Structure of Materials

Prof. Anandh Subramaniam
Department of Materials Science and Engineering
Indian Institute of Technology, Kanpur

Lecture No - 26
Defects in Crystals

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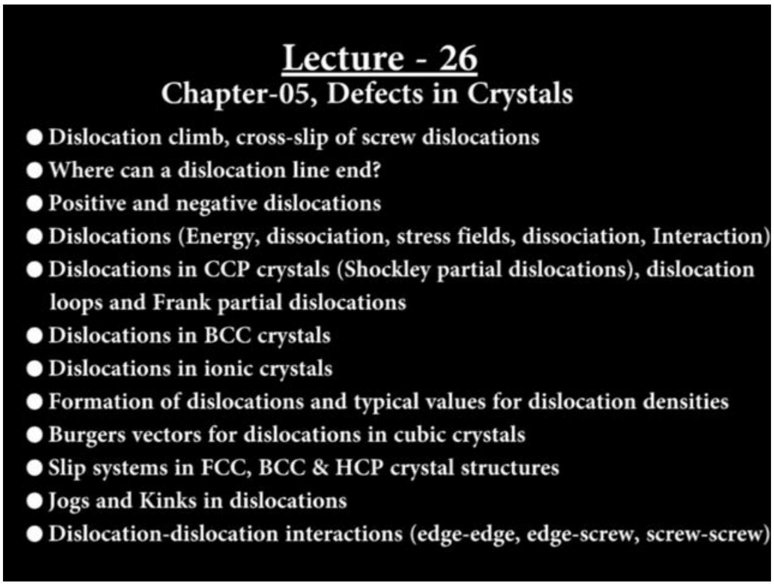

Dislocation, as we saw can lied on the slip plane but, additional to that they can actually leave the slip plane.

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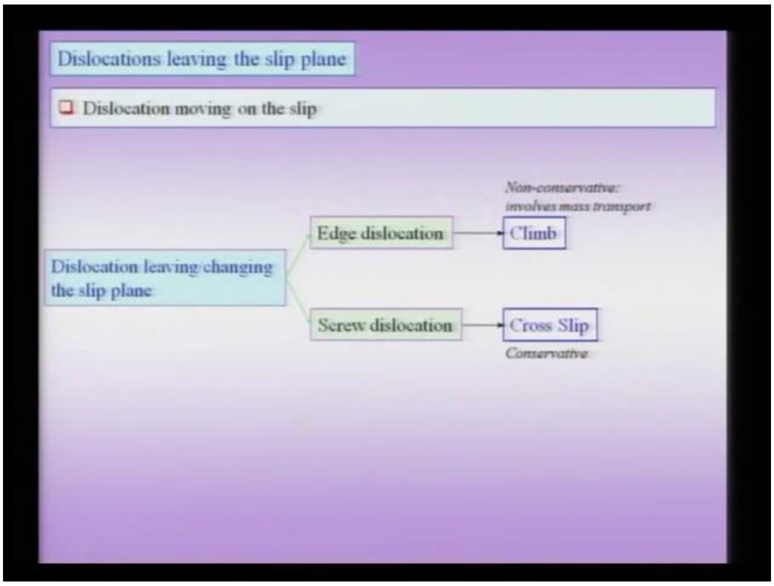

And, it depends on the types of dislocation to deiced what kind of the mechanism by which they would leave the slip plane. An edge location can leave the slip location it is known as climb, dislocation leave can leave its slip plane by the process known as cross slip. The fundamental difference between these two mechanisms is that, the climb is the non conservative process and involves mass transport and we will see in the coming slide why this is so. These two process are very very important as far as plastic difference goes because if the dislocation moving on its slip plane get stuck in some obstacles then future plastic deformation for the motion of the dislocation would not be possible.

And then, if sub stress is sufficient then some of the other process like or climb can take place and does causing the continued motion of the dislocation. Of course, we have to remember that in the case of the edge dislocation the process climb also needs sufficient climb also a needs sufficient temperature for mass transport take place. So, what is meant by the climb of a edge dislocation?

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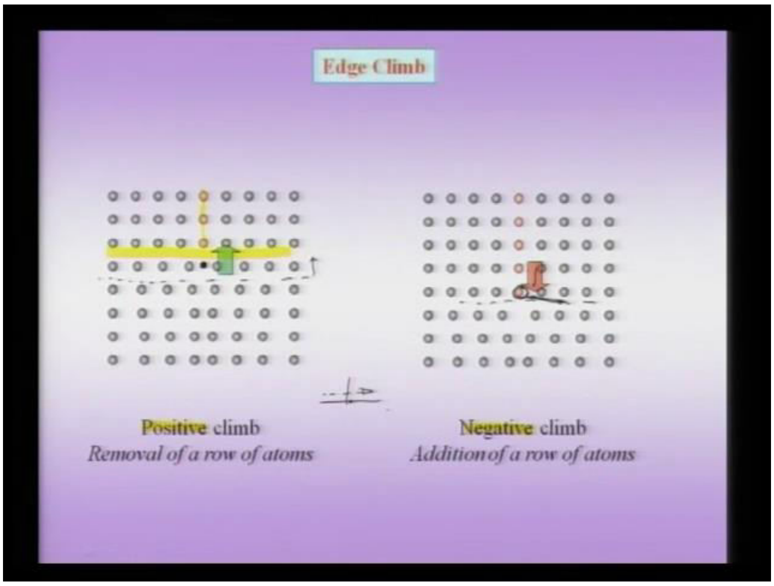

So, in this figure for instant there is a edge dislocation sitting here and the extra half in the atom ends here. Therefore, the slip plane is the plane which is here as drawn in the figure. Now, the slip plane can move plane above, suppose my initial slip plane was a plane below so, let me draw a below here. Now, the original slip plane was here then it has actually moved a slip plane above. But, correspondingly it can also move a slip plane below and this can become my new slip plane. So, how does it take place?

This means that the entire row of atoms have to either be comitia that means the row of atoms have to vanish so, originally there would been a row of atoms here. That means, the half plane would have ended here and this entire row of atoms have to diffuse into the crystal so that you can have a the positive climb. So, this is known as the positive climb. Correspondingly, in a negative climb the entire row of the atom for instant, this row of atom here have to diffuse away from the bottom of the half plane.

So, that the dislocation oh sorry their this is the other way about were in the entire row has to come in take this position so that this location can climb down. Now, what would happen if a row of atoms have to diffuse out from the centre of the crystal from the edge of this half plane? What would happen is that, vacancy concentration in crystal would come down and this would enable the climb of the dislocation. Now, both these process of the either of the discussion in of atoms or out of the atoms would involve obviously high temperature were in this would become diffusible.

And therefore, if the dislocation moving on a particular slip plane for this is my slip plane and this is my extra half plane and my dislocation get struck in some of the plane and the n it could move to slip plane which is parallel and continue its motion. And, this is the advantage or this is the role that climb place in plasticity. So, this is simple to understand the process of climb for an edge this location were in the dislocation moves one plane parallel to itself up or one plane parallel to itself down. A screw dislocation can leave its slip plane by the process know as cross slip

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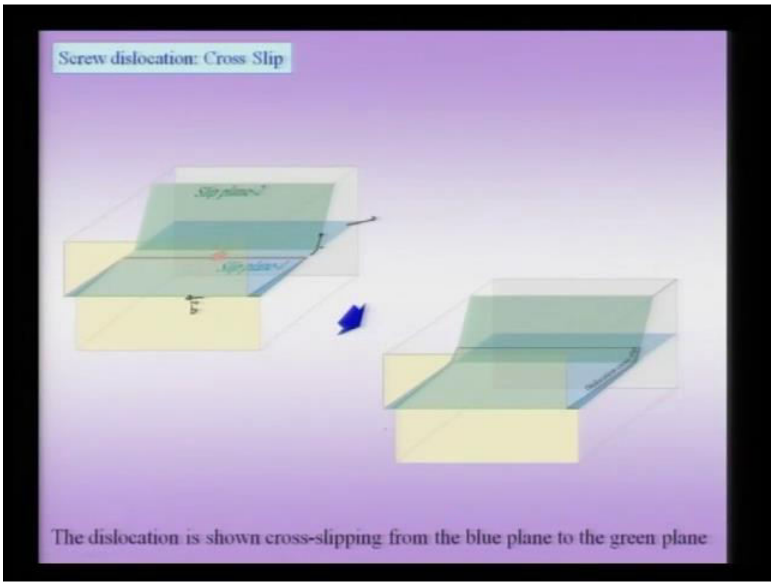

which is been symmetrical shown in the diagram here. In this case, you see that the plane the first the active slip plane is the blue plane and for now you will assume that both the blue and green plane are crystal or graphically equivalent planes. And, we know that the burgers vector is to be in this direction which is parallel to the dislocation line. So, as the dislocation line is moving towards this green plane and then it intersects this green plane and for now I will assume there is some reason for instant, there could be obstacle and obstacle is not only the reason for instant, there could the obstacle which stops the motion of the dislocation of the line on the blue plane.

Then, if there is sufficient sphere stress on the slip plane 2 then the dislocation can actually cross slip and leave this blue this slip plane and start moving on the green slip plane. So, this process by which a screw dislocation changes a slip plane and we have to note in this plane we are not considering the change of the slip system but, nearly a slip plane within the slip system. Then, we consider this process has cross slip process of course, if there are completing kind of slip system then cross slip can also lead to a change of slip system as well.

So, this is the process by which a screw dislocation can leave a slip plane and as you can see this involves no real mass transport so, cross slip can easily occur, it provide that there is stuffiest stress on the slip plane for continued motion of the dislocation. So, we have seen that there are two mechanism by which a dislocation can leave the slip plane, edges dislocation can leave the current plane by climb and screw dislocations can leave the current plane by cross slip. Now, we can ask the another question. We have told and in the previous lecture that dislocation line cannot end within the crystal so, were this dislocation line end?

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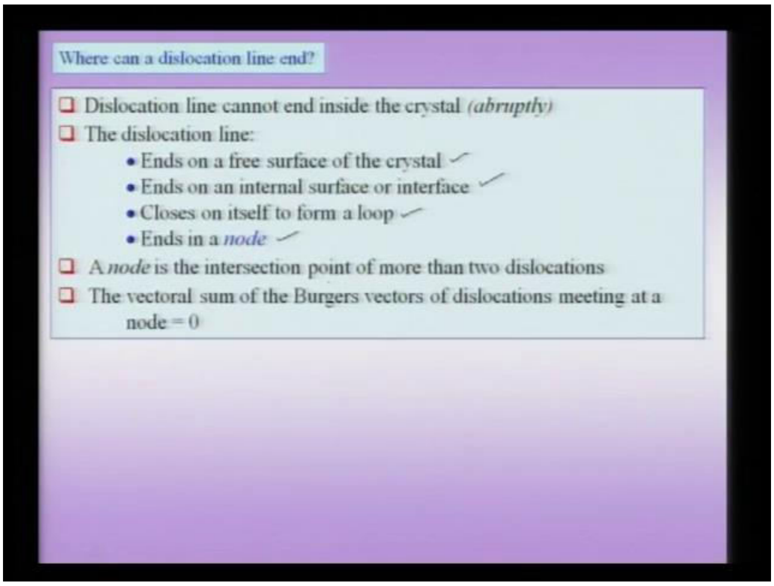

So, dislocation line can end either on the free surface of the crystal or it can end on the internal surface or an interface and such internal interface surface could interfaces could be for instant, green boundary. It can close on itself to form the loop and we will take up some of these loops also. And finally, it can end in a dislocation reaction that it has more than dislocation line and this is called the node. So, the node is the intersection of the more than two dislocations and we have to note that the factorial thumb of the burgers vector of this dislocation meeting at the node is 0. So, it is clear that it dislocation line cannot end within the crystals. So suppose, let me do a hypothetical experiment were in I insert an extra quarter plane of atoms into a material. So, initial what we are doing throughout was inserting an extra half plane.

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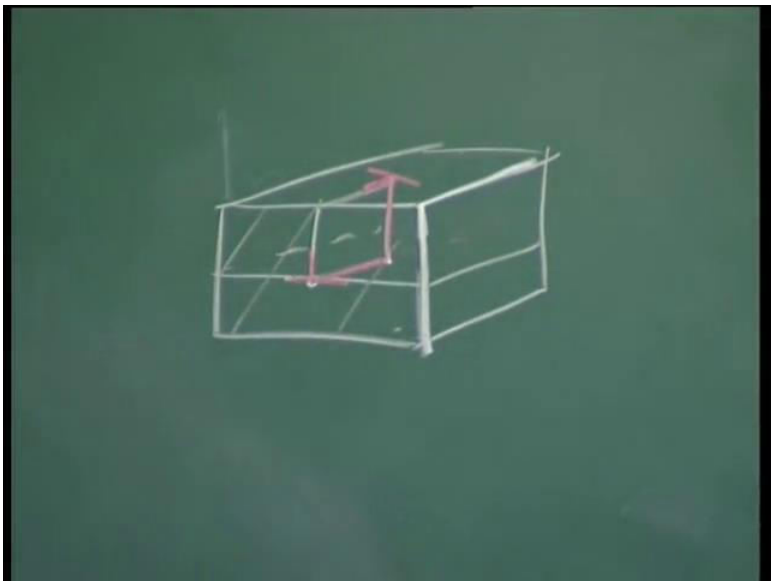

Suppose, I have the crystals into the crystal and I insert an extra half plane in to this crystal. So, this is my extra half plane for instants, this is my dislocation line. This is what I pointed out. Now, what if I do not? So, this case dislocation lines ends on this free surface and the back free surface and the back free surface. What if I do not introduced an entire half plane but, I terminate my half plane some in the crystal. So, I do not end my crystals dislocation their and my dislocation line here. So in other words, I do not intersect my half plane but I insert a quarter plane. Now, in this case it seems as this dislocation arbitrarily ending here at point but, this point not true because what is happening is that this dislocation line actually takes a bend and it leaves on the top free surface.

