead to an increasing configuration entropy of the system, why is that at vacancies is stable equilibrium defect or can be available in a certain concentration, a stable equilibrium defect at any positive Kelvin temperature, why dislocations are non equilibrium defects.

So, we start with a familiarly equation, delta g equal delta h minus t delta s, and here at any posting Kelvin temperature, if a system has a configuration benefit then it can be stabilize by the presence of for instance this case a defect. So, we have already seen the this entropy changes positive in the presence of dislocation, the configuration entropy given by k non omega.

However, larger value of delta h may be, suppose it cause a lot of energy positive value of delta h 2 put a defect, but if there is even in smallest of the benefiting coming from the presence of that the fact. Then there will be a temperature at which this will be offset, this freedom will go to 0, and after that even high temperature the term will become negative. So, if there is entropy benefit, then there will be a temperature some temperature that which this is this delta u will become negative, even them that cost is very high for that configuration, the configuration with for instance defect.

Now, actually when we talking about configuration of entropy, the important point be noted, that this configuration entropy includes positional electronic rotational and vibrational multiplicity of stage. But, here for instance we are now leaving with only positional states to make a matter simple, so there is the larger consideration we need to take often, but we are talking sort of a restricted and acting of importance here.

In the presence case the energy cause we know goes as g b square per unit length of the dislocation line, and we have seen that the configuration entropy benefit is also there, because now there is dislocation can exist in many equivalent state within the ((Refer Time: 42:00)). So, very small crystal things are different, but if we have a large crystal, then there are many equivalents states with the crystal, dislocation can exist leading to the approximately equal state of the energy.

Now, this equation tell us there must be a temperature, where the dislocation can becomes stable in the crystal, but unfortunate point that is that this temperature calculated is above the melting point of all known materials. And therefore, dislocations are not stable defects same crystal, it is not that this equation cannot become negative, in other word is not that a dislocation cannot be the stabilize theoretically. It is just that as a practical difficulty that all crystals known would melt before the dislocation becomes stable in the crystal.

And that is why that we called dislocation are non defects, not because dislocation cannot give a entropy benefits, this why can give entropy benefit, and therefore this part of the term would always be in favor of first any finite temperature, while just term is a one which is opposite direction.

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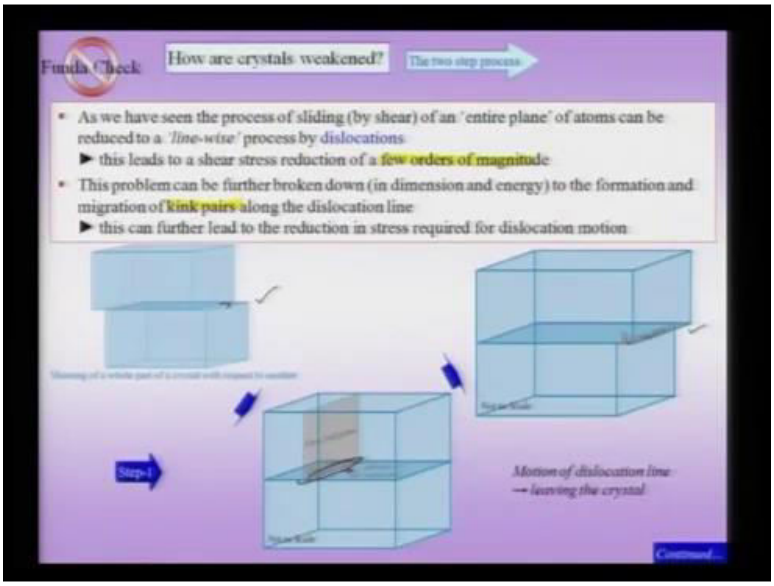

So, we have to understand, that this location are non equilibrium defects from this prospective, the second questions we asked these are the most important thing we started of the role of dislocations, what is it is role in the beginning the crystal. But, now we will have a certain more deeper perspective on this, and we will ask the questions, how are crystals we can. The first thing is presence of dislocation which is line defect, which we consider the crystal and we already seen that this beginning, and the shear stress is of the order of a few orders of magnitude this is an important thing, so few order of magnitude.

Now, this problem of shearing then entire crystal, which is now shown here in the left hand side, suppose I have the perfect crystal analyzing to shearing. So, this is my problem of shearing the entire crystal, I broke down into and even give a example of the carpet analogy, therefore I broke it down into the aligned defect which is the dislocation moving through the crystal, and creating a small steps.

