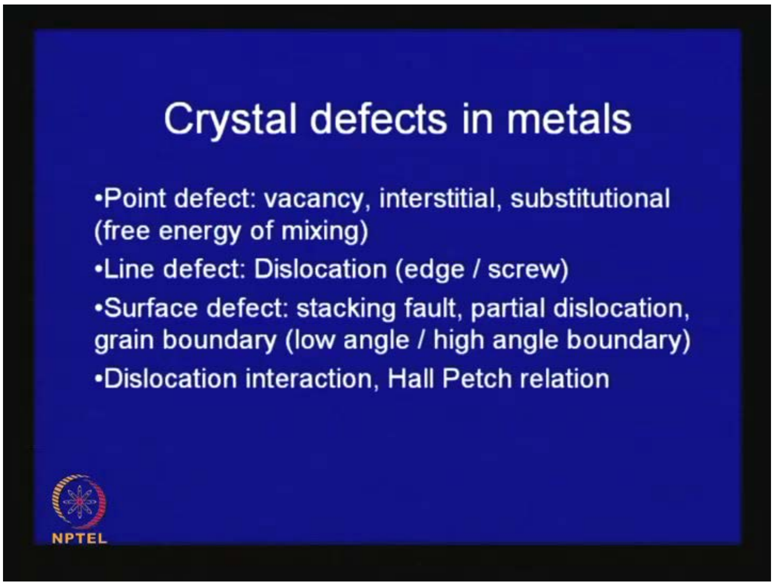
**Principles of Physical Metallurgy**

**Prof. R. N. Ghosh**
**Department of Metallurgical & Materials Engineering**
**Indian Institute of Technology, Kharagpur**

**Lecture No. # 13**

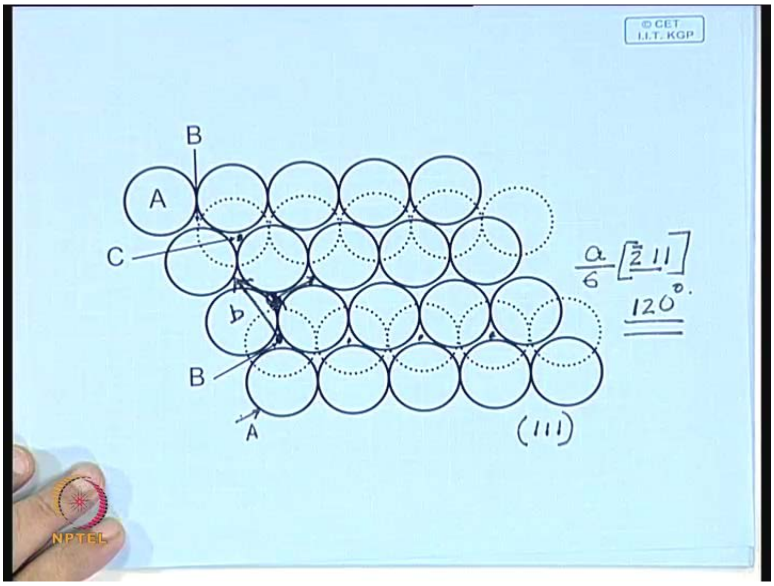
**Crystal Defects in Metals (Contd.)**

(Refer Slide Time: 00:26)




Good morning. We shall continue with our lecture on crystal defects in metals, and last class we introduced the concept of stacking fault. See, so far we have been talking about dislocations, which are perfect that means the burger vector is equal to I mean the burger vector has the least in particularly in face centered cubic crystal the burger vector of a perfect dislocation is a by 2 1 1 0 type. But we found out that energy of this type perfect dislocation is more than partial and we also showed you with the hard sphere model that it is much easier to move. As say I mean with the help of partial displacement or partial displacement vector.

(Refer Slide Time: 01:30)

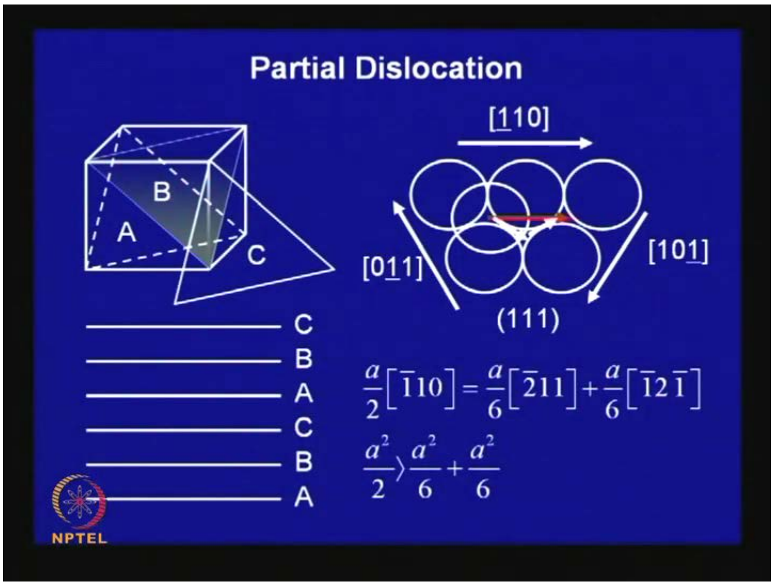



In fact what we said is in face centered cubic crystal the different layers are arranged in a fashion, which is shown over here, and if you consider the first layer as a layer A, say this layer is A and on the top of it we put another layer of similar hard sphere. So, these sites are called B; these sites are B sites. So, obviously what you find then when you place an atom on the B site part of this C is blocked. So, you cannot put on hard sphere over here, and so and if you have a situation like something like this, you have the next layer part of that next layer is occupying B position, and part is occupying C position.

Now, you see C position is like this next B position here is you have an atom here, now you cannot keep an atom here this is C. But you can keep an atom here so basically this is that perfect dislocation burger vector. So, what is happening is has if this movement here this atom has to go over this sphere part of this sphere whereas, instead of going like that if it moves through the valley, it is more energetically favorable. So, that means this perfect dislocation is split up into two partial, one like this, another from here to here like this and these are called partial dislocations and there burger vector is of the type a by 6 2 1 1 kind.

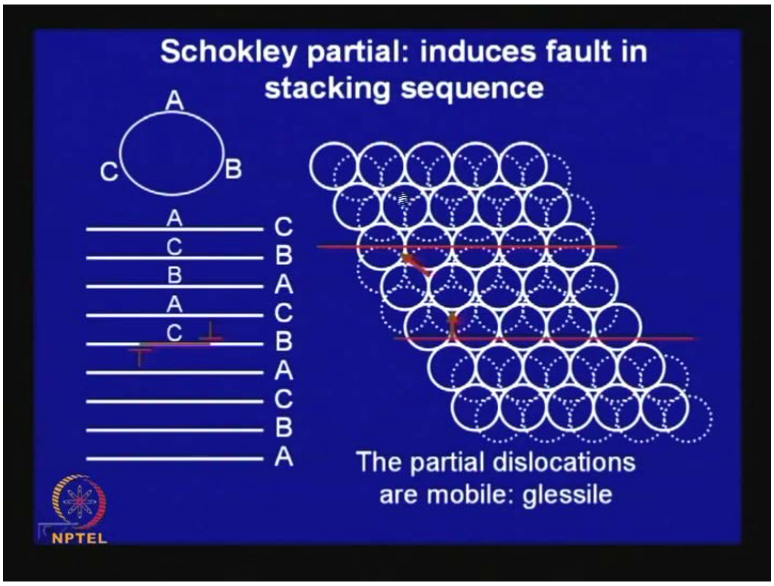
So, if this plane is 1 1 1 then the burger vector will be lie on the plane. So that conditions should be satisfied that is direction should lie on this plane and similarly, you can find out this burger vector you can find out this and you will find that angle between these two will be 120 degree. On this plane you can have three vectors of burger vector of these one this, this, other like this.

(Refer Slide Time: 04:14)




And same thing, which is shown over here and it was shown that if this perfect dislocation splits up into two partial, which is shown over here and then you calculate the energy, which is equal to square of the burger vector. So, in this perfect dislocation energy is a square over 2 and partial dislocation energy is a square over 6. So, two of this if you add up this a square over 3, which is less than a square over 2. Therefore, this is energetically favorable as well. Now what happens if such a partial dislocation exists in a face centered cubic structure. In a face centered cubic structure you can visualize that this 1 1 1 plane is the closed pack plane. So, this is 1 1 1, if we called this as layered A the layer on the top of it you can make it by joining this. So, this is this second layer we can call this layer is B and the third layer passes through this corner which is layer C and this sequence is repeated A B C A B C whereas, we recall it hexagonal the sequence is A B A B A B kind of thing or A C A C A C kind of thing.