So in other word, this is one at the surface locater and this is the another edge dislocation located on this free surface. So, this quarter plane also clearly tells us that dislocation line cannot end inside the crystal and actually as to end on the free surface.

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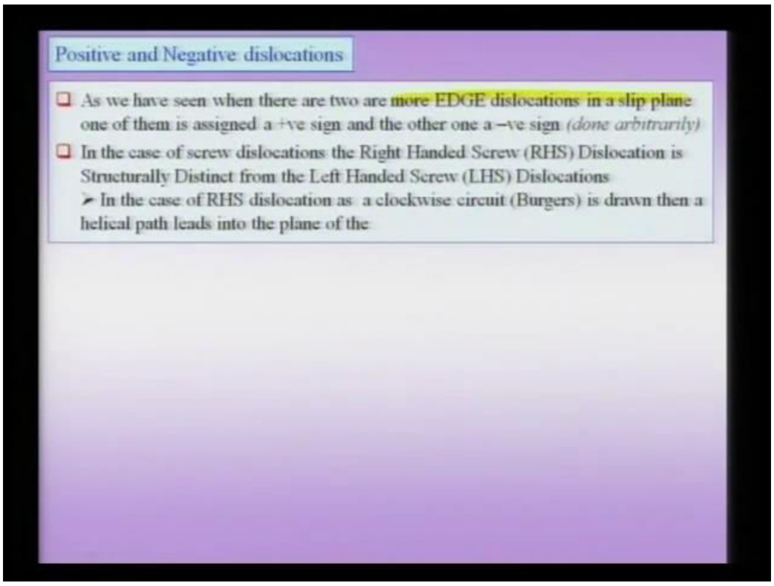

Earlier, we are dealt with the concept of positive and negative edge dislocations and there are few comment which are note worthy here in this context. Now, when do we have to consider the positive or negative edge dislocations is when there are more the none dislocation on a slip plane. Then ornately we assign one of the is dislocation as the positive sign and other have a negative sign. So, a simple example would be, suppose I have my slip plane here.

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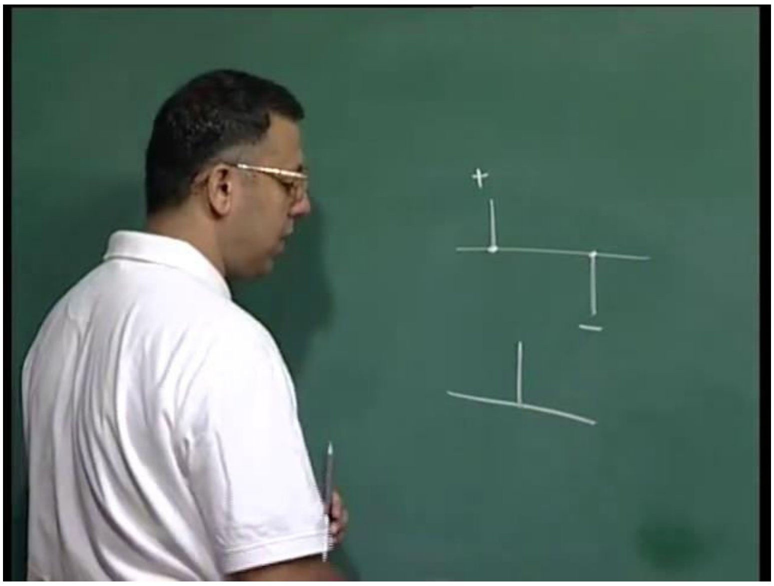

And, I want one dislocation like this, another of course, these are the half plane I am showing here, another dislocation here, another dislocation here. So, arbitrarily I will cal this positive and I will cal this negative. I could have cal them another way above and if I adjust a single dislocation and in a slip plane it is not better what I call it, I can call it neither positive or negative. So, there is no fundamental difference between positive and the negative dislocation expect that it is way of the differentiating more than one dislocation on a slip plane. Now but, this is not true for the sake of

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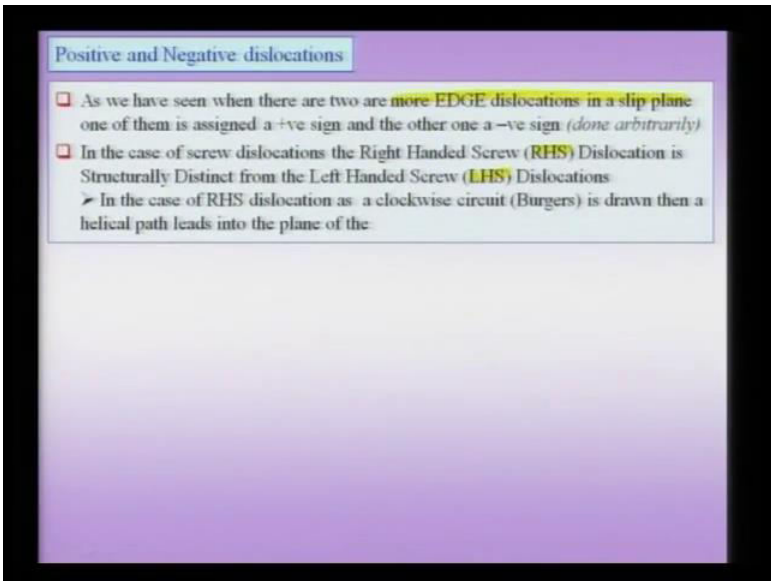

the case of the screw dislocation were in the right handed screw the structurally different from left handed screw. So, we have to note actually there are two kinds of screw this dislocations. The right handed screw actually, if you draw the right handed screw then the dislocation the vector you will actually you let into the plane on the board, if you are sitting on the left hand screw then actually you will come out of the board. So, this is a fundamental difference between a right handed screw and the left handed screw.

So, if you call for instant the right hand screw has the negative dislocation and the left hand screw as a positive dislocation. We have to remember the structurally the positive and the negative screw dislocation are different why in terms of the edge dislocation they are exactly identical as far as the crystal course. So, this fundamental difference between a positive and the negative edge dislocation in the case of the edge and in the case of screw has to be kept in mind. Next, we come to the important topic of energy of dislocations.

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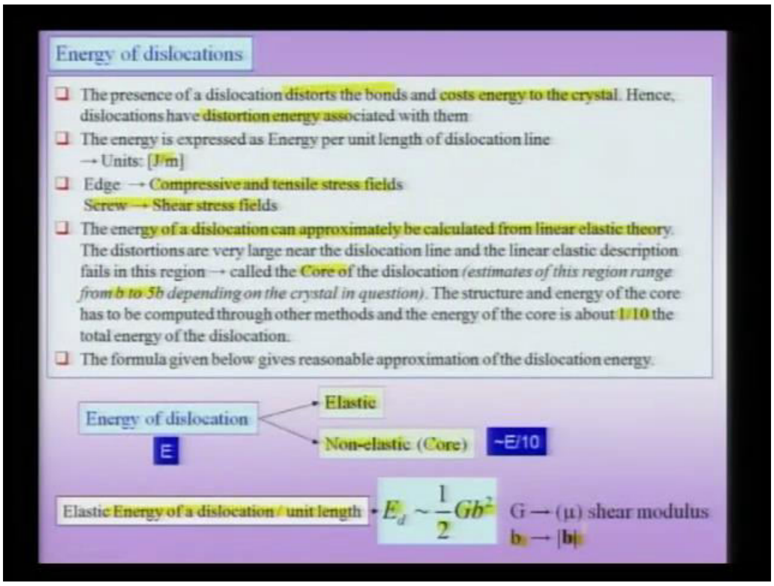

Now, it is clear that at present of a dislocation it starts the bonds and cause energy to the crystals. And therefore, a crystal in the presence in the dislocation is associated distortion energy. Now, this energy obis ally for a dislocation is expressed in units of joule of per meter that is energy per unit length of the dislocation line. Now, there is a fundamental difference between the edge and the screw dislocation in terms of kind of stress field and we will soon see the stress fields they are associated with. The edge dislocation compression sight and the field while the screw dislocation are associated with only with the sphere stress fields. And therefore, the energy associated with the edge or a screw is also different and therefore, they are not exactly equal.

Therefore, if I dislocate the line is not straight and if its bending then the energy per unit length would change from point to point or if you take a small segment along this, were ever there is certain component of edge and screw the energy will be different compared to certain the place in the dislocation line were the amount of screw and edge character changes. Therefore, we have to remember that in any case screw and edge dislocation both are associated with energy and therefore, this energy is responsible for many of the behavior of the dislocation, we will soon consider. The energy of the dislocation can be approximately calculated using the linear elastic theory and this linear elastic theory as we are pointed out is valid is only to about the two burgers vectors from this dislocation line, were in the dislocation line which is called core other dislocation, the linear elastic theory fails.

And therefore, we cannot calculate the energy accurately here, in those cases we have to us the atomic methods actually. Calculate the energy more accurately were in the in the we assume the more kind of course, there is technique were in the use even the continue or an approach or approach which is similar to the continues approach to calculate the core energy. But, the important thing is that the core energy is one tenth of the totally energy of the dislocation and in many cases can actually be ignored while trying to calculating the total energy of the dislocation. The core region again is about between about 5 and be and fiber b depending upon the bonding characteristic of material and depending upon the certain edge of the screw of the dislocation.

But, for most purposes, most common proposes a formula given before below here like energy of dislocation is about the course about us g b square by 2 is more than sufficient for calculating the energy of the dislocation. So, if I look at the total energy of the dislocation I can divided in to the elastic part and the non elastic or the core part. The elastic part is the dominant part of the energy which is the long range coming from the long range stress field. The core energy is confined to every low distances near the dislocation line and this energy is about 10th of the total energy of the dislocation and in most cases can even be ignored.

Now, if I look at the formula for the elastic energy for dislocation per unit length you can see that it is located, it is approximately half g b square. Now in other words, the elastic energy varies as the square of the burgers vector so, this is an important point to know note that b is the models of the vector. So, it is very important to note that therefore, the longer the burgers vector dislocation has it the energy will not just be linearly grow it will grow as the square. So, this is the very important point regarding the energy of the dislocation.

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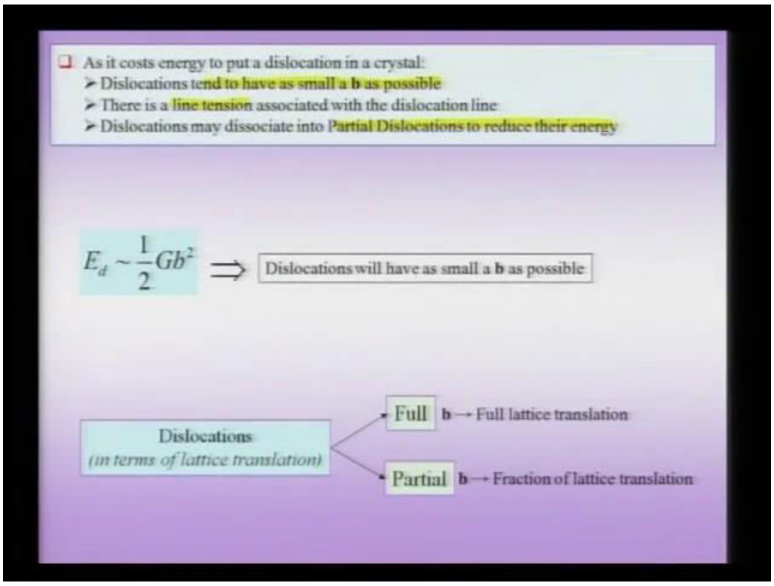

And, from this formula it is clear that if I have the dislocation it will tend to have has small has be possible. 2nd thing since it cost me to put the dislocation line, the dislocation line is associated with some sort of the line tension which is nothing but, on the other side of viewing of the dislocation energy. And, we will also see that because the presence of this energy of a dislocation, at this location may acutely split to spacious to reduces it is energy associated with the dislocation. So, to summarize the energy aspect (Refer Slide Time: 10:07) that there is the distortion of the bonds.