So, those the carpet analogy, so my shearing entire crystal, now I am breaking down the problem line wise, and those lines moving in and giving me step of b. So, but there is the further reduction in this problem dimensionality possible, which we can lead to further weakening of the crystal, and that is what is called the kink pair mechanism.

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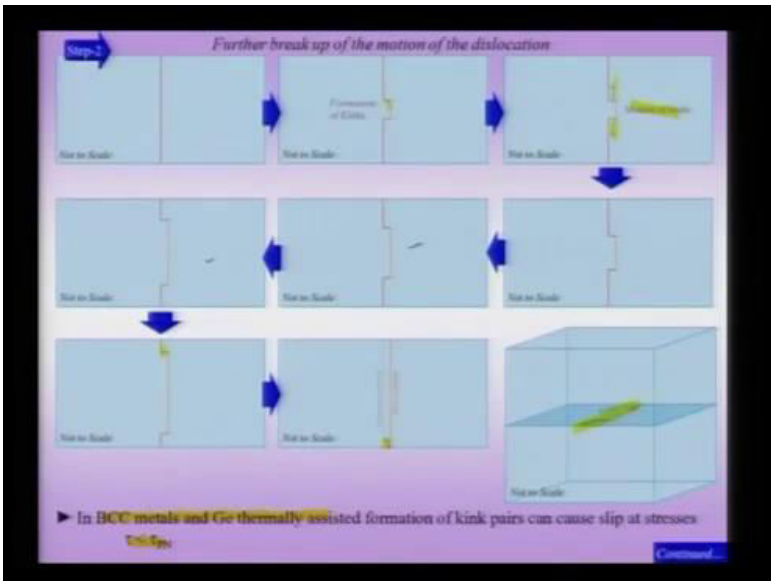

So, how is the kink pair operate, suppose I had perfect dislocation line, I can have a king the dislocation line, and I am not talking about the double kinks, and as I show slide here that these kink scan be created by thermal fluctuations. So, thermally activated you can have a double kinks formation, and I pointed out what is the kink, a kink is a defect in a effects, dislocation is a line defect in the crystal a kinks is a defect in the dislocation line.

So, this are now thermally form kinks under the application of external stress this kink scan actually moves out towards as shown in this slide here the right hand sides, so kink scan move out. And when this kinks leave the crystal surface, we can see that it moves on out little bit more, then little more, and finally when it leave the crystal you can see the slides. So, here it moves out ward more or little moreover little more and finally when it leaves the crystal, it has actually moves the dislocation by small b.

So, when I was trying to share entire crystal, I can move the entire crystal, and create small step or a step of n times some atomic parameters like burgus vectors. But, I could break down the problem into moving dislocation line creating that burgus vectors, but further I could break down the motion of the dislocation lines itself, into formation and motion of kinks. So, this is a now second order problem and this can found in certain BCC metals I have shown here, we found in BCC metals and functions general also could have this mechanism.

And this would lead to this motion of a dislocation below the pulse stress, and therefore this two locations a can nucleate the kink scan, and therefore the kink scan move and hold this dislocation can move by burgus vectors b. So, this can be thought of as a side wise role left within the role of the carpet itself, so now, this is three dimensional perspective of the kinks.

So, this is very, very interesting that not only can I shear the crystal weaker by presence of the dislocation, but I can even further we can the crystal by the presence of this kinks in the dislocation lines, which is the defect within the defect. And now, that defect can leave to the a weekend of the crystal.

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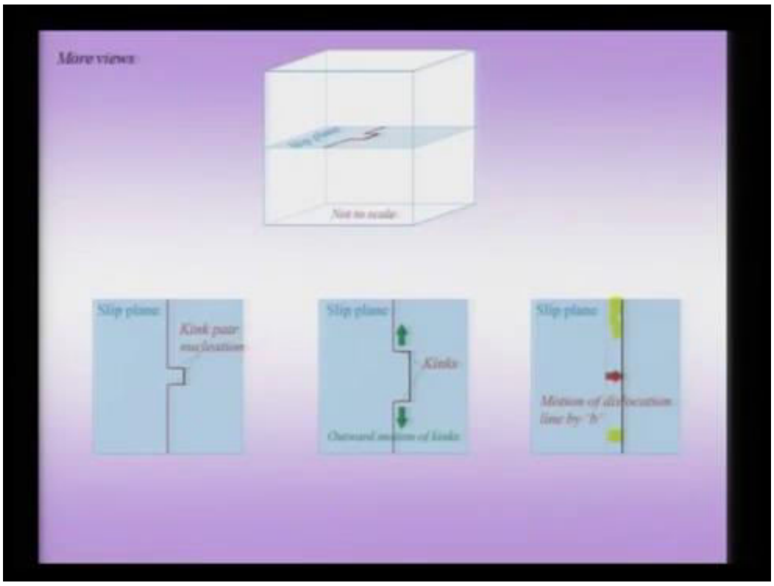