(Refer Slide Time: 05:47)

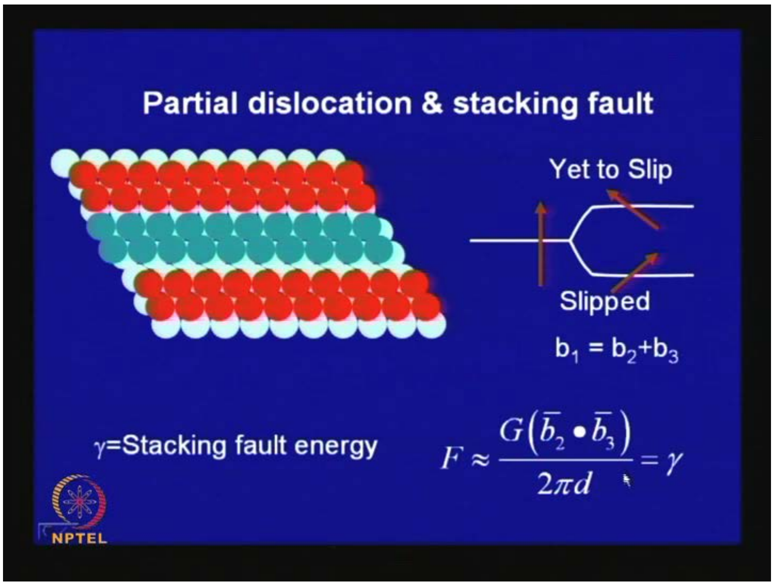



Now, here imagine that here a such a thing happen a part of number of atoms these two rows of atom. They have more through one partial vector burger vector which is shown over here, it has move from this point to this. So, that means this layer has now B has move to C so which is shown over here B has to move C. So, if it will be bounded a part of this has happens mean in this region. So it will be bounded by two dislocations, which is shown with the opposite sign that means this will not be exactly opposite. But the two burger vectors they will be suspending some angle and for simplicity we have represented it is an edge component.

Now, this is where this stacking sequence is disturbed what has happen is, you can see instead of that B layer moves to C and C layer will move A. So, this how it has changed now if this parts of the crystal it has undergone that kind of a partial movement displacement. So, this becomes C this is A, this is B, this is C. So that now look at this stacking sequence here it is A B C A B C. But look at a cross this is what you have C A C A, which is something like a part is repeating like a hexagonal stacking. So, this fault or the stacking sequence is called stacking fault and so that means we can consider that this fault to be a two dimensional defect.

So, around cross this area there is a fault stacking sequence and we call this stacking fault energy and this partial dislocation known as Shockley partial dislocation and Shockley generation of the Shockley partial induces a fault in stacking sequence. Now this stacking there is a fault there will be an energy associated with it so there is surface defect it has energy it something similar to surface tension. But this partial dislocations they are mobile, they can move on this glide plane, the glide plane is fixed.

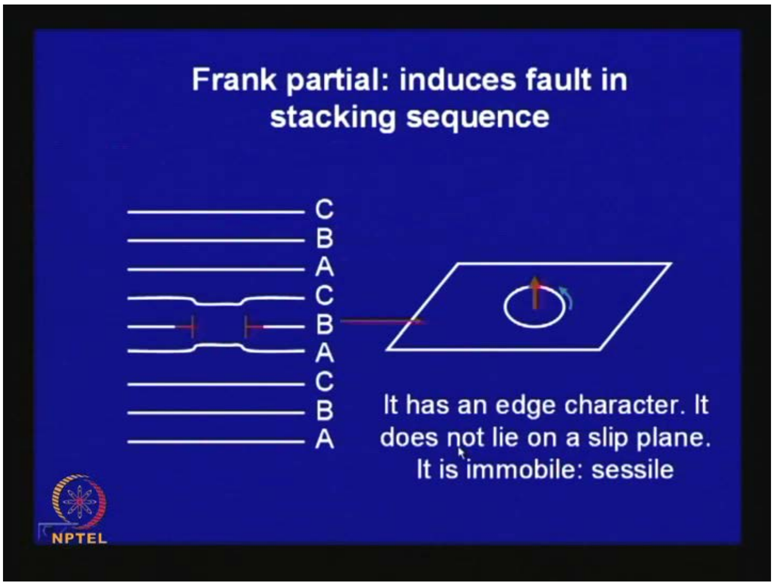
(Refer Slide Time: 08:43)




Now, this is a pictorial view of the same thing. Here this part where a stacking there is a stack stacking fault is been created over this zone. So, there is a partial dislocation here. There is a partial dislocation here, which is diagrammatically represented here. A part of its somewhere on this side the two join and this perfect dislocations. But here we have two partials, which are shown here. So, it means that this is yet to slip or here you know this side is slipped, this is has undergone partial slipping and this side is yet to slip because, dislocations we remember is that a boundary between the slipped and unslipped region.

This portion is slipped this is yet to slip whereas, over here there is a partials here and this is represented like and these two vectors, you know they are like this approximately what we can say there will be a repulse force acting between in that two and which can be calculated like this G b 2 dot b 3 over 2 pi d, where d is the distance between the two partial and this will be determine this distance will be determine by the magnitude of stacking fault energy. If the stacking fault energy is high this distance between the separation distances between the two partial will be low.

(Refer Slide Time: 10:32)



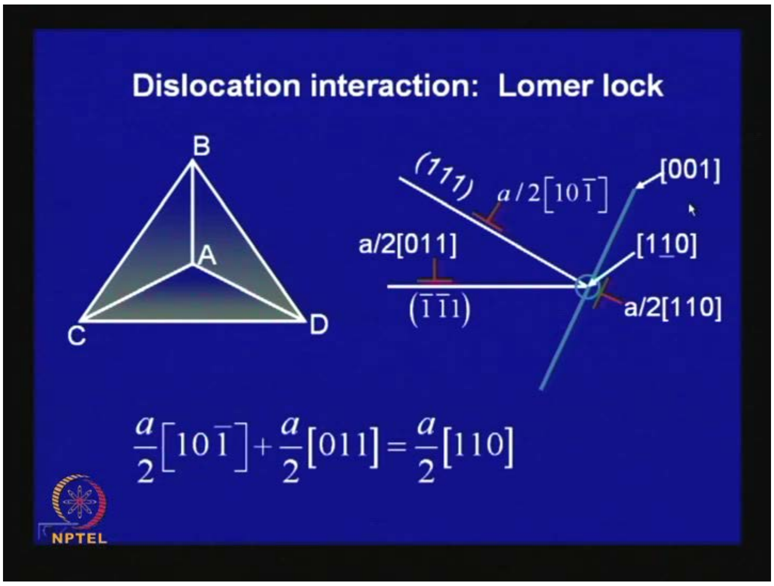

Now, Shockley type of partial can be created by through slip. There is another way the partial or stacking sequence can be disturbed in a face centered cubic crystal, which is shown over here. Say at any temperature you have some vacancy in the lattice. Suppose if some these vacancy if this concentration of vacancy is more than equilibrium, which can happen. If you suppose heat a piece metal to a high temperature and concentration of vacancy is a function of temperature and then if you quench then the suddenly that entire the total number of vacancy cannot eliminate itself.

So there is excess vacancy and this excess vacancy can condense or can accumulate in one of the slip plane and which is shown over here. If they accumulate on B plane over here. Here this as accumulated so there what you have because of the accumulation of vacancy excess vacancy, which are accumulated here. You have an edge dislocation created something like, which is shown why this involve and the burger vector of this is perpendicular to the plane and which is shown diagrammatically over here. This is one of the planes B and on the plane this is where the dislocations are this is vacancy have contains and quails and this has the direction this has sense which is marked over here.

This is positive sense and this is the burger vector. So it is this burger vector is perpendicular to the dislocation line at every point. So, this is type of dislocation is a pure edge dislocation and this pure edge dislocation it will and we know that edge dislocation can slip on only one plane that contains the dislocation as well as burger vector as well as the dislocation. So, here the plane is not a flat plane it is basically a cylindrical surface and cylindrical surface which is not necessarily a slip plane. Therefore, this type of dislocation is called frank this type dislocation is an immobile and that is called frank partial dislocation. Now why partial because if you calculate this vector, you know basically displacement.