The distortion of the bond is very savior closer to this dislocation line and as you go far from the dislocation line the distortion is smaller. And, but never the less, the energy of the dislocation is spread across the large region in the crystal and the approximately the energy of a dislocation can be calculated approximately half g b square. There are more accurate formula for the elastic energy calculation but, we will assume for now the half g b square. Now, the energy is coming from the case of an edge dislocation and then sphere stress in the case of screw in this distribution. And, ignoring the core contribution is not the serious error in calculating the energy of a dislocation because this dislocation has the energy associate with it also succeed with line tension which in other side of the point of the energy of the dislocation. And, because of this the dislocation would like to have as small has the b as possible because the energy goes at the square of the burgers vector and also it will tempt to partial were ever it is possible. So, in the case of the cubic close pack crystal we will take up an example were the dislocation actually split into partials.

Which dislocation?

I quite dint understand your question?

Sir, this is the dislocation,

I am not quite shore but, this is actually this energy field can interact vacancy or the that we will see very soon.

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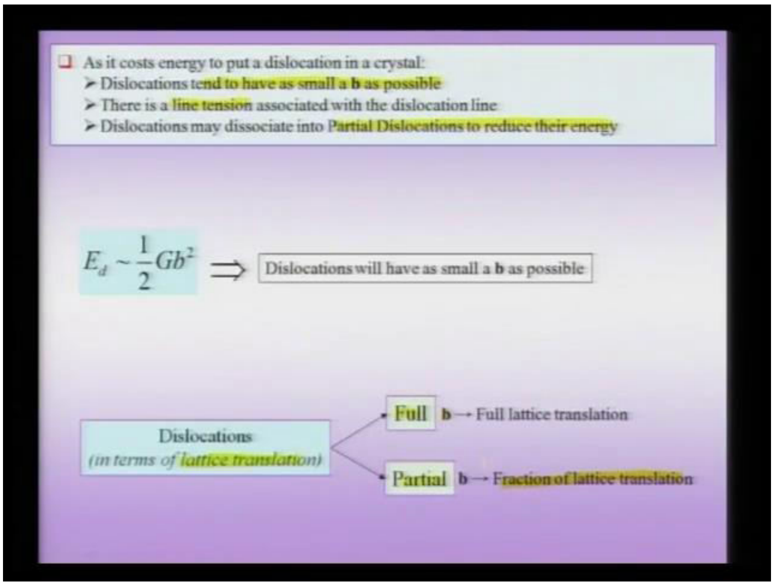

So, in terms of the lattice translation if a dislocation has a the burgers vectors is the full anti translation then you call it a full dislocation and if the its the fraction of the lattice parameter you call it a partial dislocation. So, we will soon take up examples.

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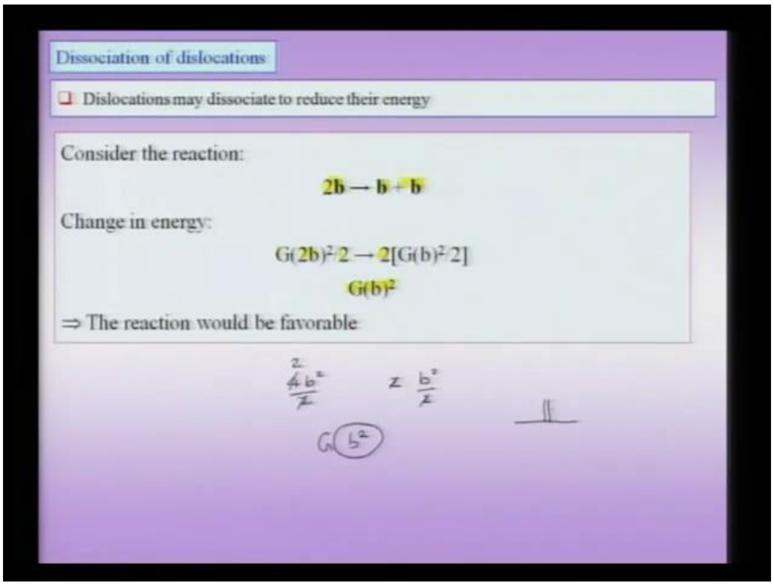

So, full and partial dislocation especially in the context of cubic close pack crystal. So, let us consider how a dislocation can acutely split and or the split its strength and therefore, reduce its energy. So, this is kind suppose, I have the dislocation of strength 2 b now, the energy of that dislocation would b g into 2 b square by 2 this approximate formula and its energy their fore would be 4 b square by 2. Now, suppose it splits into two half dislocations of course, these are not partial dislocations b in this case we can assume is a full lattice translation vector and this is illustrative example. Therefore, the energy would be coming into y square. So, you can see you can that there is the reduction energy of g b square as dislocation goes from a burgers vector 2 b of burgers vector of b plus b.

So, let me write down the energy of the left and right. So, you have the energy of about 4 b square by 2 on the left hand side in the right hand side you have got g into 2 b square by 2. And therefore, you got b square here and this is 2 b here therefore, the reduction energy is b square and of coerce. Therefore, there is the reduction of g b square as this dislocation reaction takes place therefore, the forward reaction is energetically favorable and the reverse reaction not favorable. But, so clearly you cannot have the slip plane and suppose I can visualize dislocation at the burgers vector b then what I mean by suppose an edge to dislocation what I mean dislocation 2 b is nothing but, two half blades right.

And, this is not the favorable situation as far as a dislocation flows so, this presence of this the reduction in energy when dislocation split into partials can drive and, disassociation dislocations. And now, let us next consider the stress field of this dislocation and this is the very very important subject. Because, now the stress field of dislocation is the long range stress fields.

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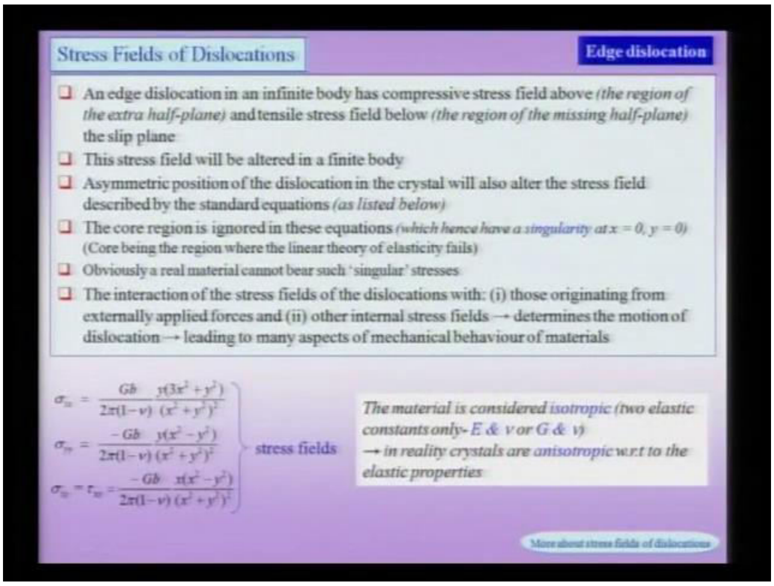

And, during plastic deformation this stress fields can interact with the other stress field in the material like once it can interact other dislocation, it can interact with the stress field of vacancies, they can interact with the stress fields of co here not precipitates, it can interact with the stress field grain boundaries etcetera. So, in various fields the stress field is responsible for the behavior of the dislocation in a material. And, when we are talking about the stress fields 1st of coerce, we will start with the very ideal kind of situation were in the dislocation is present in a infinite body. That means, I do not have any surfaces or edges in the body and we will start with the description of the edge of this dislocation in an infinite body. So, in an infinite body I can identify a mid plane.

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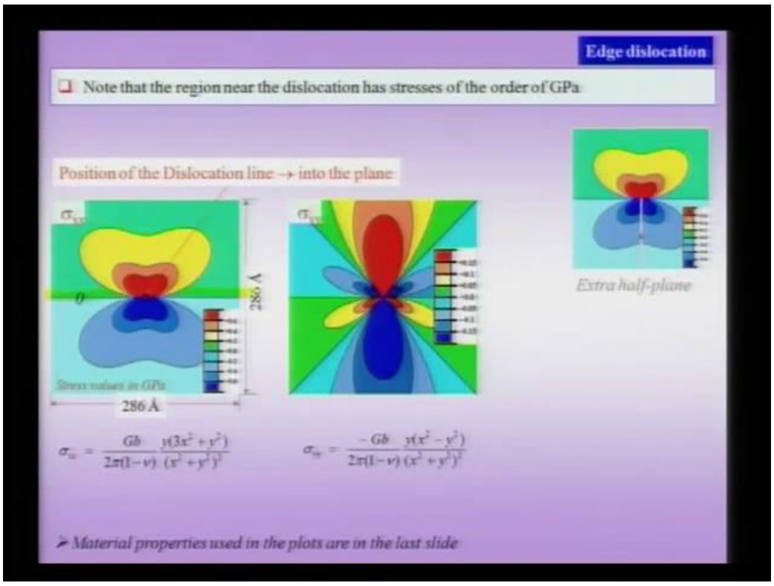

For instant, in this diagram you can see in this diagram this is my mid plane. So, this above this mid plane (Refer Slide Time: 18:30) you can see that of course, in this inverse there is in this diagram,

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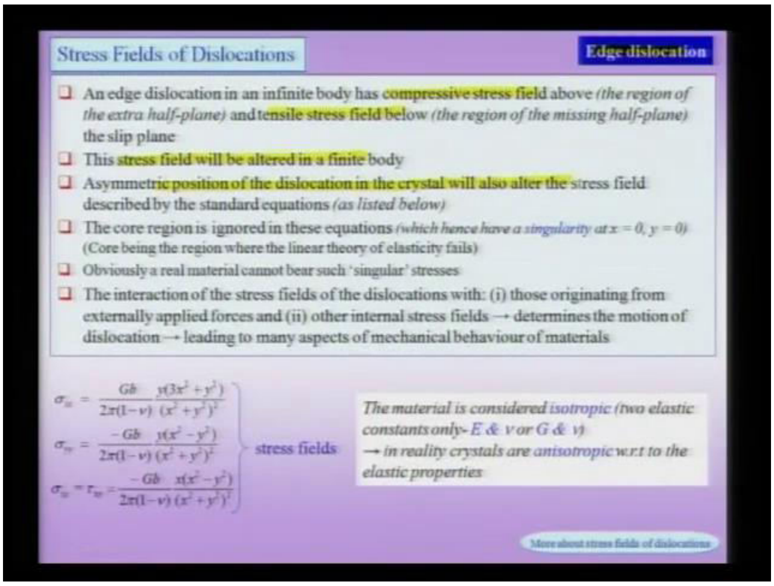

compress in one side of the plane and there are other side of the mid plane and this continues to the semi infinity. So, this is how the stress field are in an edge dislocation in an infinite body. Now, these stress field will be order dislocation is present in a finite body and also it will be alter if this dislocation is in a symmetric position in the crystal.

So, these are something which will alters these stress field of the dislocation. So, this ideal stress field would be at this dislocation in an finite body. The 2nd approximation would be that the dislocation is present in an finite body and there will be significant change in the stress fields of the dislocations and we will take up this some of this aspect. And then, if the dislocation is present a symmetric in the finite body in the then that will led to future alteration in the stress field. So, let me draw this three cases (Refer Slide Time: 18:30) on the board.

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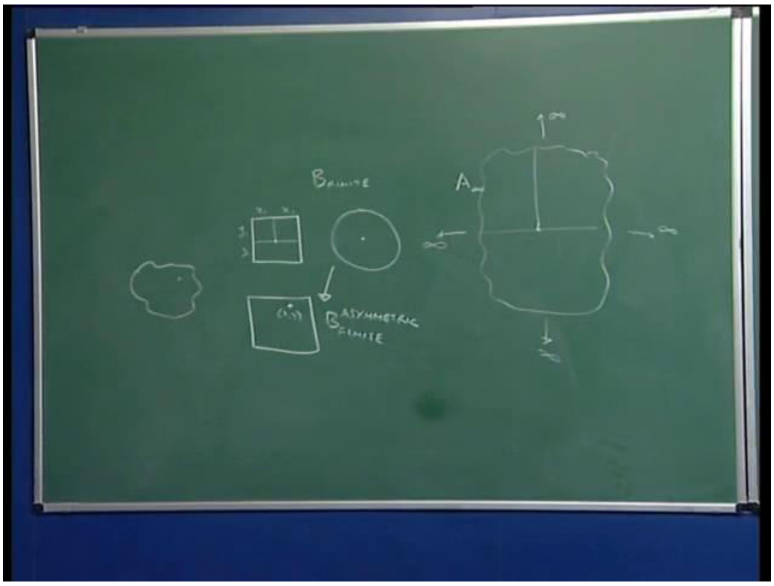

So, initial case of course, are an infinite body going to infinity in all directions and I am assuming that the dislocation present in the body here. In other words you can vitalizes this planes in extra half plane and this is my dislocation. 2nd case, I can consider is this same dislocation in a finite body. So, finite body of course, could be any orbiter shape but, I will let me take the simple case, it is the either the square or the rectangle prism or a cylinder that I will assume that dislocation is present in the centre.