So, you can see that the kinks pair is nucleated and kinks plain moves, and finally moves the dislocation by this crystal, and further again you can have a kinks plane nucleation of the most of dislocation that further b.

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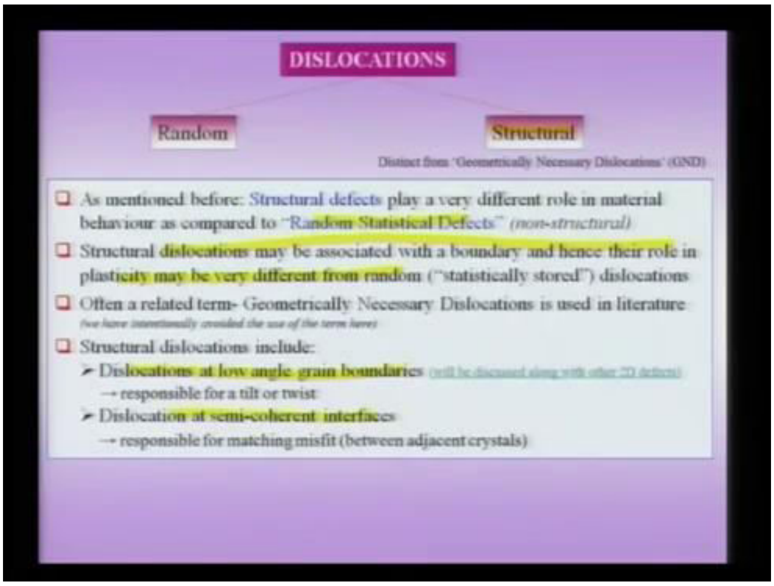

So, for what dislocations we are talking about a random dislocations, or sometimes as terms use its called statistically in a dislocation, but we will avoid the use of some terms like geometrically necessary dislocation in this context. And we will call this other kind of dislocation structural dislocations, and we will distinguish done from the statistically presence from dislocation. Structural dislocation maybe associates with the boundary, and hence their role in plasticity may be varying different from the random dislocation, so very important.

Note that, once you defect is a structural defect, and one of this examples we already seen in the case of semi coherent precipitate, the dislocation presents are interface is a structural defective. And example structural defecting colds this location green boundaries, and this location in semi coherent interfaces, so you could have inter faces associates with structural dislocations or a green boundary associates with structural dislocations. Now, what is the kind of ah role that they can play these structural dislocations in terms geometry of the crystal, they can accommodate tilt in a between two crystals.

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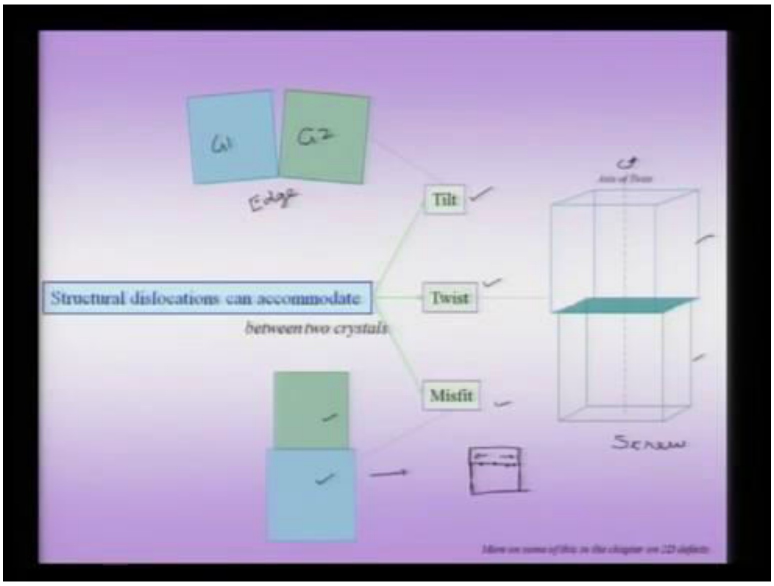

For suppose, I have 2 crystals, and for instance in this case they could be the two crystal we just from the orientation, so the this could be green 1 in a crystal, and this could be green 2 in a crystal. So, both of them are the same material on the other side, but now they have been mis-oriented by small angle, I mean small angle typically in a angle about less than about 10 degree about they are about.