You know on this side A layer you know this B has gone to C. So, this part has been moved over here or this has basically this distance by this displacement, you do not come to occupy that similar A side. So, basically we can calculate this burger vector, this burger vector will be direction is perpendicular to the closed pack plane closed pack plane, in this case is 1 1 1 and this burger vector is equal to a by 3 1 1 1, a by 3 1 1 1 and distance between two 1 1 1 are closed pack plane in face centered cubic crystal is equal to A over root 3, this distance is a over root 3 and this type of dislocation has been mention is immobile and we also this dislocation terminology is use this sessile. While Shockley dislocation partial is sessile can glide it is sessile and this cannot move this is sessile.

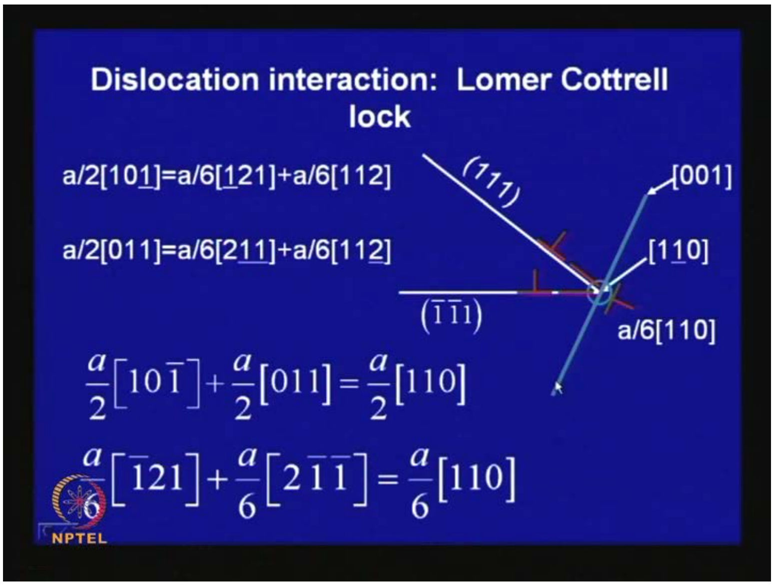
(Refer Slide Time: 14:49)




Now, let us revise it that Lomer lock and in terms of what happens this Lomer lock. We considered formation of the Lomer lock, when two dislocations moving on intersecting slip plane, if they joined together along the line of the intersection. In that case a certain type of dislocation reaction can take place, which is shown over here and this is also and this is accompanied by reduction in energy. Because, here this burger vector square it is a square over 2, this is also a square over 2 if you add that two it is a square, whereas the product dislocation energy is a square over 2. Therefore, this is energetically favorable and look at this is line along that line of an intersection, so that means it is basically it is line along the intersection and its burger vector is a by 2 1 1 0.

Calculate this line of intersection and the line of intersection is 1 1 bar intersection line of intersection with 1 1 1 with 1 bar 1 bar 1 is 1 1 bar one. Therefore, character of this dislocation is edge dislocation edge character and it can move on a slip plane you can calculate this slip plane which comes out to be 0 0 1. So, a dislocation slip plane is this, which is not a normal slip plane in a face centered cubic crystal therefore, this dislocation is immobile. Now, what happens if the crystal has the low stacking fault energy? So instead of this perfect dislocation it will be made up of two partials.

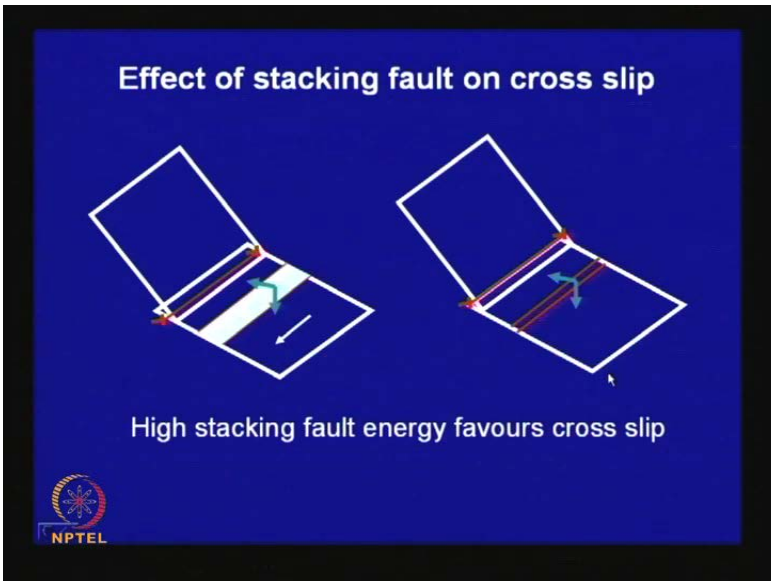
(Refer Slide Time: 16:54)




So in that case, this is shown over here. They are made up of two partial and the leading partial when they interact, which is shown here. The leading partial when the interaction you get another partial dislocation, which is a by 6 1 1 0. The character is still same the edge character you can show. But look at that energy this is also energetically favorable. It accompanied by substantial reduction in energy and this type of lock is associated with the stacking fault lying on here as well as here. So what happens when this type of lock formed? It will (( )) further movements of dislocation on this plane say if another dislocation is generated.

Somehow on this plane at this trying moving to this dislocation and will try to repel. If this effects similar character it will try to repel that. Similarly, a dislocation moving on this will repel by this. So that means when ever this type of lock is generated in the crystal it makes dislocation movement difficult or it makes the material stronger. We call this in technical term the material undergoes strain hardening.

(Refer Slide Time: 18:24)

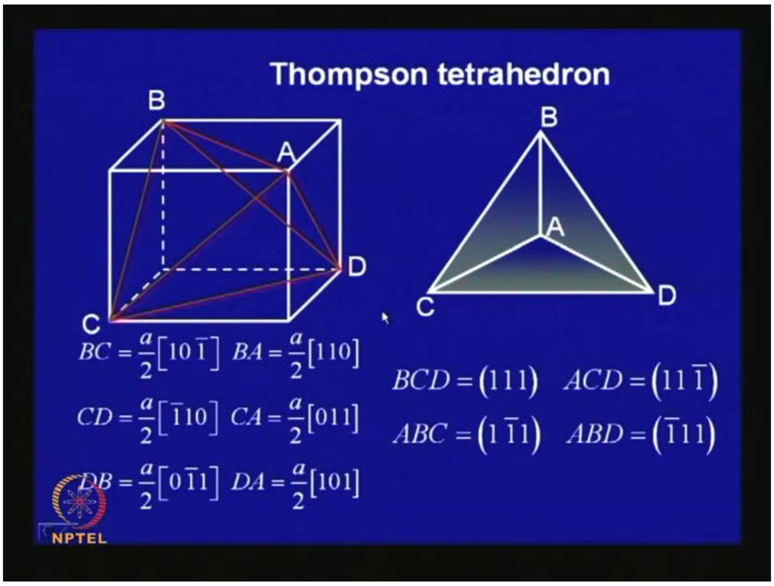



Let us look at; what is the effect of stacking fault on cross slip plane? Take up a two case these are two intersecting slip plane. Let us say and here on this plane somewhere here down this plane, somewhere here there is a dislocation barrier something like. Let us say a Lomer lock is there and whenever let us consider these two partial dislocations, which is separated by a faulted region and character of this dislocation had it been perfect. So this is the burger vector of the perfect dislocation, where ever where as the burger vector of this partial is shown over here, this and the two resultant of two is parallel to the dislocation direction.

Now, here when it is moving it comes out the cross this dislocation barrier it cannot continue its movement along this direction on this plane. So, what is the alternative? Alternative means they may be another slip plane, which intersect this slip plane somewhere here. It can possibly cross slip on to this. But only screw dislocation can cross slip and for that to happen you have to apply a stress high enough. So, that this two partial joint together become a perfect dislocation lying along this line along this line and when this becomes a perfect dislocation this can cross slip on to another the cross slip plane.