So, this is the 2nd possibility and of course, in both case I can draw an extra half plane. But, this is not percent in symmetrically present in the body this distance y 1 is same as the distance y 1 this distance x 1 same as the this distance x 1. But, now I can consider so the stress field one as you go from case A which is the infinite case to case B which is finite case to a case were in now the dislocation is not only present in a finite body but, it is present in the symmetrically in a finite body.

So, it is not present in the right in the centre but, in some passion which can be known as x y in the body. So, there will be the future alteration with respect to the stress field as you go to the B. This is finite and this is as symmetry. So of course, there can be more complication that I can assume very orbital shape body and were in even there is absence of any kind of the point of the centre I can put it dislocations somewhere in the body and try to calculate the stress field. But, we will start with most ideal situation initially were in now this dislocation is present in a infinite medium. And, when I am talking about these stress field I am typically ignoring the what you might call the pore region of the dislocation (Refer Slide Time: 19:28) which cannot be computed using the elastrator theory.

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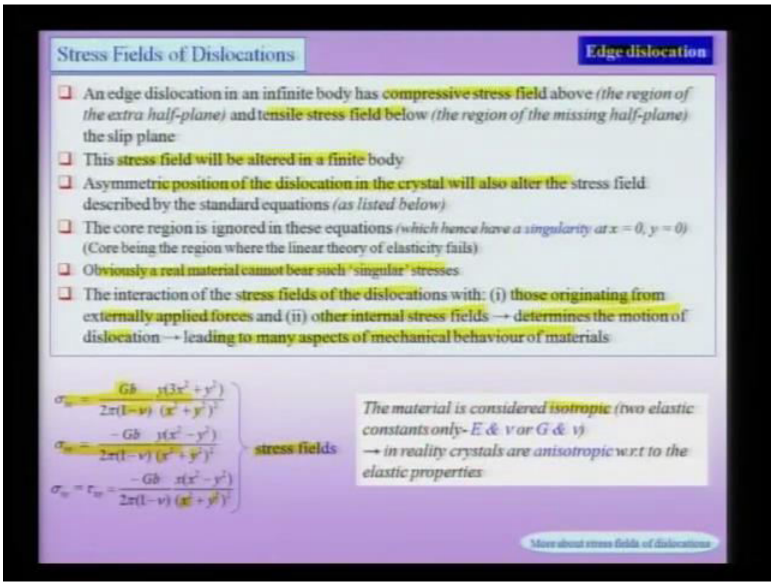

So, whatever the equations for instants, the equation is written below in the formula are all derived using the linear elastic theory. And therefore, the validity of these equation is only about the few burger vector from the dislocation line.

And, when you look at these equation for instant, now look at the sigma equation. So, you can clearly see that it depends on the share models of the material and we know that any quantity of the material dislocation has to be upset of the burgers vector. And since, now I am stack about the edge dislocation you have the factor 1 minus new and which is coming here and you can clearly see that this dislocation stress field. Of course, we will understand in terms of the quant or plot of the stress which is easy to visualize compare to the equation itself. We will see when I put x is equal to 0 and y is equal to 0 in any of these equation, then the stress field then districts field will blow up. That means, there is obviously singularity of the stress field centre of the dislocation line and these equation are not valid in this region. Therefore, we have to understand the validity of these equation is beyond the decor region of this dislocation.

And, so we will see the plot of these equation to understand how this stress field look and how we can understand later on how this stress field will interact with other stress field present in a material. So, obviously we cannot talk about single stress in the real material because it cannot bear the very high stress. Now, these dislocation stress will become very important when I talk about its interaction with other materials. But, we have to remember that 1st thing this dislocation stress field would interact with those originating from an external applied force or from the other stress field which are present in the within the material.

So, these two aspect determine the motion of the dislocation living to the many aspects of the mechanical near the dislocations. So, two kinds of stress field you have to separate, the once which I externally applied which can get transmitted now to the dislocation and therefore, cause its motion or can then cross one of the phenomena. The 2nd thing that I need to worry about the internal stress present in the material from before and these internal stress can come from, as I pointed out many other kind of defect covalent etcetera and these extraction finally, the external and internal would determine if this location. For instant, going to move on which slip range is going to move and therefore, the plastic behavior or the evolution of this system with this dislocation with this time. In this equations we have written down the here.

We assume that the metrical is isotropic, the equations get little more complicated when you are assuming an isotropic material property t. But, just to for now we will assume the isotropic properties we have to deal with only two fundamental constants g and new which will now complete describe the elastic behavior or the elastic stress field in this case of the dislocation. We have to of course, understand that the real crystal is actually an isotropic and therefore, if we are talking about the single field single crystal which is cubic like a copper or any one of those sodium chloride.

Then we need to put in at least three elastic concepts in the case of cubic and if the symmetry of the crystal is lower than we need to feed in more and more elastic constants which would now describe the elastic behavior of the material. For now, in these lecture series will assume that material of isotropic and of course, the degree of error were introduced by this isotropic it could depend up on the degree of an isotope in the material. But nevertheless, these can quite describe the at least the essential or the qualitative features of the stress field. (Refer Slide Time: 19:14) Now, if I look at the plot of these stress fields on the left hand side is the sigma x x plot and other stress in the left hand side sigma y y plot.

Now, we note that we have already noted that I should not try to understand this stress field and it is close to the dislocation line. In other words, very close to the dislocation line which I show here were the dislocation is present, these equation are no longer valid which I call the core region of the dislocation. To be on the sigma x x field I can see that the complete above that this entire region is tensile and the region below the mid play is all compressive. So, middle region of course, the line at the centre is 0 so, this is my 0 line.

So, there is an half space which is completely compressive and there is an half space which is completely ten size as with respect to the sigma x s x stress field. Look at the sigma y y stress field, you can see that there are many region of interest that in this region it is you can see the green color is all the positive stress field green and you can see here the 0 line here somewhere here in the stress field. So, the blue field are all the negative or the compressive and the green once and the red once for instant, this region all are ten size. So, we can have sigma x and sigma y plot and obviously if I want to correlate my sigma x x plot with the presence of the extra half plane and the extra half plane is in the compressive region

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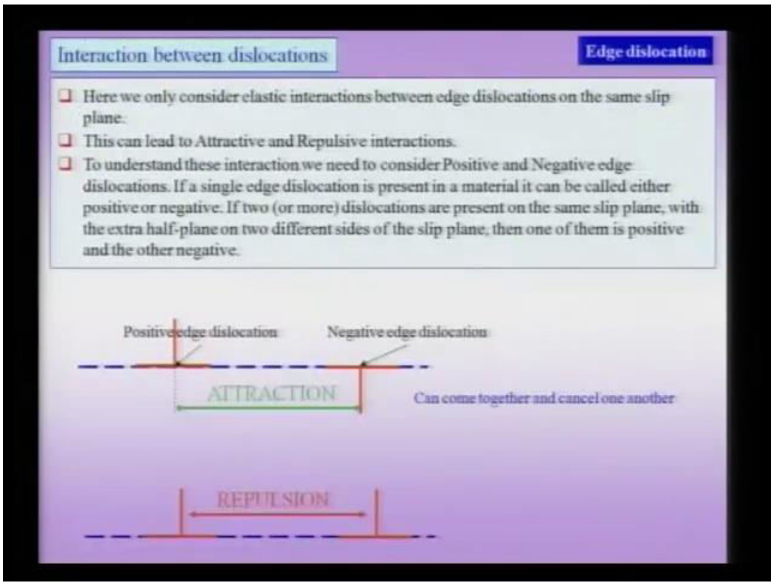

of the stress field. So, this is how compressive region were in my extra half is present. (Refer Slide Time: 19:14) So, now this is the typical plot of the sigma x and you can remove you can infract coordinate with this characteristic butterfly kind of the shape. And, the important point to note that is the stress in the core of the dislocation very near to the dislocation line or all the order of the. So, you can see that this is about if you look at the line between yellow and the red which you can locate here within the yellow and the red you can see suppose about a half of the gega.

Now, the reason that is very interesting that acutely now I am describing a dislocation which very high stress field and these are the self stresses of this dislocations. And because, the dislocations are very agencies which cause there slip this high stress field cannot in other word, it is not very valid kind of the argument to talk about plasticity being caused by these stress fields. Now, what is the role this hole plays? One of the important roles that dislocation stress field would play would be its interaction with other defects in the materials. And, we will take up those interaction that one by one, the most important of them being interaction with other dislocations in the material. (Refer Slide Time: 27:34) Now, if I have two dislocations in on a plane also you can see the figure below that there are there is slip plane which marked in dash blue line.

And, in you have the positive dislocation present in left-hand a side and a negative dislocation side left hand side in the right hand side. Then, because of presence of these stress field this dislocation can interact with each other and has you no the one dislocation would have a compressive region of the top. So, this is my compressive region of 1st dislocation of the compressor region of dislocation present here and the compressive region of the compressor other dislocation would be present here.

And therefore, the compressive region of this dislocation we attracted to the ten side of the other side of the dislocation and viscera. And therefore, these two dislocation one positive and one negative would actually be attractive. On the other hand, both the dislocation at the same side assuming that this is positive also be positive dislocation and (Refer Slide Time: 27:34) still I am discussing the edge locations. Therefore, these two dislocation would actually repeal each other. So, if I try to bring these two dislocation towards each other in the 1st set.

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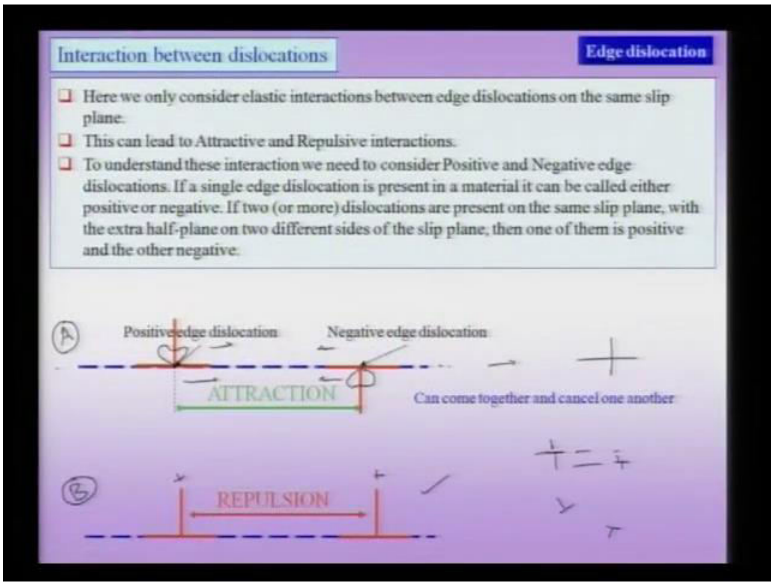

So, this is my case A, the attractive case and the case B which is my repulsive case. In case A the energy of the system would reduce as these two dislocation come together towards each other. And, in case B I need to actually apply more stress to drive these dislocation towards each other and in case B the energy of this system would increase as these dislocations came to each other.

Now so, we have consider the simplest case thing can get extremely compacted for this which I can have one dislocation with slip plane here and then another dislocation plane here. Then, you would have the various region in which there is the attraction and dislocation and actually you can divide into many quandrems depending upon the angle. Now, you have x of set and the y offset between these two location and you can start drawing entire regions there will be attractive or impulsive attraction. So, let start with simplest with this case so that, we note that dislocation attract each other and what would happen in these two dislocation came together in this picture and we will also see if there is if the force of attraction cross the pulse force. Then these two location can spontaneously move towards each other and actually come together and cancel each other. So, in this case they were acutely do the cancellation presence of the extra half plane and therefore, the dislocation would vanish.

So, this system is the reduction in system this system is the repeals system. And obviously, as you pointed out we can acutely take more complicate cases were one dislocation as certain orientation and other dislocation in other orientation in crystal and find out the interactions. But, in these cases we will not have the define analytical formula or with the of calculation may not be the that simple. We will take up other interactions the other kind of very soon. Before that lets take up dislocations and cubic close pack crystals. In cubic close pack crystals we know that the slip system consist of a dislocation

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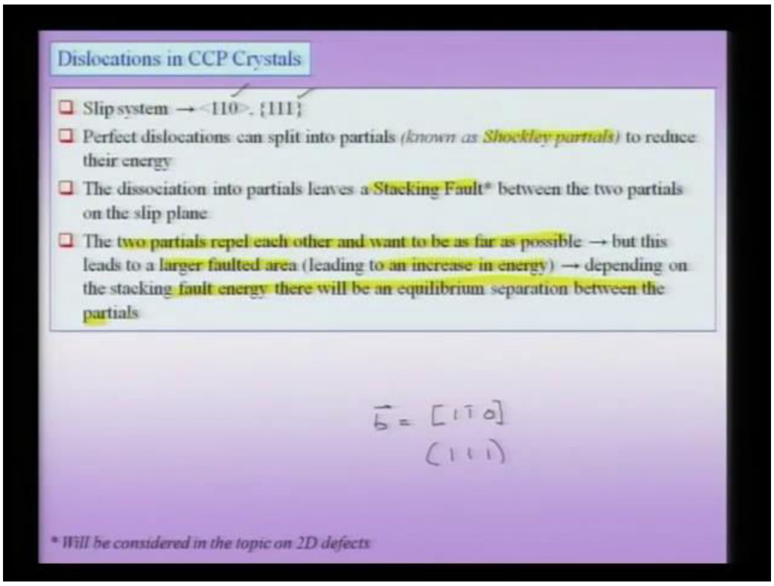

in on a close pack plane along a close pack direction. So, the burgers vector will be the close pack direction close pack plane on the close pack plane. Now of course, this is the family which I am indicating here. Suppose, I am talking about the specific burgers vector like for instance b I need to take the specific value that it can be 1 1 bar 0. Then such a burgers vector will present on the slip plane on the 1 1 1 and now if I take my dot you can see in the 0. That means that this direction contain this plane, in c c p crystals or the cubic crystals close pack crystals perfect dislocation have a tendency to split in to partials to lower their energy.