So, these dislocation can actually accommodate, this still and we will see on later, when we will do two dimensional effects that how this is actually accommodated, but we need to remember. That these structural dislocation can accommodate tilt, we can actually twist 2 crystal, a crystal one forensic in the top, and assuming a material the same type green 2.

And I can accommodate small angle twist, of crystal one with respect of this my crystal that I can twist, by crystal one with respect to crystal 2, and this twist can be accommodate by in this case, screw dislocations. Tills are accommodate by edge dislocations, this should be my this is screw dislocation, and this would my screw dislocation which accommodate the twist.

And finally, I can have suppose, I have two different crystal, crystal one with the small lattice parameters, sitting on the crystal two with the larger lattice parameter. Then this between this crystal can be accommodate later to this would be that, now if this crystal is a bit actually grown on crystal, then I would find that this would expand the crystal green crystal expand to set on the blue crystal.

And therefore, they would have the same size this mismatch would be; that means, the I will have to make the crystal green crystal larger, and pull it fit it up of this blue crystal, and therefore the limits strains. And when this crystal rapidly actually grows a little larger, then strains can be accommodate by the presence of dislocations of the interface, so you will have the interfaces this fit dislocation.

So, though we are not gone in all of this aspects in this various slide, but important to remember a dislocation can play structural role. And when they play structural role for instance they have a material like plasticity will different from those dislocation, which are randomly present in the material, and the kind of structure role they can a perform, is they can accommodate till between 2 crystals.

They can accommodate to between this crystals, and they can also accommodate mismatch in lattice parameters between two crystals, of course they could always will be combination of all this effects. I could have a tilt come a twist or a miss feet come twist extra which also can be accommodated by the presence of dislocation, but this are nice interesting steams examples, which lustrated the structural role of dislocation in materials.

And this is very important keep in mind, suppose there were this misfit between or twist between two crystals have been accommodate by screw dislocation, which are now presence of along the interface. This dislocation would have a tendency not to live the interface, because if they live the interface then they are going to alter the angle of twist.

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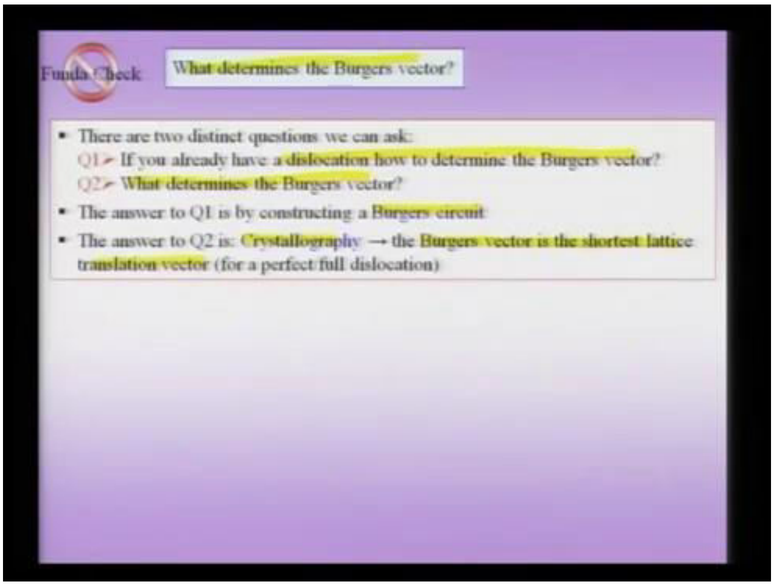

Another important fundamental aspect, which we have seen this I would like to mention one line is that often a distort is that, the question where asking what determines the burgus vector. So, the answer is that if you already have a dislocation in the crystal, then I can use the burgus circuit to determine this burgus vectors, but what actually determines the burgus vectors is the crystallography.

And therefore, if some would you ask question, how what determines the burgus victory has to be the crystallography, because the burgus vector is lattice translations vector for a perfect dislocation.