So, effect of stacking fault energy on cross slip is if this stacking fault energy is a low the dislocations are separated by a large distance, you have to do additional work to join the dislocation together and in other extreme case if this stacking fault energy is high in that case something situation is something like this. So here the work to be done to join the two dislocations will be less. Therefore, what we can say that whenever the material where this stacking fault energy is low, there cross slip is more favorable. The deformation by cross slip you can say this keeps an additional mode of the dislocation movement or you can say this contributes to strain softening whereas, formation of lock contributes to strain hardening.

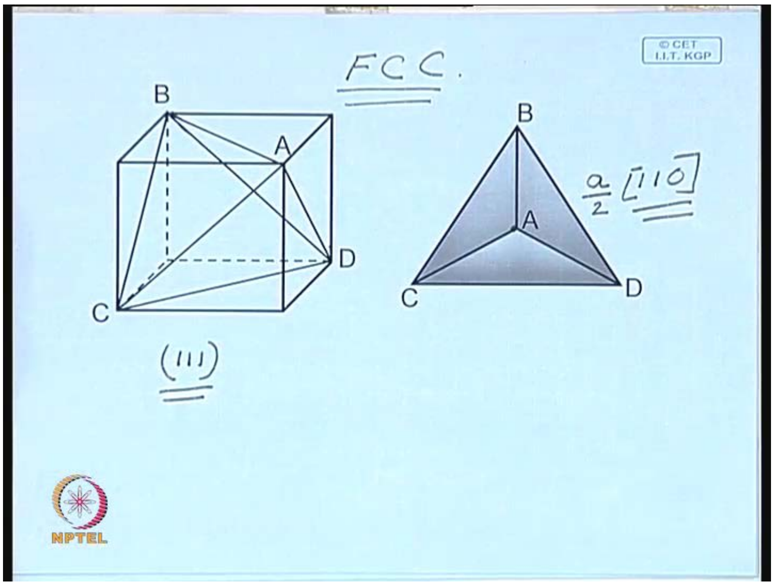
(Refer Slide Time: 21:25)




Now, we have just seen how when one dislocation meets with another they interact with each other, and there are very large numbers of such interactions are possible. We look that few of these, we looked at formation of Lomer lock, and when these Lomer locks are associated with stacking fault, this lock is much more stable and this type of lock as known as Cottrell Lomer lock. So this is one kind of interaction. We also looked at in interaction when a dislocation is moving on a particular plane, and it intersects the dislocations which are perpendicular to the plane, and in that case what we have is the interaction is far as dislocation.

So, in that case it forms jogs and or steps in the dislocation line, it can form jog and kink while kink can glide but  jogs cannot glide and if this jog will exert a registering force of the dislocation location. So, formation of jog also leads to strain hardening makes a difficult for the dislocation to move but  formation of Lomer locks will contributes, its contribution to strain hardening will even be more and that will be many such possible interactions and these interaction can be very easily visualize.

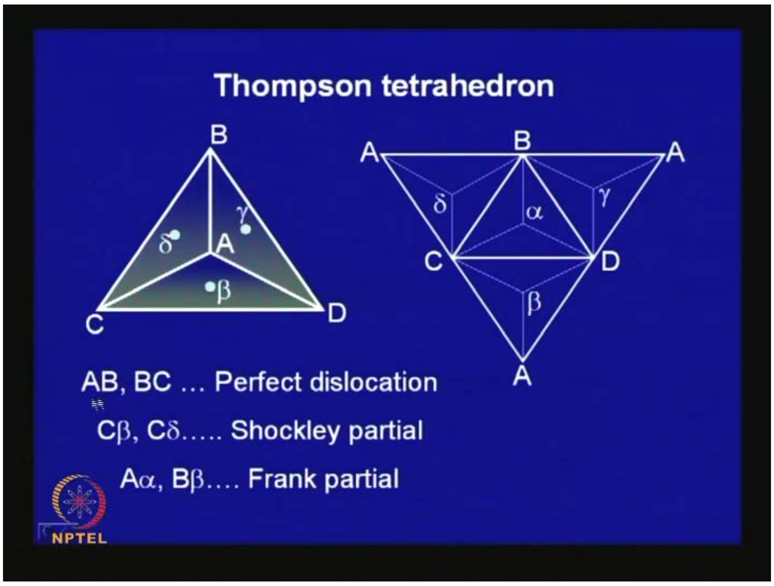
(Refer Slide Time: 23:02)




If we consider, as say geometric construction something which is shown over here. So this is we consider these interactions primarily only for face centered cubic structure. In a face centered cubic structure, this is you can say imagine, this is a crystal, it is a cube single crystal and look at how these 1 1 1 planes are meet. This is 1 1 1 plane, this is another 1 1 1 plane, this is another 1 1 1 plane and this is the fourth and this four slip planes 1 1 1 type slip planes they make one tetrahedron, which is shown over here and they are designated this vertex of tetrahedron as designated as A B C D.

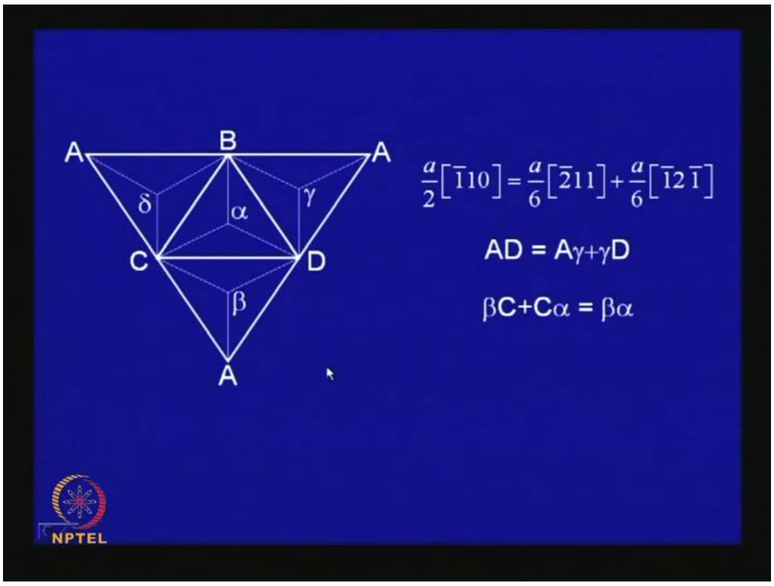
Now, here each of this side represent a perfect you can say the dislocation of a burger vector of type 1 1 0. This direction as represented by this is 1 1 0. So, each of this edge are like that and it is possible to find out or write down this induces of each of this plane and direction and you can try it yourself but  in this slide it is shown over here. This vectorically what are the magnitudes like B C is A over 2 1 0 1 bar and these planes induces will be different and these planes is subtend an angle between them. You can calculate the angle between these 2 1 1 1 plane and this angle it is easy to calculate this angle will be close to around 55 degree.

(Refer Slide Time: 25:11)



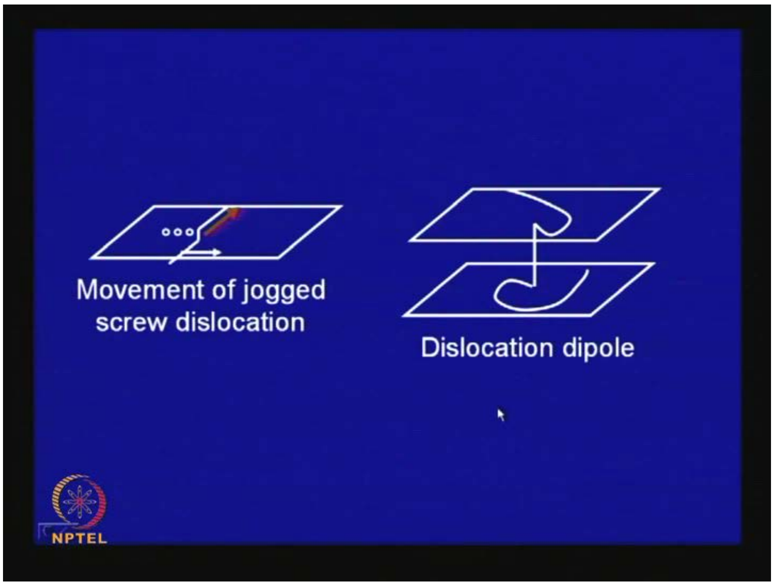

Different types of dislocations can be represented in terms of the tetrahedron, which is called Thompson tetrahedron. Like this perfect dislocations these edges of the tetrahedron they represent perfect dislocation burger vector of the perfect dislocation. Now, a perfect dislocation on a slip plane breaks down into disassociates into two partials like B delta, delta C. So, these are known as Shockley partial and where as you think about frank partials. Frank partial dislocation burger vector is perpendicular to the 1 1 1 plane and you can imagine you can draw a perpendicular say from C vertex C to the plane C, which is just opposite facing C. So, that means it is lying on this particular point here. So, these are called frank partials. Now it is much easier to write down different and visualize the dislocation interactions using this type of representation.