So, there are two kind of the partial which are found in in c c p crystals: one is known as shockley partial and another is the frank partial. So, in this context pleating of dislocation lower its energy will consider the shockley partial which will see very soon. The region between the two partial on the slip plane is a which we call the stack fault and this stack fault is the two dimensional effect and it is associated with the stacking fault energy.

So, when the two shock partial tend to repeal each other and try to be as far as between each other but, if the distance between the two partial increases then the faulted region increases. And therefore, it cause more energy to the crystal and there will be equilibrium between the two opposing forces. Now so, this is what I am saying here that the two partial repeal each other to be as far as possible but this leads to the larger faulted area and it will lead to the increase in the energy. And, depending on the stack fault energy there will be equilibrium separation between the partials.

So, and of course, we consider little more details but, for now let me will draw this symmetrically like this.

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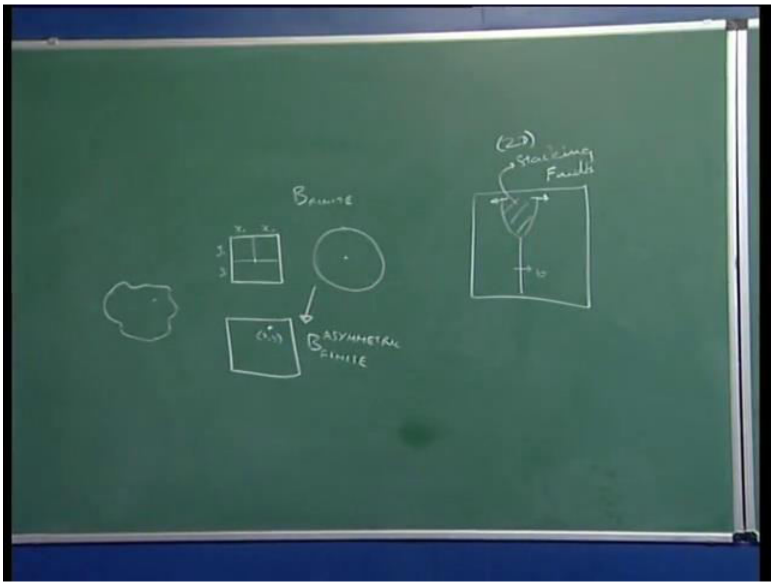

Suppose, I had a full dislocation line so, this is my slip plane and I have the full dislocation line and this full dislocation line at a note partials. So, the region between the partials for instants, this is my full burger vector b and we will see that this will split into partials. So, the region between the two is my stacking fault and we will take up this stacking fault and when we talk about the two dimensional defects. But, for now just remember the fault with cause two dimensional effect which cause energy. And therefore, even though these two repeal each other so the tendency of these partials as far apart the possible but, still because now they go far apart it cause more energy to the system then the equilibrium separation between the partials.

And, there are materials which have a high stacking energy there are materials with low stack in k materials. Suppose, you have high stack ink energy then the partials would be close and if I have the low stack ink energy partials would be far apart as compared to the material which stack ink fault energy is high. Example of the high stack ink energy would be aluminum example with low stack ink energy would be something like copper. So, we will talk about that more that the in the case of the stacking fault construct the two dimensional effect. So, let us consider the configuration of these partials in the case of an cubic close pack crystal.

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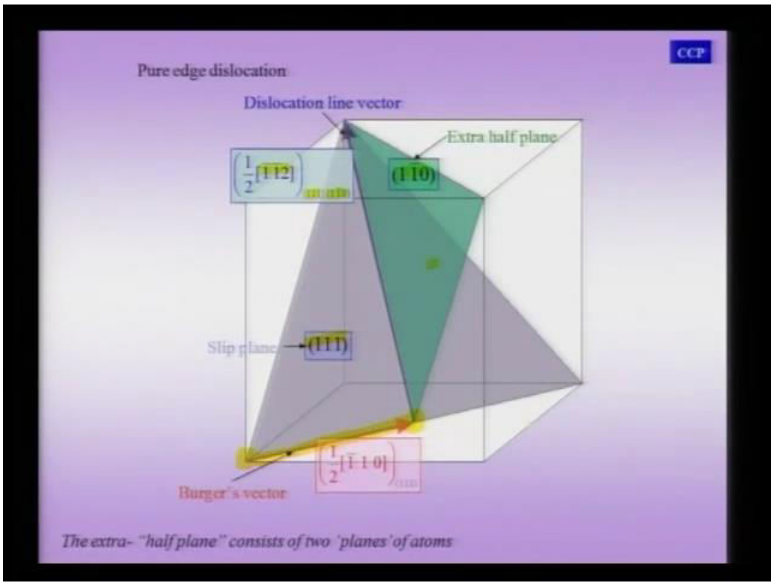

So, in the cubic close pack crystal as you can see the burgers vector is the red vector shown in this figure and typically it is one of the members of the 1 1 bar half of the 0 family. Now, dislocation line, the extra half plane you can see in this figure is an 1 bar 1 1 0 half plane and the slip system is 1 1 1 plane. Therefore, we known that the dislocation vector, the d vector as to be the type 1 bar 1 bar 2, in this case specific example it is the 1 bar 1 bar 2 could be any of the depending upon the family of the slips system. Acutely the member of the family you are considering it could be 1 1 2 of kind of the vector. Therefore, this 1 bar 1 contained in the 1 1 1 plane and the 1 bar 1 1 1 bar 0 plane. So, 1 1 bar 0 bar being the extra half plane the strip being the 1 1 plane and therefore, the interaction of two existing is my line vector location for the h for this location.

So, this diagram shows you the geometry of the extra half plane for the full dislocation in the cubic close pack crystal. Now, an important point to be noted which is that acutely this burger vector now acutely is an crystal translation vector. That means, it connect 1 point 1 lattice point to the other lattice point in the crystal's but, this corresponds this burger vector corresponds 2 extra half planes. So, this burger of is associated with the insertion of a crystal plain which is indicated in green but, this crystal plane acutely consist of 2 atomic planes.

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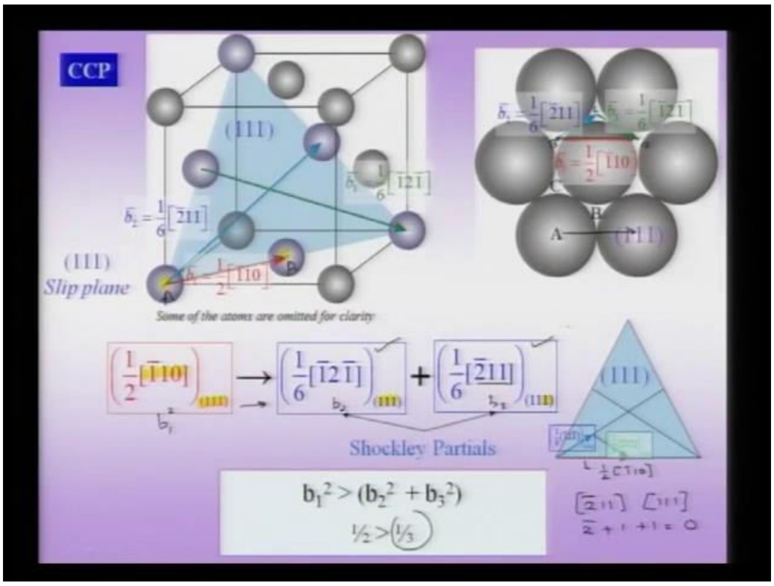

And, when these two atomic plane separate out from each other we have the two partials in the case an q h this location o. So, what are the partials and what are the kinds of vector they are, what is the physical significance. So, let us start with the equation 1st that the full burgers vectors is 1 bar 1 0 half 1 0 which connects my atom in the corner 3 atoms in the centre which corresponds to a full burgers vector. Now, this lies on the 1 1 1 slip plane.

Now, this can split into 2 partials which are now the stocky partials and the vector associate with the stocky partial one six two 1 bar 2 1 bar which lies on the 1 1 1 plane and the 2 bar 1 1 which also lies on the 1 1 1 plain. So, how can we conform this lies on the 1 1 1 plane? So, we make a dot product for instant, so this is I have to make the dot product between now the to the 2 bar 1 1 plane direction lying on the 1 1 1. So, I multiply 2 into 1 bar is 2 bar plus 1 into 1 1 plus 1 into 1 1 which is equal to 0. So, this tells me that this burgers vector or this partial burgers vector 2 bar 1 1 lies e on the 1 1 1 plane.

So, you have two members of the 1 2 1 type of the direction which lie on the 1 1 plane which forms on the burgers vectors for the partial dislocation. Now, let us see if I can satisfy my reaction completely so that, you can verify by clicking that you have here one six minus one six plus minus two six that makes the minus two six which is minus 1. So, you can see that minus 1 by 2 minus half is the burgers vector here. Similarly, you can confirm that dislocation reaction is valued but, would this why would this dislocation reaction take place that is I should use the dislocation energy. So, let us confirm the actually dislocation energy is less now if I now do the b square for this and the b square for this. Suppose, I call it b 2 then I call it b 3 now the sum of b 2 square plus b 3 square is one third and the sum of b the b 1 squire is if you can see that half is very large than one third. Therefore, this dislocation reaction goes in the forward direction to reduce the energy of the crystal.

Now, what is the significance of these two vector we have shown here? Of course, the vector additional of these vectors gives the first vectors is the simplest of all but, we need to understand the physical significance of these two vector in the cubic close pack crystals. So, what does my b 1 connects b 1 even connects the lattice position to another lattice position and in the language of the close packing we can call this a position being connected to another a position on the slip plane. Of course, I can draw this a to a connection as a vector here or equality I can draw it like a vector which is shown here, the red vector which joins drawn here.

Now, if I super impose on these the other two vector b 2 and b 3 the b 2 vector will be the blue vector which is one six 2 bar 1 1 and it is shown here in this dislocation. In this triangle also same thing this is my red vector which is now my half 1 bar 1 0 is my red vector. And now, this is my splitting into two partials the blue vector in the green vector which have 1 2 1 kind of one sixth 1 2 1 kind of a indices. But, physically this one sixth 1 2 bar 1 1 vector connects now. Suppose, I call this as a position then these positions starting point of the blue vector with b position and ending point will be the c position.

And therefore, my blue vector which is one sixth 2 bar 1 1 would connect to my b position to my c position and the green vector would connect the c position in to the b position. So, what I have done here? I have taken the a to a connection vector and translated so, there is super impose on the b 2 c kind of a vector. So, this is my b to b kind of vector and these two blue and green vector take to the b to the c position and b to the c position. So, these blue and green vectors when they are super impose on the 1 1 plane along with the atoms make it clear that what is the physical significant of these two vector on the slip plane with the aspect of the c c p crystals.

So, to summarize the important feature (Refer Slide Time: 31:53) of the partial dislocation and the cubic close pack crystals that slip system is obviously the close pack plane 1 1 1 and the close pack direction relying on it which is the 1 1 0 kind of the vector which I have shown in the diagram as the red vector. So, there are has you can see there are many members of this family and it can any one of those members but, is only thing that it has two be a close pack plane and the close pack direction lying on it.

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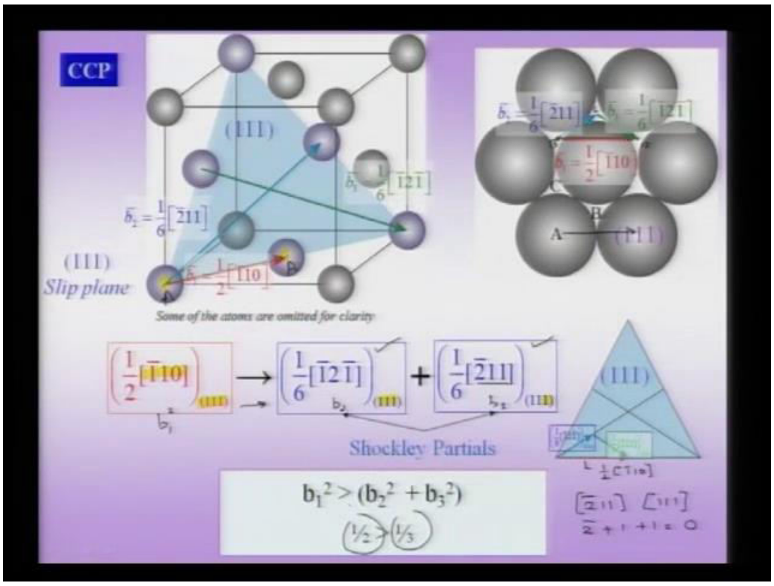

Now, the energy of this vector v 1 square is about half b 1 square is half and this would tilt into partials of the type one sixth 1 2 1 and this would lead to the reduction in energy of the crystal. And, this one sixth 1 2 1 type of the vector actually connect b 2 the c position and c to the b position along the 1 1 1 plane. So, this is the physical significance of these two vector has far as the cubic crystal goes.