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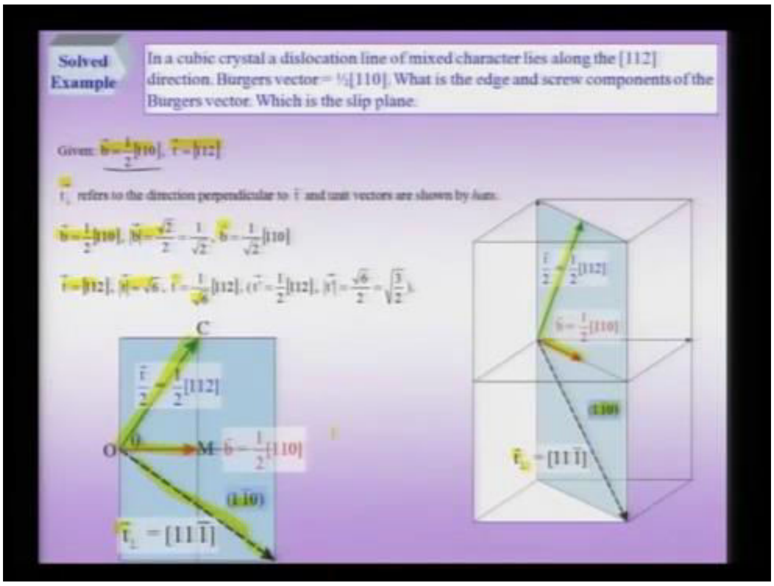

So, this precipitate kept in mind, let us take a few simple examples, and maybe I just grows over these little fast, but what students can do is actually keep this lattices front out try to parallel solve this problems, with the region nothing but, problems in geometry. And there the concept involved very, very simple, so question the we are asking here is that in a cubic crystal, dislocation line of mixed characters lies along the 1 1 2 directions.

Burgus vectors of this dislocation is half 1 1 0, what is the edge and screw components of the burgus vectors, what is the slip plane, so we have given that the burgus vector is b vector is half 1 1 0 and the t vector is 1 1 2. So, this two are given to us, now we know that, whatever components it is resolve the b along t and perpendicular t, if b is parallel to b that is the screw component, and these perpendicular that is the h component.

So, let me see the burgus vectors here, this is my now b and now this my t vector which shown here, in the 3 dimensional participate, you now this b vector can be resolve into a components parallel to t component perpendicular to t. So, I need to know the two direction, the directions of t and directions of t perpendicular, so this subscript perpendicular in implies it a directions perpendicular t.

This is all this question I am asking, and we also know the plane containing t and b is my slip plane, it is a obvious in this case slip plane is 1 1 bar slip, and now I am not asking for general family of plane, but a very specific plane which contents t and b. Therefore, I need to write the very specific plane which is 1 1 bar 0, and in this whole problem vector as a referent shown the arrows about, and this kinds of hards represent unit vectors along towards directions.

So, b is 1 1 0, therefore the mode of b, value of b is root 2 by 2, I can calculate the square root 1 square plus 1 square plus 0 square by 2, it is root 2 by 2 which is 1 by root 2 the hardest 1 by root 2, 1 1 0. Therefore, the unit vector the along b direction is 1 by root 2 1 1 0, the t vector is 1 1 2, which is given to us the model of t vector is root 6 the length of this vector root 6, and t hat is 1 by root 6, 1 1 2 which is the unit vector along the t directions.

So, now, in this picture is now the 1 1 0 plane picture, we can see that this is now my b vector has directions, the t vector which is along connecting o and c and the t perpendicular direction is also shown in this picture.

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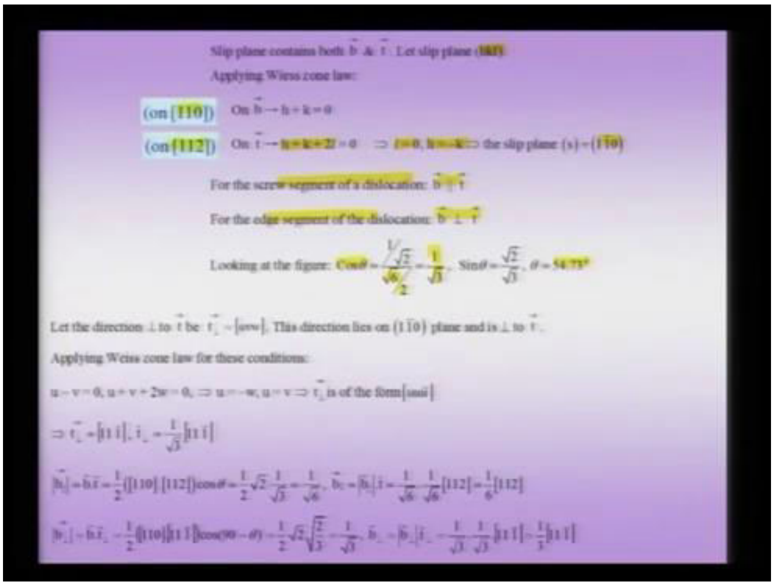