(Refer Slide Time: 26:33)




So, one of these it is quit easy say this is a look at this dislocation moving in one of these plane. Say suppose A D so A D is breaks into two partial D gamma gamma A or gammaf D or A gamma gamma D A gamma gamma D. These are the partial and imagine another which is on this plane C beta C beta and C alpha C beta C alpha. So, C beta C alpha and here it is basically if you look at say similar another intersecting plane and then they can interact and get this kind of dislocation B beta alpha and these are perpendicular to the edge beta alpha is perpendicular to C D.

(Refer Slide Time: 28:09)

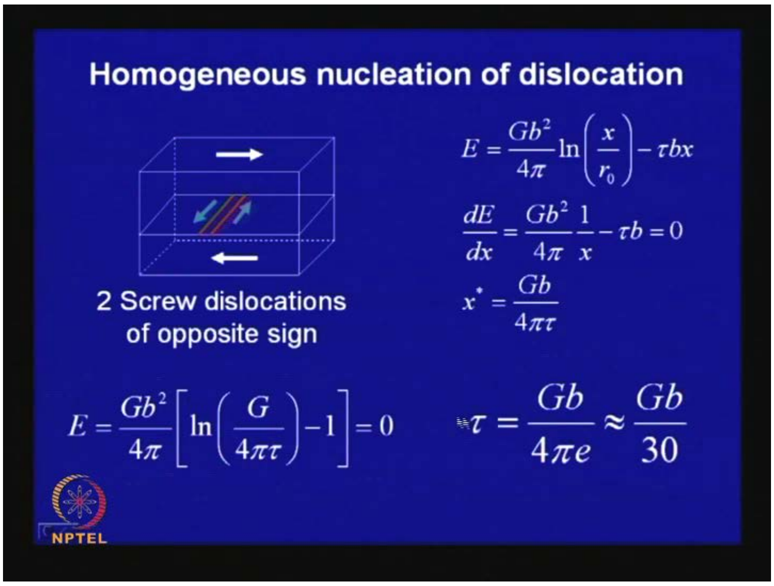


So, this is the way you can visualize this dislocation to interact. Now we also mention that the dislocation when they are moving on a slip plane, they will interact with dislocations which are threading. Say suppose a dislocation moving on this slip plane is intersecting with this dislocation, which is threading through the plane. In that case a step is created which is shown here and one of these steps say suppose one of this dislocation is a screw dislocation and this step this is a jog, which is come out of this slip plane. So this character is a burger vector and this dislocation moving along this and this burger vector of this dislocation.

So this component is the edge component. So if this screw dislocation continuous to move along this slip plane, it will leave behind it has to it has to drag the jog. If it drags the jog along with it, it will leave behind a trail of vacancies, which is shown over here and this vacancy will exert a force on this dislocation and which will lead to strain hardening. But they can be extreme other cases this jog you know this length of the jog is very large. In that case these two ends of the dislocation they are other free to move, which is shown here. In that case it forms a dislocation dipole and this is the one way of increasing the dislocation length you look at substantial through the movement of dislocation, how the dislocation length has been increased and we will see shortly that increasing length of the dislocation means also means that the strength of the dislocation goes up, it will lead to strain hardening.

So dislocation has we have seen say if you have a perfect crystal, then the crystal is very strong suppose to be very strong. But presence of dislocation makes it weaker and makes it mean able to plastic deformation. But if you continue to compete and generate more and more dislocation. Within the crystal again the crystal becomes hard. So, dislocation can be explained both can explain why real crystals the yield strength of the real crystal is low and why when it when we deform it as the number of dislocation density increases. There will be lot of dislocation dislocation interaction and which will make it strong.

(Refer Slide Time: 30:57)



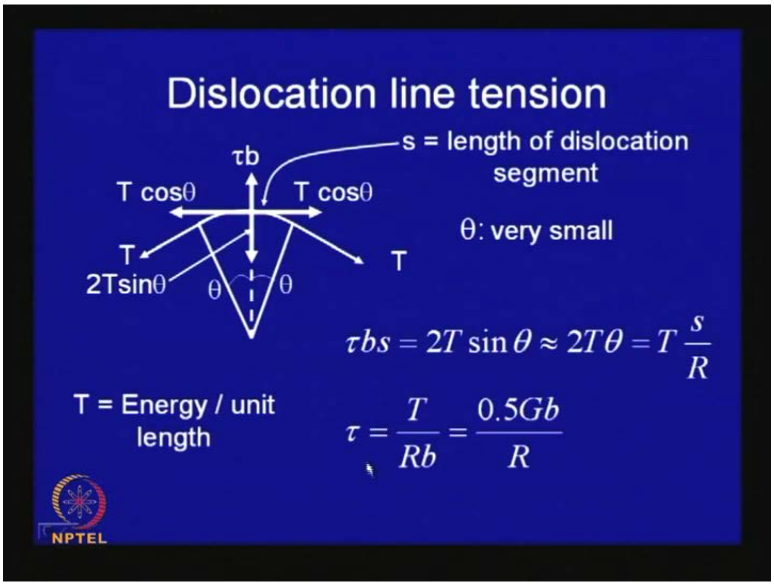

Now, let us see that if the crystal is perfect how dislocations are generated within the crystal. Say suppose if you imagine this is a perfect crystal there was no dislocation and to generate dislocation, you will apply shear stress which is shown and now with the application of the shear stress, imagine that two screw dislocations of opposite sense. So, this is the positive direction here, this is the positive direction for the other one and so this type of two edge screw dislocations are created and this separated by this small distance x. In that case, what is the energy of this type of configuration? Now, we know the energy of a dislocation that is equal to G b square over 4 pi l n x over r naught.

So what we imagine that dislocation when it is created separated by a distance. So, then x and r zero is the core dislocation core, we can assume that this dislocation course size is the order of burger vector b. So, this is the energy elastic stored energy of the dislocation. Now, subtract which is done work done to separate to create dislocation. So, tau is the force and you need to move the dislocation by a distance then the force on the dislocation is tau b and you are moving the dislocation by distance x. So, this is the work done, so this is the total work done.

Now if you differentiate and find out what is that maximum energy, which has to be supplied to create this spear of screw dislocation of opposite sign? So, you differentiate this and then we can say that to find out its maximum value at what separation distance the magnitude of this energy is maximum. It differentiated equate it zero then you will find with algebraic simplification you will find the critical distance of separation is equal to G b over 4 tau. You substitute this back into this equation you get this and now for spontaneous generation of dislocation, we can say that for this process to be spontaneous this energy ratio should be very low are approach or becomes zero.

If you put this condition and that case this is l n G or you can say G over 4 pi tau will be equal to e and therefore, tau is given by this and approximately you can say that shear stress needed for homogeneous nucleation of dislocation is of the order of G b over 30. So, which is very high therefore, to generate dislocations, this is not possible. I mean if the material is perfect this cannot it is impossible, you can say this also says that a perfect crystal will be very difficult to deform, because to create a dislocation there you need to apply very high shear stress. So since homogeneous nucleation of dislocation is impossible, then what are the dislocation sources in a real crystal?