Now, when the such a part splitting take place of course, another way to understand is the that suppose it is blue rigid dislocation I was talking about then I can understand that (Refer Slide Time: 35:13) this red vector the full dislocation vector and the associated extra half plane the 1 bar 0 plane, the green plane in this case is acutely the crystal plane. But, it consist of two atomic planes and when you form two partials these atomic planes separate out and lead to partial burgers vectors and 1 2 1 that is the one sixth 1 2 1. So, and this splitting is made freezable because there is reduction in energy as the dislocation splits into partials.

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Now, we have talked about another kind of the partial in the cubic close pack crystal which is called the frank part dislocation and let me draw these frank part dislocation by considering.

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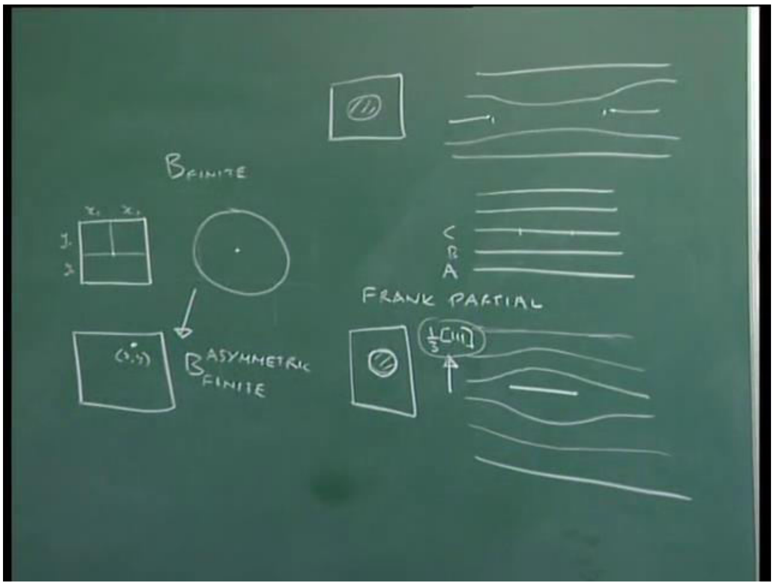

Suppose, these are my 1 1 1 planes and now you know the repeat distance suppose, I call this A B C and so four. Suppose, in this case I introduce a now the small region of extra atoms suppose from here I introduced. So, this is my extra row of atoms then plane around this would be distorted and as you go far away from this you will find the distortion comes less and then you will have perfect planes far away from this small segment. Looking down on the plane so this is nothing but, the disc of atoms I have introduce inside of the crystal. Now, this kind of the this kind of a dislocation as a burgers vector of one third 1 1 1 type and obviously this is not a dislocation as in the case of the sickly partials. And so, this disc of atoms lead to the dislocation loops the boundary boundary of this dislocation atoms is the dislocation loops which is the frank part dislocation.

So, this is the frank part dislocation and so these are the close pack plane when I am trying to understand the actually. I am describing the disc of atoms actually I do an experiment were I do a disc of atoms and then that would also lead to a so, this the disc again this is the missing portion of the original plane of atoms. Again, this would lead to the plane on the silk plane if I look.

So, I will see the region were is absent and therefore, this is also a frank partial. So, this would be interesting frank partial dislocation were in can remove a disc of atom and this would be extreme frank partial were in I introduce the disc of atoms. Then you can notice that the burger vector for this partial is one third 1 1 1 and it is not lie on the slip plane. So, this frank partial can be viewed as the dislocation loops and in this context is very important to note that when we consider the mix dislocation line on the split plane that means, the dislocation which is curved for instant it could be complete loop or a second segment which is curved.

Then, such a dislocation which is curved had a mix character from point to point but, those kind of dislocations I will different this kind of dislocation because, now this is the pure edge dislocation which is curved. Therefore, it is possible to have the curve pure edge character while it is not possible to have pure screw dislocation which is curve in that case dislocation lied on the slip plane and in this case it does not lie on the slip plane and this is not missile. So, after having consider frank partial dislocation and dislocation loops in the c c materials let see what is the configuration of edge dislocation in an b c c crystal.

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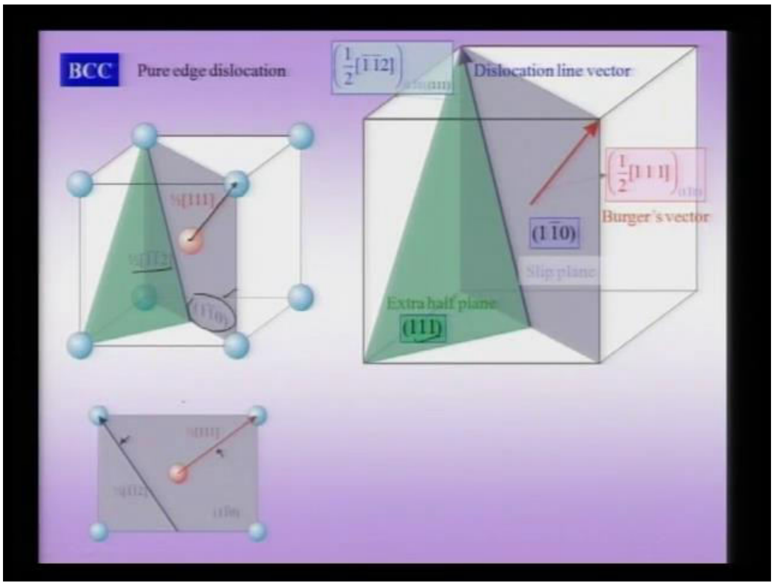

In b c c crystals now my b c c crystal does not have distingue close pack plane in the case of the cubic close pack crystal plane. In this case, we shall see later that more than one kind of the plane would competing to be part of the flip system but, never the less in b c c crystals there is a close pack direction which the 1 1 1 direction. And therefore, the fundamental of the short lattice translation vector is this vector which I have shown here which of the half 1 1 1 type. Therefore, the dislocation burger vector is constant it is definitely half 1 1 1 but, the slip plane depending on of course, the kind of the crystal which I have to take into account.

That in one of the possible slip plane is 1 1 bar 0 but, there is no well defined high density plane or a close pack plane. And therefore, the slip system in some of the crystals can actually the slip plane can actually. So, in this case where is my extra half plane? My extra half plane is perpendicular to my burgers vector and the dislocation line and this is extra half plane I have shown here and the dislocation line is along the 1 1 bar 2 direction which is shown here geometrically. So, this is my extra half plane which is now my 1 1 1 plane it lies and this intersect my slip plane which is 1 1 bar 0 along the 1 bar 1 2 kind of the direction. But, the burgers vector is a constant which is along the close pack direction in the b c c crystal which is 1 1 1. So, this is also shown in the plan view where in my dislocation oline vector which is here. This is my burgers vector and my extra half plane is the one which is green which is coming out of this plane of the board.

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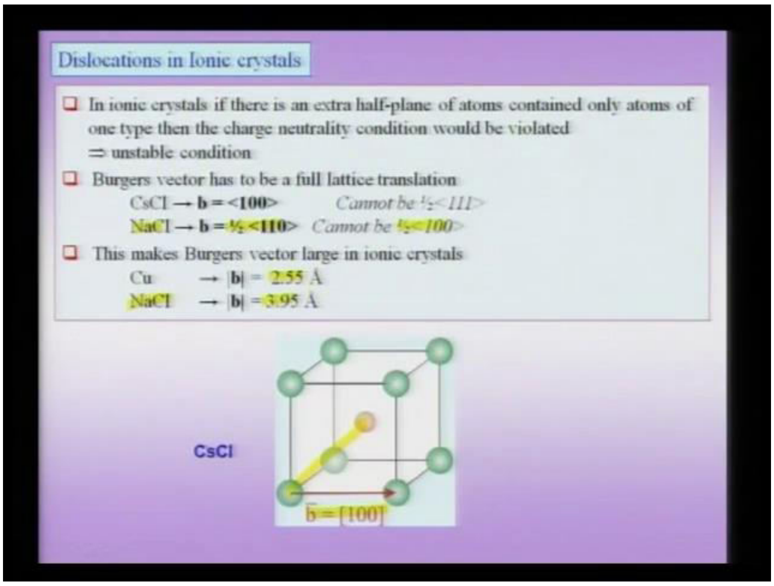

Now, let us proceed take up the few examples of the dislocation of the ionic crystals. Now, in dislocations suppose I am talking about an edge dislocation in an ionic crystals. If I have the extra half plane continuing only one kind of the species it could be sodium chloride of the if I have the dislocation having only sodium atoms. Then, obviously this is not the neutral condition and this is not and stable condition. And, we have to remember for instance, example below the burgers vector has to be the full lattice translation vector. And therefore, b in this case is 1 0 0 and not the vector connecting the c s atom 3 c l atom, that not the full burgers vector. In sodium chloride which is f c c lattice which is f c c lattice the burgers vector is half 1 1 0 and it cannot be half 1 0 0.

Because, now the burgers vector connects one lattice position to another region to another even in the ionic crystal, the burgers vector tents be large in the ionic crystal. And therefore, they cause more energy to be introduce in an ionic crystal. For instant, the copper and the burgers vector 2.55 angstroms, if you compared with sodium chloride it is about 4 angstroms. And therefore, it is a large burgers vector coasting of an energy. So, the simple rule for the ionic crystal is that the burgers vector has to connect one lattice region to other and the fore cannot connect the position in one sub lattice occupied by one kind of a ion to another sub lattice which is occupied by another kind of ion.

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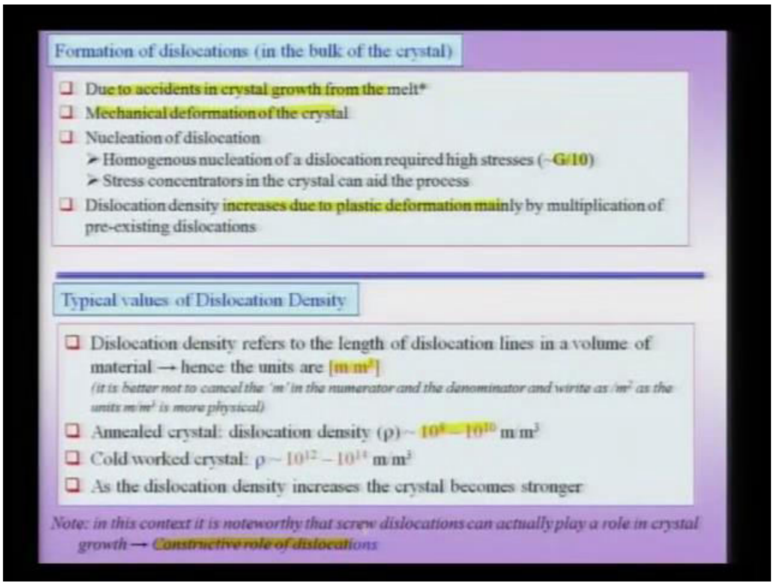

So, next question we ask our self, how come dislocation are present in the crystals? In other words, how do dislocations form in a crystal? So, there are many method by which dislocation can form and of course, one of the easiest simplest visualize is the they are due to accidents crystal growth from the melt. So, suppose I have the molten metal defining this is not perfect and you could have the dislocation which is in the crystal. Later on, we will see actually construct role of the dislocation were dislocation in crystal growth but, it the different issue but, we will come to it very soon very interesting kind of the rule. When you do the mechanical deformation of the crystal high stress concentration locally can lead to the nucleation of a dislocation.

And, a nucleation of dislocation suppose homogeneously as to take place then it requires very high stress of the order of 10th of the share model of the crystal. But, if they are certain other stress concentrate on the other crystal then this can add in the nucleation of a dislocation of the crystal which can take place during the plastic deformation. That means, I externally apply stress and important point to note is that dislocation density increase during plastic deformation mainly due to the multiplication of the pre existing dislocations.

And, in other words overall the number of the dislocation density is acutely increasing and we will also see some of the mechanism by which such an increasing dislocation density is possible in a crystal. So, a dislocation can come from some of the sources which have motioned here. Additionally, we will later on talk about certain kind of dislocation which we call the structural dislocations. We have already seen that when you have the defect they can be random defect or they can be structural defects.