So, now, if I want calculate the slip plane, which is the plane containing b and t, I can apply this zone law the fact that it lies on, it contains 1 1 0 direction and the 1 1 2 direction both. And I apply this on law that the slip plane is h k l, therefore h plus k 0 giving this 2 h plus k is plus 0 is equal to 0, and h plus k plus 2 l is equal to 0 assuming that the 1 1 2 directions, the t directions also lies on the slip planes.

This leads the fact l 0, and h equal to minus k and I can write my slip as a h, h bar 0 or 1 1 0 in terms of list tensile. For the screw segment we know that the b is perpendicular to t, and for the h segment b is perpendicular to t, now if you look back at a figure ((Refer Slide Time: 55:05)) you can calculate the angle between the theta angle between the t vector and b vector. And that is nothing one by root 2 by root 6 by 2 from pure geometry, and that turns out to be 1 by root 3, and this gives me theta value of 54.73 degrees, so this angle between my b vector and t vector 54.73 degree.

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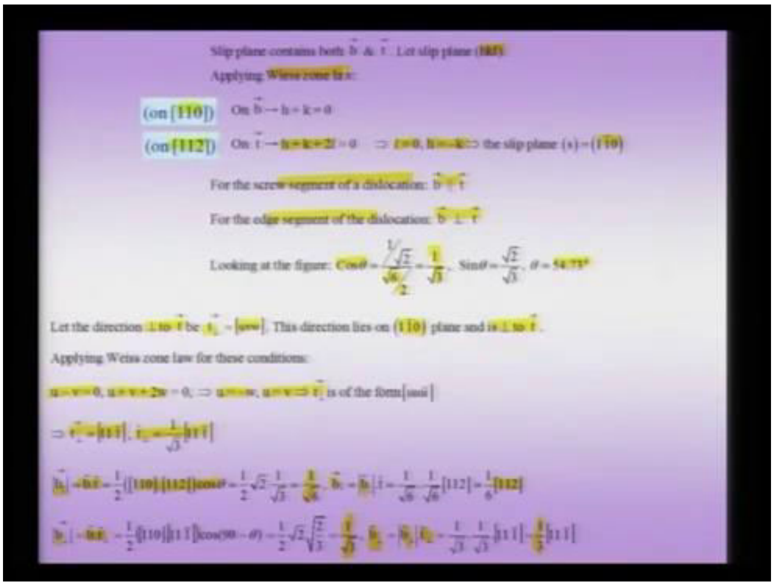

Now, if the direction perpendicular to t is t perpendicular is u v w, this directions lies on 1 1 bar 0 planes the slip planes, and this perpendicular to the t vector, so this is obvious. Now, I can again apply ways on law assuming this 2 conditions, for the u v w direction, which is now the directions perpendicular to the t, and this for applying this on this 1 1 bar 0, u minus b equal to 0.

And applying it to the condition that is perpendicular is now the t vector being 1 1 2, therefore now my condition be u plus v plus 2 w is equal to 0. This gives me that u has to minus w and u equal to v, and therefore I can write my miller indices of the t perpendicular vector as you u bar u u u bar which is nothing but, 1 1 1 bar.

So, my t perpendicular is 1 1 bar, and t perpendicular cap is 1 by root 3 1 1 bar, so now, my this direction is 1 1 2, on the directions perpendicular to a my t vector, which I call the t perpendicular, which lies also lies on the slip plane which is the 1 1 bar 0 plane, as in this is of 1 1 1 bar. Therefore, I can write down my b parallel and b perpendicular knowing the geometry, that b dot t is has the value right here, again calculate dot product being the b vector, and the t vector which is 1 by root 6.