(Refer Slide Time: 34:54)



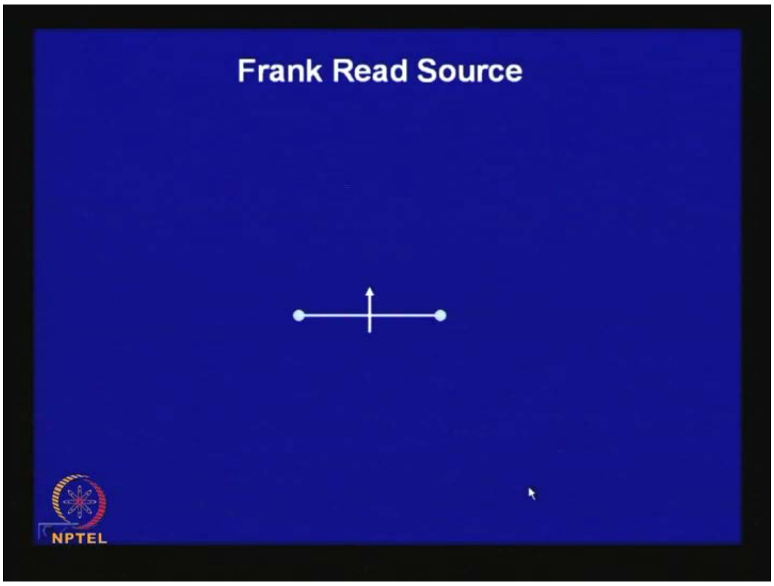

Now, one source which is shown which we will talk about this is because say suppose this dislocations not necessarily straight and the dislocation lines may be curved and this extend of curvature will depend on the magnitude of the stress that you applied and it is possible to drive an expression relationship between the line tension or between the applied shear stress and the radius of curvature of the dislocations and which is shown over here. We know the dislocation has an energy associated with energy; we can visualize this to be you can say as a vibrating spring kind of thing.

If you have elastic string you are pulling it you can visualize dislocation to be a similar line, a line on which you are applying a tension. Now you if you apply a stress on the say suppose this is a string and you are applying a stress then this will try to bend like this something similar is happening which is shown over here. This is the dislocation line and we can say that along the line there is a tension line tension acting on it and this is the stress, which has been applied to the dislocation. So, this is the force which is trying to bend the dislocation and when the dislocation bends its length increases and since it has a line tension it will try would have a natural tendency to shorten itself.

So there will be a restoring force acting on it, which is shown here. If this is the tension and you this is along this is the tension you draw a perpendicular a perpendicular here you can say this is the centered of the curved dislocation and this angle is theta and if this radius of curvature is large. We can say this angle is very small and this component is horizontal component is equal to T cos theta. So, you have horizontal component acting in this direction you have an horizontal component acting in this direction and both will cancelled out there equal and opposite they will cancel out. So, net force on the curved dislocation, because of line tension will be along this and this magnitude is equal to twice sin theta and if theta is small, we can say this will be sin theta is equal to theta.

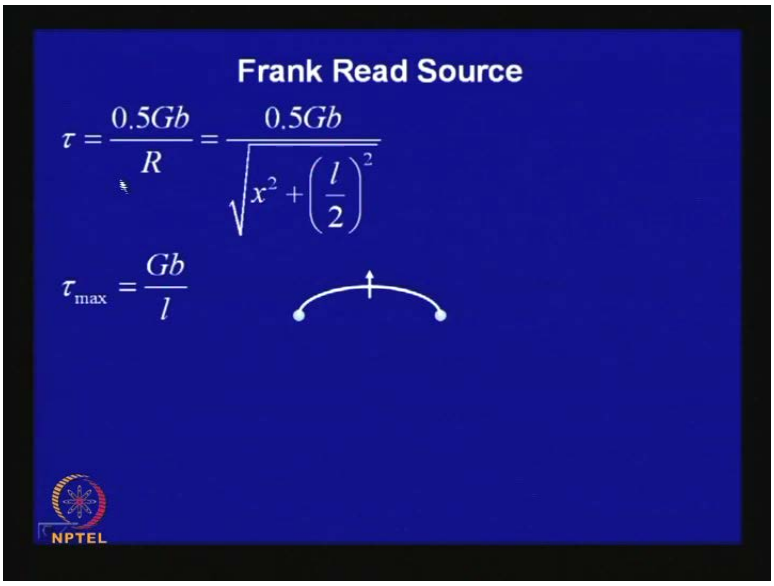
Therefore, this restoring force is equal to 2 T theta whereas, the applied force is this and now let us look at it here this length segment of this is s. Now, what you see here is the force acting on this dislocation segment is tau b; this is the force per unit length times dislocation segment length. This is the total force acting on the dislocation and this is the restoring force equate that two, you can say equate that two and remembering that theta is very small this can be represented as s over R. So, basically this s cancels out, so what you have is approximately it comes out to be T over R b, R is the radius of the curvature of the dislocation. The shear stress comes out of this magnitude and we know that line tension is approximately for dislocation is equal to 0.5 G b square. So, what we can say the tau is equal to half G b over R.

(Refer Slide Time: 39:32)




Now, consider a case like this. You have a dislocations segment, which are print here. So this point cannot move and you have applied a stress.

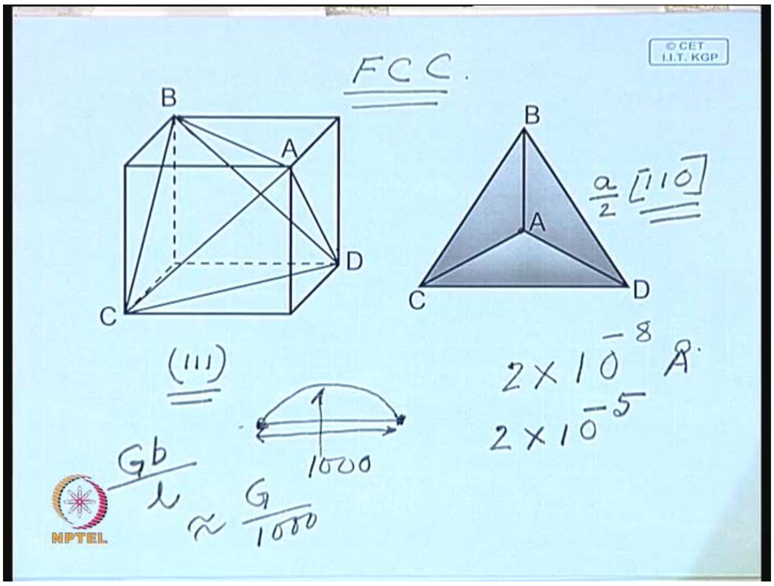
(Refer Slide Time: 39:46)




Now, here if it bends like this. Then this tau the applied stress can be written as 0.5 G b over R and this R you can say that center of curvature, the center of this curved dislocation lies somewhere here and distance of the center form this line is x. If it is shown then this R will be x square plus half l square root over. Now, you think about say so that means this applied shear stress is a function of this distance of the center of this curvature curved dislocation line from this linear segment from these two points.

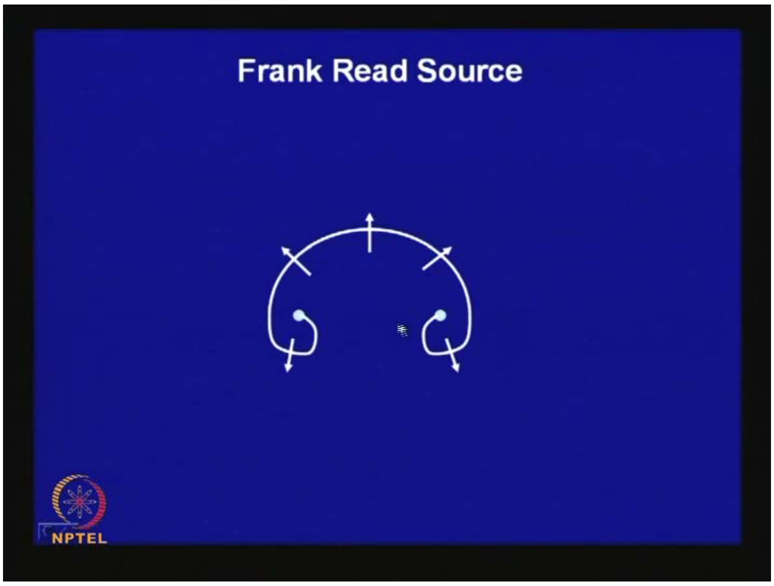
Now what is the maximum value tau, when will this tau will be maximum. Obviously, when this denominator is minimum and denominator is minimum when x is zero that means center lies in between the two these two points. So, in that case what we can say the tau max value G b over l. Now, considering that burger vector this of the order of atomic spacing say b is of order of the atomic spacing.