In the case of structural dislocations their origin could be very different for instance, when you have a for instance of phenomena were in recovery then when you other words you take in the cold work crystal and you recover the crystal. They could acutely small reduction in dislocation density but, additionally you could have a ray of dislocation developing into a what you might call a angle boundary and in that case this process is taking place in the during recovery of the cold work metal. So, those kind of origin are slightly different the multiplication we are talking about here. So, what is the typical value of the dislocation density in a material?

So, if you have take as we seen in dislocation density is defined as length of the dislocation line in a volume of a material. And, in anal crystal this value typical about it can be lower for instant, it can be 10 power 4 or 10 power 5 meter per meter cube. But, in a cold worker typically rises about 10 power 12 meter per meter cube. So, there are methods or they are process active but, acutely lead to the increase in the dislocation density as you are plastically deforming the.

This actually a very surprising aspect because we know the first step of plastic deformation is the motion of the dislocation living the crystal. If dislocation are living the crystal during the plastic deformation, how is the density increasing? So, we will consider at least some example, one example of how I dislocation density can increasing during plastic deformation. So, this is the very surprising aspect and we will also consider the constructive role of screw dislocation in crystal growth in very soon.

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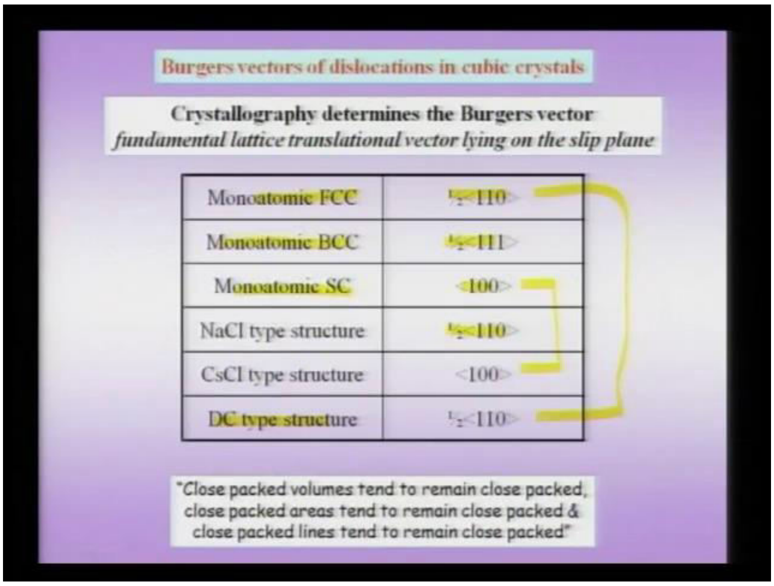

Now, what is the burgers vector of the dislocation in cubic crystals? We know that it has to be the fundamental of the shortest lattice translation vector. So, from cryptology we know that in mono tonic f c c it is half 1 1 0, in mono atomic b c c its half 1 1 1, in simple cubic it has to be 1 0 0 in sodium chloride now belong to the f c c lattice. Its 1 1 0 and the c l c s same which is a simple cubic has to have 1 0 0 and the demon cubic structure which is f c c lattice also has to have similar to the mono f c c which is half 1 1 0. So, the in cubic crystal the burgers vector it is easy to determine.

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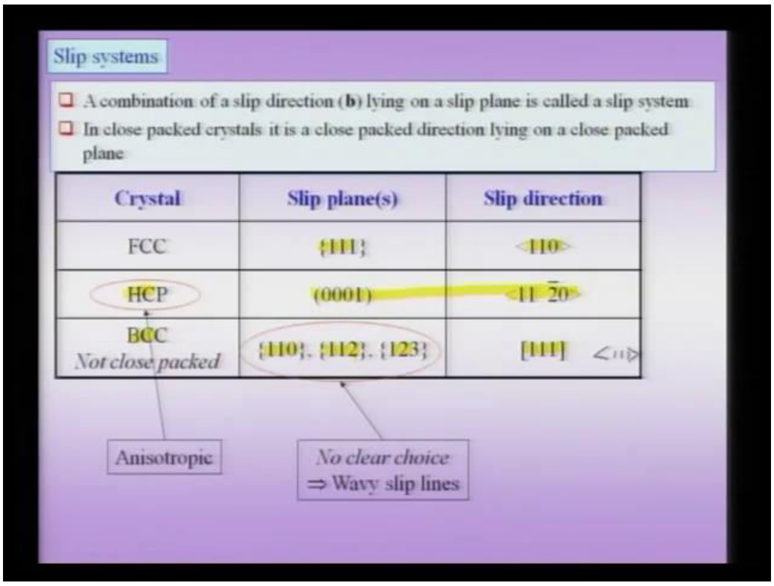

So, if you look at the system and here in we already consider the f c c case were systems is 1 1 1 type of the plane and the vector 1 1 0 type of the vector lying on the slip. But, the important example and in this h c p the close pack plane is the closely plane and this is the close pack direction lying on the slip plane which is a of the type 1 1 2 bar 0 which is now forming the slip system. The interesting point to be noted in this slide is the case of the b c c crystal which is not have any close pack plane and we already seen the example of 1 1 0 kind of the slip plane the geometry of that. But, there could be other slip planes like 1 1 2 or 1 2 3 which are slightly lower density has compared to the atomic density 1 1 0 plane. But, these could also be slip planes but, never the less the slip direction remains constant which is of the 1 1 1 type. So, the factor most use the different arrow in this case so, if I am using this plane so, this has to be 1 1 1 type which is the slip direction in an b c c crystal.

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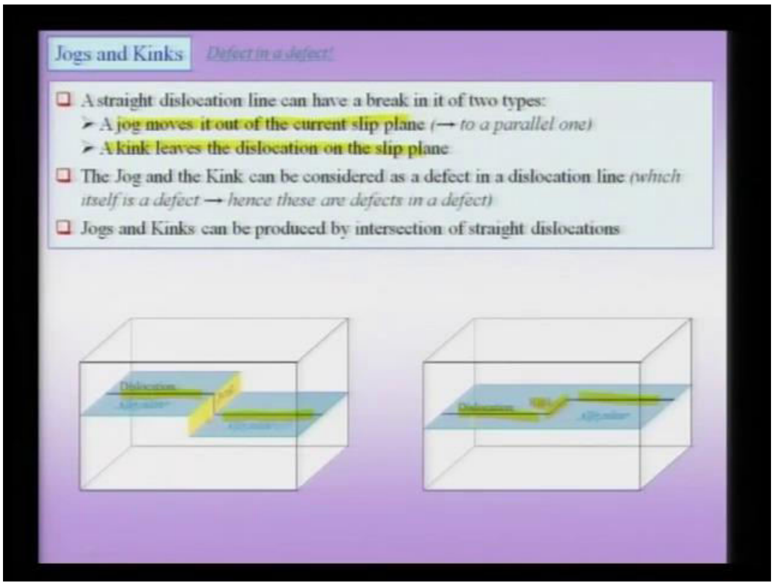

Now, we have consider so far, mostly either the uniformly curve or dislocations or this locations which are straight. Now, there are possibilities were in a dislocation line as the small defect in it and these there are two kind of defect which are possible in the straight edge location or a straight edge dislocation. And, these defect are the jogs and the kinks and this is interesting to note that jogs and kinks are not defect themselves. They can visualize the defect in a defect there are defect within the dislocation line.

So, what is the jog? A jog is a case were in jog moves the dislocation line moves out of the slip plane, the current slip plane to one which is parallel while a kink leave the dislocation line on the slip plane. Shows the jog were in now a dislocation line which is present in the upper blue plane goes to the lower blue plane and this region is the jog in the dislocation line. In the case of a kink, dislocation line remains on the slip plane but, never the less there is the sort of the sharp bend in the dislocation line and this is called the kink. And, if this is my slip plane then these kink might be move along the slip plane.

Now, to reiterate there are ways two kind of the defects which are important when many of the as usual you see the later that this jogs and kink actually can be produce by the dislocation reaction. That means, if two dislocation interact with two each and then actually have the production of the jog and a kink. In the case, of the jog the dislocation line moves out of the slip plane to a parallel one were in the case of kink the dislocation remains in the same plane. Kinks have an additional important role with regard to lower range of stress with respect to the ideal sphere stress of a crystal.

In the beginning of this topic we have made a this chapter on the dislocation frame made a calculation were we have said that if want to deform a entire crystal by applying sphere then the sphere stress require which is the theoretical sphere stress and out of the gega pascal's. And, we notice that with the presence of the dislocation we actually we consider a crystal the but, they could be a 2nd step in this whole thought process which is the further weakling of the crystal and which is we will consider later is the formation of the something known as the double kink mechanism.

So, kink have an additional role with respect to weakling of the crystal costing plasticity in certain kind of crystals.

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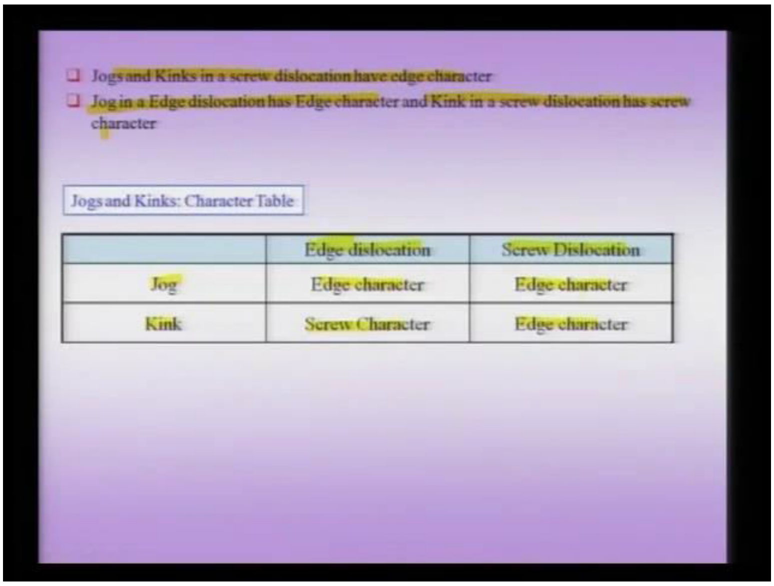

Jog and kiks screw dislocation are edge character jog and there in the edge dislocation. So, that character table has been summarized here. So, if you have the jog in an edge dislocation it will have the edge dislocation and if you have the jog and screw dislocation it will have edge character. On the other hand, screw character and the kink and the screw dislocation as the edge character. In other words, expect for the kink edge dislocation all the others have the edge character to their. So, this is the important note because now this (Refer Slide Time: 54:24) small segment which is a jog or a kink can be different of character has compared to the original dislocation. In other words, kink can edge dislocation can have the screw character, this is something important to note. So, this is table gives us a characteristic table for the jogs and kink in straight dislocations.

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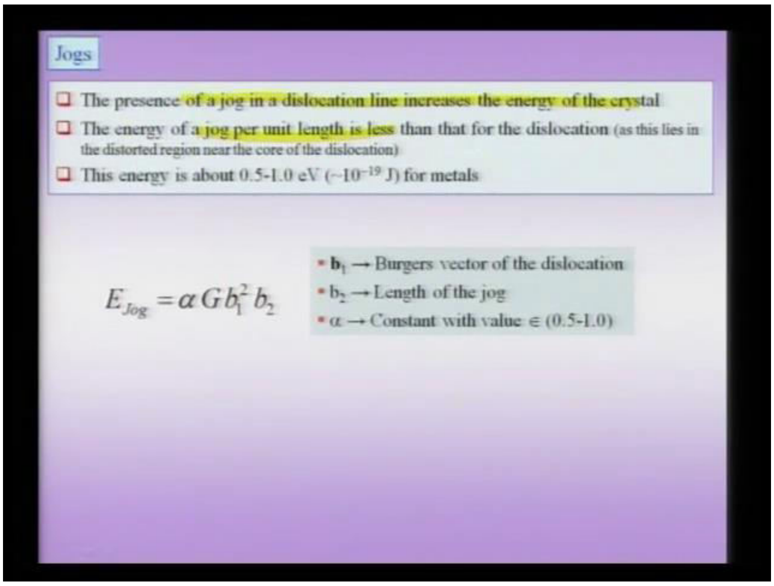

We will briefly consider the energy of the jog and obviously the presence of an important point to note is, the obviously the present of the jog in a dislocation line straight dislocation line increases the energy of the dislocation. And, but the jogs energy per unit length compared less compared to the straight dislocation. Though, the extra length produce by the jog cost you energy but, length energy is lower as compared to the normal dislocation energy something to be noted. Therefore, whenever you have the plastic deformation and jogs and kinks are produces in the dislocation then this cost energy to the dislocation. And, this is perhaps obvious because now we are acutely we are increasing the dislocation line length. An important point to be noted is that this jog and kinks can actually be produce by dislocation, dislocation interactions.