And therefore, the my b parallel is mode b into the t vector which is 1 6 1 1 2, so my b parallel component is 1 by 6 1 by 2, the perpendicular component. Again, I calculate the modeless, I can calculate by taking the dot product between the b and t perpendicular, which comes out 1 by root 3, and I can write down my b perpendicular as more of the d perpendicular vector, along the direction t perpendicular, and therefore it is one third 1 1 1 bar.

So, now I can find out given any kind of geometry the edge and the screw component, to any screw character to any problems to any curve dislocation or for this is straight dislocation lines having, which is constant, which is not changes characters. So, this is the not really problem going beyond, actually the very concept that for the screw components we have the burgus vectors valid to the t vectors, and for edge components the burgus vectors perpendicular t vector.

Remaining is nothing but, simple vector algebra and also in working the very soon law, so all have done in this problem to identify the slip lane, and the parallel perpendicular components would be burgus vectors.

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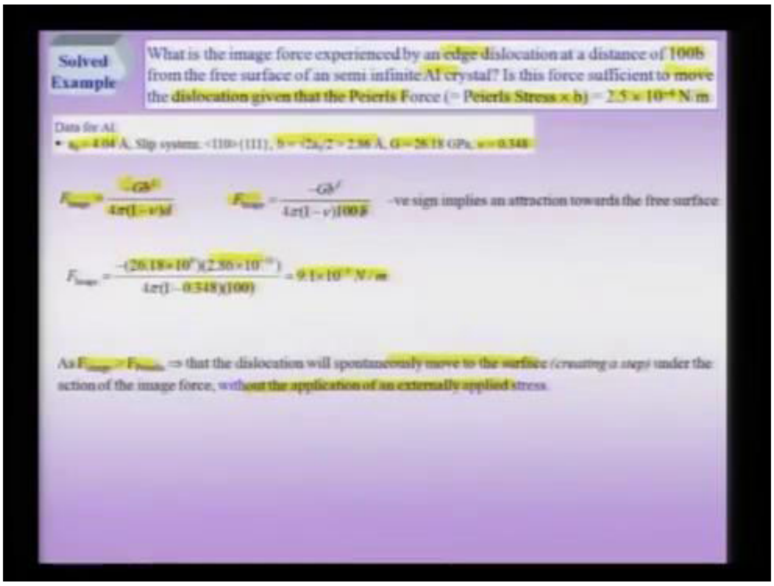

Now, we come cross and interesting case, the case that if it is very clear that, suppose I have the crystal, and I have the laying in the crystal and I apply an external shear stress that this location will move, when the shear stress is crosses the pearl stress. So, this part is not very surprising; that means, there is the external agent driving the dislocation line, but we are asking yourself the question even in the absence of the external agents can a dislocation moves.

And; obviously, there are certain nice example for instant, suppose I stress field and these stress field are large enough then the dislocation line can move. But, the most interesting example of the perhaps that case were in the dislocation is present near free surface, or in a nano crystal suppose if I dislocation is present in near of free surface, we have seen that it has attracted towards the free surface.

If this distance is very large the force would be very small, now the force is propositional to the 1 by d, and therefore it will be too small to move the distance dislocation, but if it is very near the surface or if it present in a nano crystal very small crystals. Therefore, in these dimensional are order of nano meters, then the dislocation has many surfaces to which it will be attracted, and there is the result end of all this forces would determine if the dislocation would actually end up with being this crystal.

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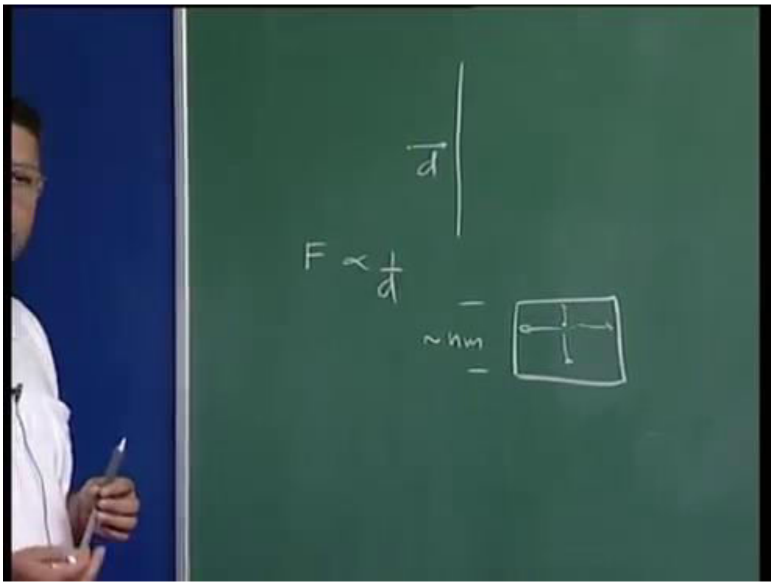