(Refer Slide Time: 41:34)



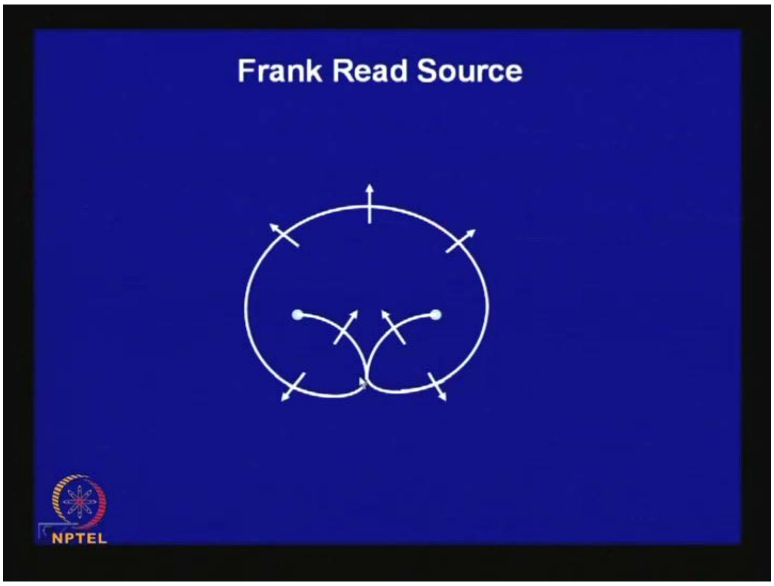

Say may be it is 2 into 10 times from 2 into 10 to the power of minus 8 Armstrong and let us say this spacing is of the order of 100 atomic spacing. So, basically let us say 100 or 1000 that atomic spacing, so in that case what is this so this is 2 into 10 to the power minus 5. So, G b over l so this is the order of G over 1000. So, by this so that means if this is small, then this strength of the crystal you can say that increase if these dislocation segment is large, then it dislocation can be generated easily and which is shown over here. So, when you reach this stage in that case you reach a stage of instability after that in a little expansion.

(Refer Slide Time: 43:01)



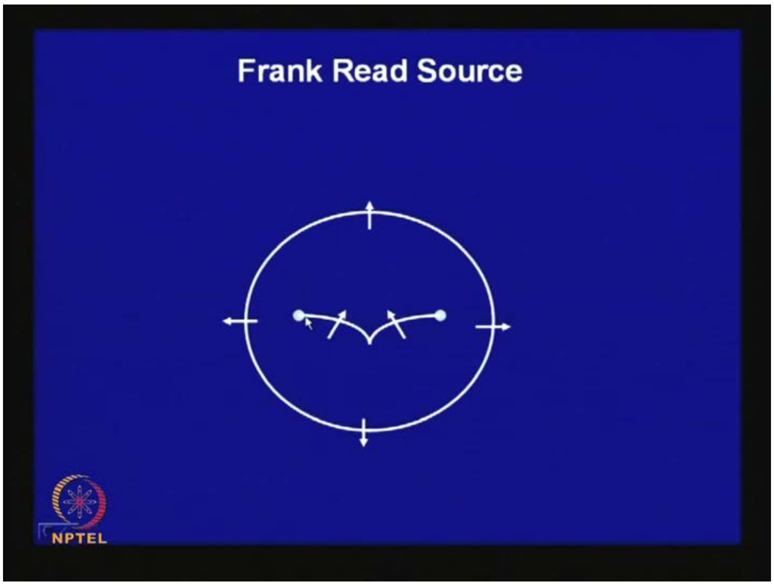

You know will form a configuration like this. Now if you look at the character this and this they have character of one is the positive screw dislocation and another is negative screw dislocations. So they will have a force of attraction.

(Refer Slide Time: 43:19)



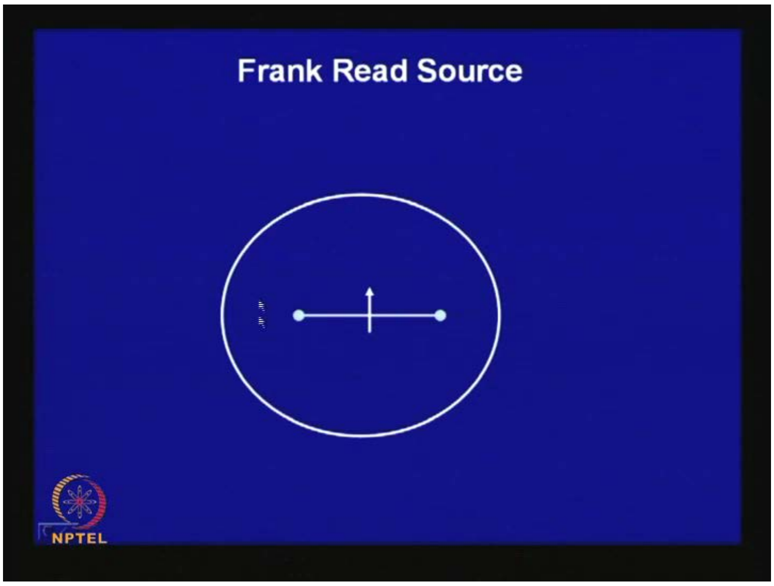

So, ultimately they will join together and annihilate it.

(Refer Slide Time: 43:23)



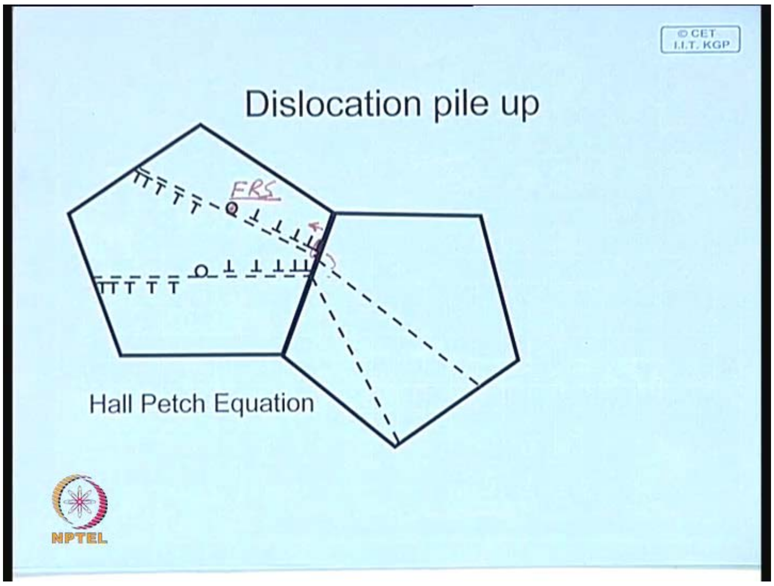

And in the process, what you will be left with you know segment like this and it will try to reduce its length.

(Refer Slide Time: 43:32)




So, finally it will come back its original configuration and it will be left with a ring of dislocation. So, this type of source is a regenerative type generates a look dislocation loop come back to its original position with application of further stress, it will generate another loop. So, in this way on the dislocation on that particular slip plane a series of dislocation can be generated and this type of regenerative dislocation source is known as frank read source.

(Refer Slide Time: 44:34)

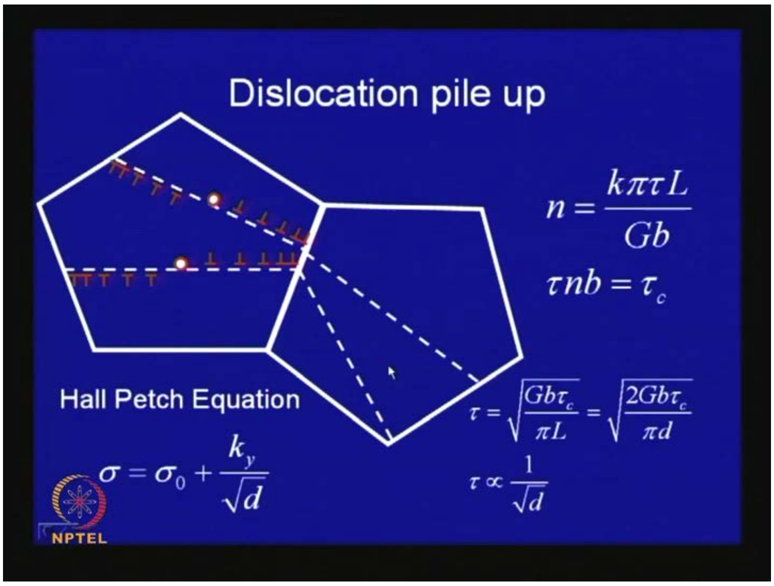



Therefore, now what happens if this type of dislocation source is operating, they are acting on a particular plane and several of these dislocations are generated. So, in that case what you will have is it you will generate a set of pile up, which is shown something situation is something similar over here which is shown. So, here is a frank read source you have a frank read source here it is generating at dislocation. Now it generates a loop so one side we have given a positive, another opposite we have given a negative sign and this dislocation moves until it meets an obstacle. Suppose the first dislocation which meets an obstacle which is a grain boundary here.