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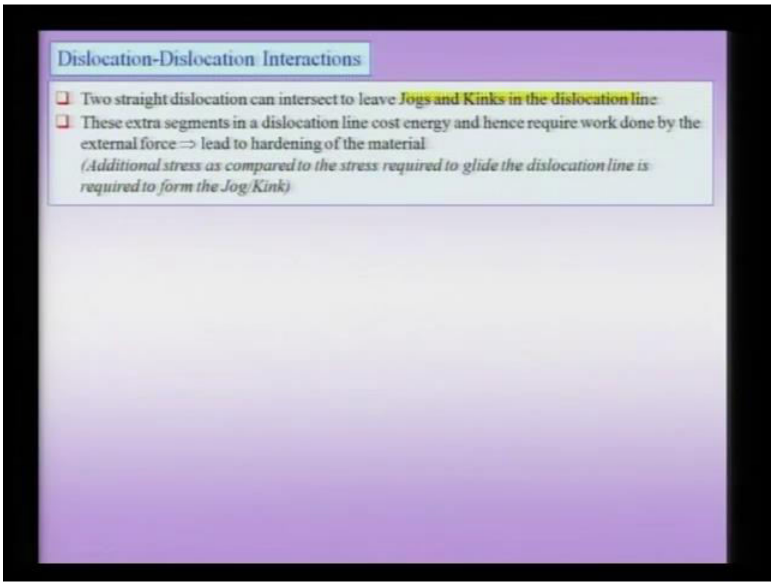

And, though its perhaps not this kind of the interaction would be more appropriate to be take up in detail in a case some plasticity. But, never the less we will from the structure material point of view it is worth wide to know the kind of interaction which can lead to the formation of jogs and kinks dislocation line. And, as we have seen that these production of jogs and kinks in the dislocation line cost you the extra energy. That means, that it also requires the extra stress in that to be applied to continue plasticity when such kinds of defect are forming on the dislocation line. So, what are the line of the dislocation line interaction I can consider and how they can lead to formation of the jogs and kinks.

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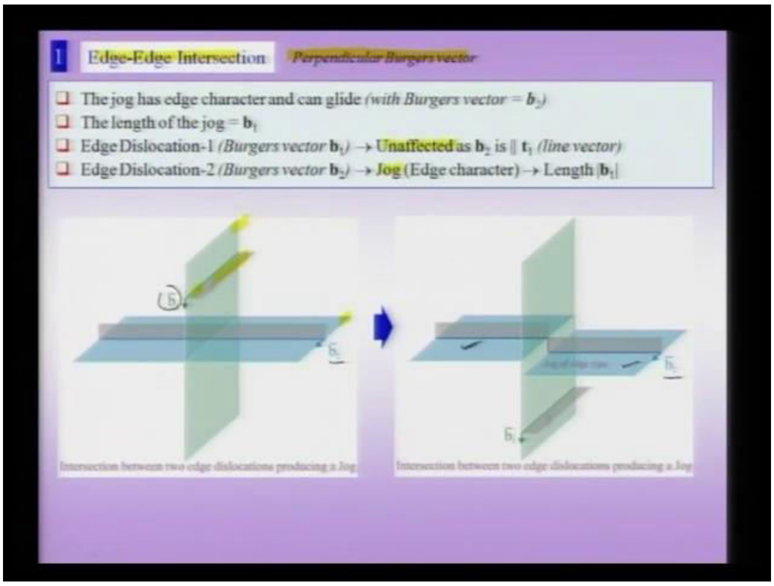

So, we will take up 4 cases: 1st one being the edge intersection on interaction between the edge and edge dislocation which have perpendicular burgers vector. So, let us consider two edge dislocation and the extra half plane which shown in grey color and the 2 slip plane are marked in green and blue color. Now, I have in this case the green dislocation line with shown the green burgers vector moving downwards towards the slip plane which constrains normal blue slip plane with the burger vector b 2. So, when this dislocation interacts with this horizontal dislocation line on which you have the burgers vector b 1 in post. In a this horizontal dislocation line gets the job in its length that means, now it gets the jog into this dislocation line and no longer it is present on the single blue plane.

But, it shifted from one blue plane which is shown here to a parallel blue plane connected by a jog. This jog as an edge character and has the length b 1 line because this length blue line is coming from what this dislocation b 1 imposes on this other dislocations which is the blue type of the dislocation. Since, b 2 is parallel to the dislocation line b 1 this intersection does not lead to any alteration in the this green dislocation line because the dislocation line vector b 2 is now dislocation burgers vector b 2 is now parallel to the dislocation line disc of the green dislocation. Therefore, this intersection does not alter the green dislocation anywhere.

But, since this b 1 vector is perpendicular to the dislocation line, blue dislocation line it is the jog as dislocation moves along its slip plane. So, first among this line considering is the edge interaction in which the green dislocation with b 1 vector traveling on the green slip plane is intersecting with the blue dislocation. That means, the blue dislocation line having a the blue vector b 2 drawn in blue color along the blue slip plane. This intersection leaves the b 1 dislocation or the dislocation b 1 burgers vector annulated while the dislocation which is blue in color has a job produce on its dislocation line. So, this is the important point to be noted when 1 2 edge dislocation line with the perpendicular vector intersect each other. So, you have one effected and another having a jog along the dislocation line length.

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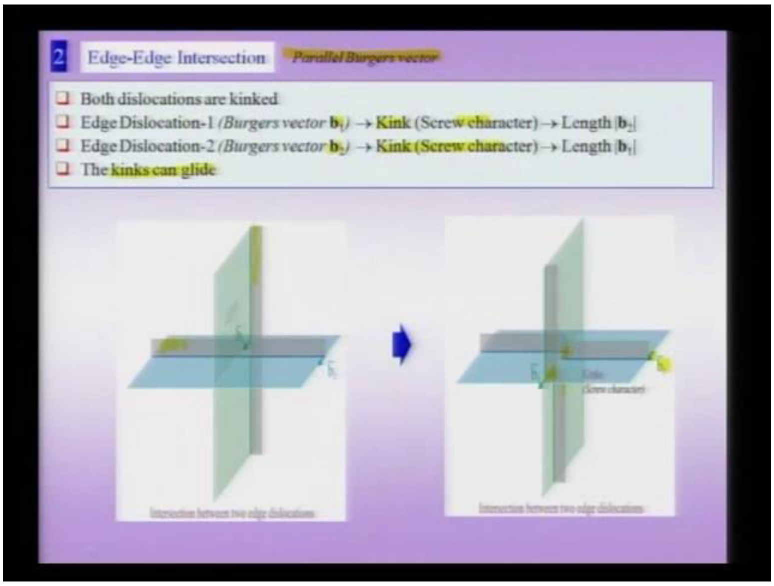

If I have two dislocation l interacting but, with parallel burger vector. So, in this case you can see their is 1 green dislocation and as usual the as you as before the extra half plane has been marked in grey and the blue dislocation, you can see that both the dislocation get kicked. So, the edge dislocation 1 which as the original burgers vector b 1 as a kink of screw character. So, b 1 dislocation develops this kink and this kink as the screw character because this kink is parallel to the vector b 1. Therefore, it is the case of screw character. The other dislocation which is my dislocation 2 with burgers vector b 2 which is now this burgers vector, also develops a kink. In other words, the green vector b 1 imposes itself on the blue vector, blue dislocation line and the b 2 impose itself on it the green dislocation laying on it.

And therefore, you have double kink formation and you can see that this kink is parallel to b 2, the green kink on the green line and the kink on the blue is parallel to b 1. And, this kink, the 2nd kink is also of screw character because now it is again parallel to the vector b 2. So, you have two kink being produce when a two edge dislocation intersect to each other and the both the kink of screw character and these kink can guide on their respective slip planes.

So, these are kink and therefore, the kind of hardening these gives during pasting deformation is less as compared to the kind of hardening which those kind of kink jog which cannot glide on the plane.

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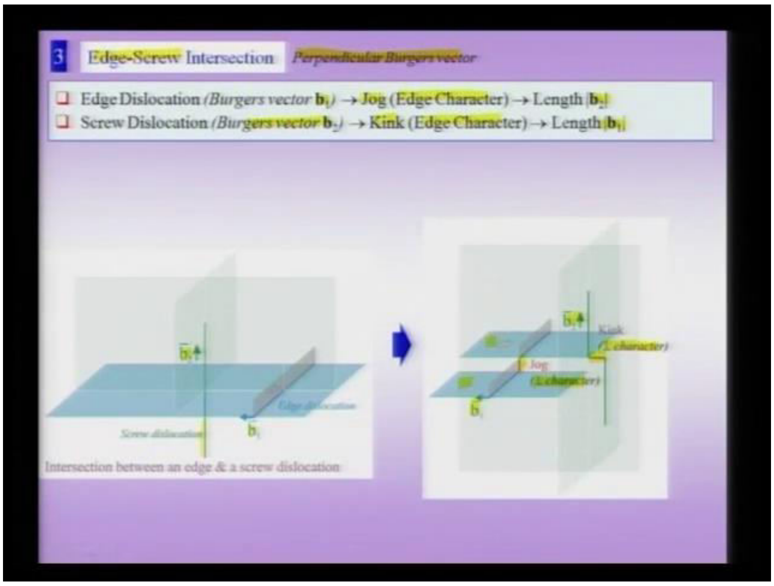

Now, next we consider has the edge screw interaction and in this case you have the screw dislocation in the which as the burgers vector b 1 b 2 and which has the dislocation line shown in green. The edge dislocation has the extra half plane shown in grey and has the burgers vector b 1. This is before the interaction and after the interaction you can see that the edge dislocation develops a the jog and this jog has edge character to it. And, this jog takes the edge dislocation from the one blue plane to the other blue plane and this screw dislocation develops a kink which is again of edge character.

So, this b 1 has been imposed on this b 1 length has been imposed on this screw dislocation. This b 2 length has been imposed on the edge dislocation therefore, you see that this small red segment is parallel to b 2 and this small maroon segment is parallel to b 1. So, each of the dislocation has been imposed itself on the other dislocation and the jog is and the edge both are of h character sorry, jog and the king both are on the edge character. Now, to summarize this dislocation reaction you have 2 edge 1 edge 1 screw dislocation interacting with each other. The burgers vector of these to perpendicular to each, the edge dislocation with the burger b 1 develops the jog of edge character and the length of the job is b 2. The screw dislocation with burgers vector b 2 develops a kink which is a edge character and the length of this kink is b 1.

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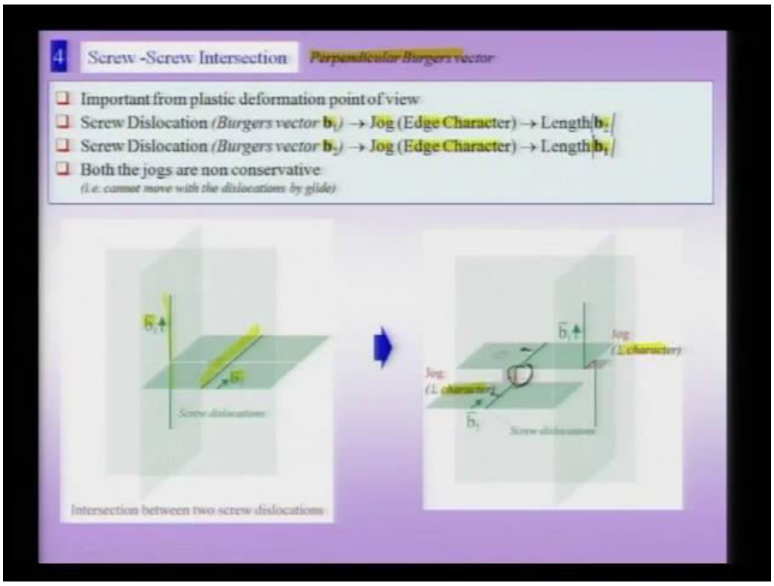

The 4th case is a screw interaction. In this case again I consider the case of the perpendicular of the burgers vector between the screw and two dislocation. And, this is the important kind of interaction from the plastic deformation on the point of view. Now, as before b 2 will impose in the b 1 dislocation line that is this dislocation line and b 1 will impose itself on the other b dislocation line. So, after the dislocation reaction you would notice that there is the jog on both the screw dislocation so and both this jogs have edge character. So, after the dislocation reaction is taken place so, there is this one screw dislocations with the edge segment in between which is the other screw dislocation which is small edge segment which is the jog in the screw dislocation.

So, to summarize this dislocation reaction screw dislocation 1 with the burger vector b 1 has the jog of edge character produce on it and the length of this jog is b 2. On the other screw dislocation 2 which is the burger vector b 2 there again the jog formed of h character and the length of this jog is b 1. So, I can may be wright it this way, this is the acutely the model of the so, I can make it write this way so, I can write this actually this mode as this way on this burgers vector.

Now, the important point to note is that both this jogs are non conservative that means, they cannot move along with the dislocation line. So, these two this segment angle most like the spinning segment in the dislocation line. These segments which are of screw character can glide freely while these segment which is of edge character cannot. So, this would be the mechanism by which the material harden. In other words, this dislocation reaction would produce non missile segment lying to the harness of the material that means, this location cannot freely on the slip plane.