So, let us ask this question if the dislocation present in the near a free surface, at a distance I have got 100 b, so let us this is the distance about 100 b, then will this presence of this image force; that means, the presence of this free surface itself move the dislocation towards it. And we now see my aluminum crystal, an aluminum crystal has the burgus vector of 2.86 angstrom, and the shear model is 26.18 giga Pascal, the poison for ratio is about 0.348 and the lattice parameter aluminum 4.04 angstrom.

Now, the question the important question is asking, is this force experienced by this dislocation presence of free surface, that is know assembling in the body. Sufficient move that this location, given the pearls force for this, which is nothing but, pearls stress into the burgus vector, and the pearls force is 2.5 into 10 to the minus 4 Newton per meter. As, force of watt 2.5 into 10 to the 4 Newton per meter, so now, what is the image force; assuming that the edge dislocation here.

So, the image force is minus gb square by 4 pi into 1 minus d, if it is screw dislocation, this one minus new factor would be replace by 1. And the important point to note is the negative value here, the negative value tells you that it is actually attracted towards the free surface. So, the image force given the fact that, now the distance is 100 b can be calculated by plug in the value of g, in the burgus vector b, the value of the poisons ratio, and the distance from the free surface.

And it turns out to be 9.1 into 10 power minus 3 Newton per meter, clearly the image force is greater than the pulse force; that means, the dislocation is spontaneously move and move to the move to the surface and leave the crystal. So, this is in the absence of the externally applied stress, and suppose I am talking about nano crystal, in which there are many free surfaces, to which the dislocation can be attracted.

Then this is implies that nano crystal can become completely dislocation free even without the application of an external stress, because now the dislocation would be attracted to free surfaces. They would move to free surfaces in the pulse stresses exceeded, as you know in the nana crystal the distance between the dislocation, and the free surface is going to be very small.

Therefore, it could happen that very small sizes and in fact it does happen for instant aluminum crystal is above 50 angstroms in 50 nano meter in diameter, then the dislocation can be spontaneously the crystal, become completely dislocation field. These are the very formed here, that the crystal can actually comes spontaneously dislocations free, without even application of external stresses, or reduce problem being that dislocation can actually move, even in the absence of externally.

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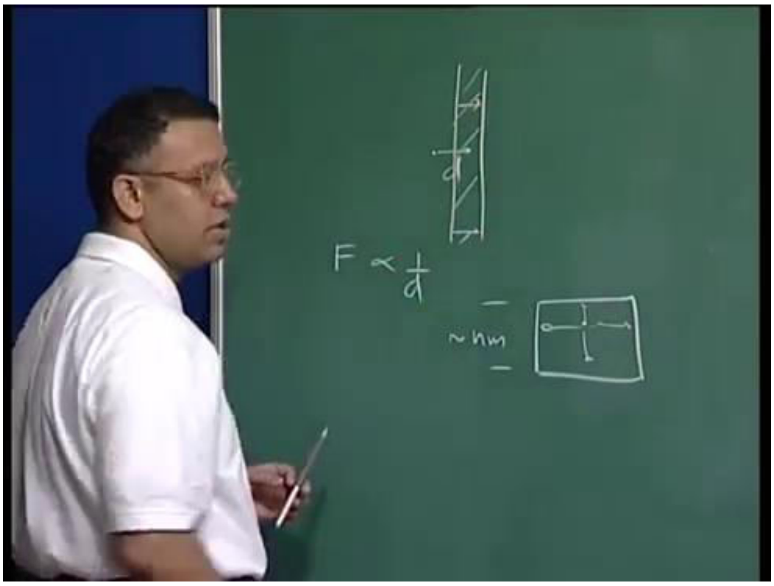

So, if you have the free surface like this, then there would be the region very close to the surface, were in my image stress would be, so large that it can support more dislocation. And all dislocation of the region would come and sit on the surface, even that of course, that these dislocation are and also the fact that, they face an image force greater than the pearl stress, which is not too large. So, this the very, very nice interesting example I consider, and with this come to the end of the topic of the dislocation. And the next locations, we take up is the topic on two dimensional defect, and that will be were in again concept we work in this chapter.