So, it stops it cannot across this barrier this dislocation boundary this grain boundary is dislocation barrier, it cannot cross this. Imagine that it cannot this then what will happen the second dislocation, which is generated which will come close it. But it will receive there will be an opposing force act on it, which will not allow the dislocation to come close to it. So in this way said series of dislocation will pile up on the slip plane, which is shown over here and when a pile up formation takes place it will result in significant strain hardening. Now the question comes up, how many dislocation can you pile up, can get piled up within a grain or within this particular on this slip plane.

Now in a particular grain they will multiple such slip planes and which is shown over here. This is another slip plane. So here also a pile up as formed. Now the question is how this can pile up you know can this pile up is it stable or it can cross the dislocation boundary as well. Now what will happen this pile up them dislocation at the head of this pile up will be subjected to a sufficiently larger stress. It is possible we will to calculate and when this stress becomes large enough, it can initiate another dislocation source operating here on or else it can be create a step in the can move into and generate a dislocation on this particular slip plane on the neighboring boundary.

(Refer Slide Time: 47:02)




And when can this happen it is possible to calculate this using that dislocation stress field and we know that when you apply a shear stress on the material, that the force that is acting on the dislocation. This is equal to tau b. Now imagine this dislocation pile up, which is made up of end dislocations, so we can say as if this is made up this is a super dislocation with the burger vector n b. So, force acting on it is tau n b. So, this you can see that force at the head of the pile up dislocation and the head of the pile up the force acting on this particular dislocation is many times magnified.

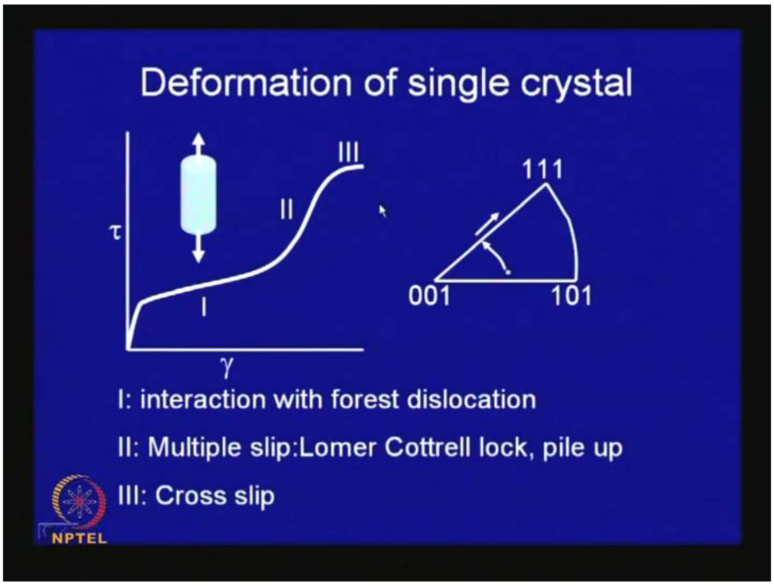
So, if there are five dislocations in the pile up this will be five times the force that is applied on a single dislocation. Now grain boundaries we can say sign the strength to the grain boundary, this is the critical stress which has to be exceeded. So that a dislocation is generated on this slip plane on this neighboring plane and the forces of the deformation can continue. Now the question comes up, how many dislocations can you pile up with in a grain? This will obviously be determine by the grain size and the number of dislocation that you can produce or say length of this dislocation pile up.

There is relationship between the length of the dislocation pile up and the number of dislocations and which is shown over here. It is possible to calculate that using the concepts, which has already been explain but  we will not go into detail of it look at this nature. This is this is factor which depends on the nature of the dislocation whether it is a mixed dislocation or is a perfect screw or perfect edge. We can take that assume that k to be 1 approximately we can take k to be 1 and in that case you see that length of this dislocation pile up is L. So, this is the length which we can say approximately is half of the grain diameter half of this grain diameter and you can substitute this n over here, which is done over here and if you take that grain diameter the d over 2 is equal to l.

Then it is clearly, it is seen that the shear stress tau which is needed for to excite dislocation source on the neighboring grain. It is inversely propositional to root over the grain diameter and this is the famous the hall pitch equation. Now, so mind you apart from this is the grain size effect apart from this there will be the normal fiction stress. Say, it is tau zero this tau will be equal to tau zero plus a constant of a proportionality k over root d and which is shown over here.

So in terms of this tensile stress we can say that the strength of a poly crystal material will be given by this type of equation. This is the friction due to the friction stress this sigma zero and this is the contribution of grain size or grain size effect on strengthening, this is k y over root d and this equation is known as hall pitch equation. So, that means what it say is if the grains are finer the strength of the crystal or strength of the material will be higher. So, this is an important mechanism of increasing the strength of the material, if you want stronger material you make it the grain size finer.

(Refer Slide Time: 51:30)




Now, with this now we are in a position to go back and analyze look at or find out the mechanism of deformation of single crystal. We recollect that this single crystal behavior or stress strength behavior of its deformation of a single crystal is shown by resolves shear stress strain diagram and if you recall there are three testing stages. Stage one, where there is very little strain hardening. Now this is a single crystal say suppose an orientation is somewhere here. Now there will be a stage when the dislocation can move only on one slip plane. So which is shown here in this as long as this orientation is within a triangle, it will move it will have can slip only on one slip system. So until it reaches this point it will be moving in one slip system.

So that is the time only mechanism of strain hardening will be interaction with forest dislocation. So that is why here the strain hardening is less. Now when the orientation reaches here you have multiple slip taking place and when slip takes place on more than one slip system, then the dislocation moving on one plane will interact with another moving on dislocation on a another. It will form Lomer Cottrell lock and there will be large strain hardening. It will also land to formation of dislocation pile up. Because it is quite likely the dislocation moving on one slip plane will reach the boundary, which is a barrier or will reach Cottrell Lomer lock. That is a barrier further movement is prevented.

So, this is the situation therefore, that is why this is where you have severe strain hardening and the main mechanism of strain hardening is formation of dislocation locks like Lomer Cottrell lock and dislocation pile up. Now finally, it is a quit possible that you as you go on increasing shear stress, so you will also reach a case say where say many of the dislocations, they may have split into partial and when the shear stress becomes large enough some of these partials, they can come together and they can join at form a perfect dislocation and if this dislocation has a screw character. It can cross slip to another plane.

So and when this mode becomes operative that cross slip then there is some amount strain softening that is stage three. So with this concept idea about that dislocation movement that resistive forces that dislocation experiences when it moves through the lattice. Say it is it experiences resistive source resistive force because of periodicity of these atomic arrangement, which is say you can say it is a friction stress apart from that it will also experience registering force. Because of other dislocations, which are present in the crystal and they can interact dislocations moving in different plane.

They can interact form different types of locks, which prevent further movement of the dislocations and this dislocation movement is also control by formation of surface defect like stacking faults and which make a which also contributes to the strain hardening and it can also depending on the magnitude of stacking fault energy and the applied stress. If a perfect dislocation this stacking fault disappears then the cross slip becomes possible and which can lead to strain softening. So this is how it is possible to explain the mechanism of the perfect a mechanism of deformations of face centered cubic crystals and different deformation in other crystals, also can be tell in the same fashion.

But, I think it will be in that case that will be going into too much deep details and this is beyond in the course I thing of introductory course on physical metallurgy. But principles exactly the same and next class we will look at a little beyond is we will also see the dislocations. So far we are taking it from granted is this is the defect, which is there in the crystal, but are they there are there any experimental evidence.

And can we calculate that what the number of dislocations which are present in the crystal, can we see the dislocations, and also we will look at certain specific dislocations arrangements, which will simulate a grain boundary. And we will also look at the nature of grain boundary or the grain boundary, we have refer to number of times that is also a surface defect. But there are some low angle dislocations boundaries can explain, and give some idea about order of grain boundary energy, but still it is still now exactly nature of the grain boundary still not known. But the concept of dislocation helps us to understand the nature of dislocation boundary, and we will take this up the next class. Thank you.