Introduction to crystal elasticity and crystal plasticity

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Week-06
Lecture-11

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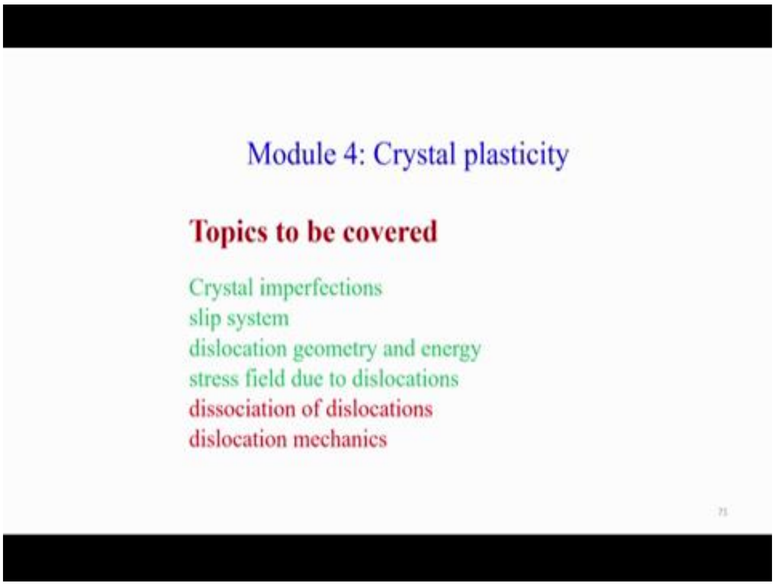

Module 4: Crystal plasticity

Topics to be covered

Crystal imperfections
slip system
dislocation geometry and energy
stress field due to dislocations
dissociation of dislocations
dislocation mechanics

So far we have discussed dislocation geometry and stress feel around the dislocation, in our last class. Now we will try further explain the next step how to dissociate the dislocation or how dislocation reaction happens so that two dislocation can react with each other and making some new dislocation and what are the typical dislocation mechanics generally we observe and how we can explain that the different uhh phenomena by the using the concept of the dislocation. So to do that we will just uhh forward to these things and we will discuss with the dissociation or combination of the dislocation.

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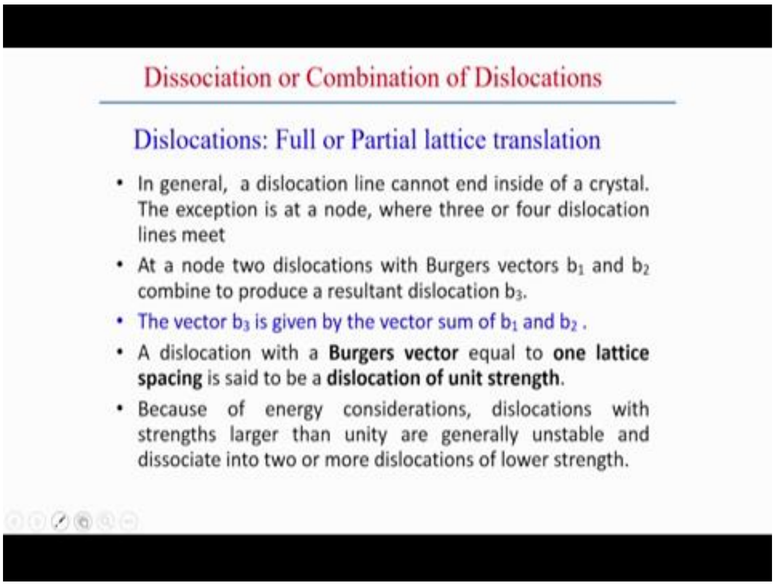

Dissociation or Combination of Dislocations

Dislocations: Full or Partial lattice translation

- In general, a dislocation line cannot end inside of a crystal. The exception is at a node, where three or four dislocation lines meet
- At a node two dislocations with Burgers vectors b_1 and b_2 combine to produce a resultant dislocation b_3.
- The vector b_3 is given by the vector sum of b_1 and b_2 .
- A dislocation with a **Burgers vector** equal to **one lattice spacing** is said to be a **dislocation of unit strength**.
- Because of energy considerations, dislocations with strengths larger than unity are generally unstable and dissociate into two or more dislocations of lower strength.

So this way is very significant to understand the energy level associated with the dislocation and whether one full dislocation can be dissociated with the two small dislocation or to partial dislocation can be associated to form a another dislocation. So this type of interaction of the dislocation is quite possible during the plastic deformation of the materials, so today uhh teaching will be focused on this thing and it will touch on the basic concept of different types of interaction of the dislocation, so let us look into that actual key points related to the association or dissociation of the dislocation.

What we understand the dislocation is that full or partial lattice translation and we have discussed in the edge dislocation that there is a shifting of one plane of the atoms and that shifting one plane of the atoms can consider as a full representation and represented by the Burgers vector. But we have not discussed if there is a partial dissociation of the dislocation in the sense that displacement of the atoms may follow other paths where there maybe the change of the energy level of the whole dislocation and to look into that the associated of the energy level maybe we can further look into the fundamental understanding of the interaction or reaction of the different dislocations.

So first thing I like to focus that in general dislocation line end inside the crystal, in most of the cases practically when we analyze the movement of the dislocation in that case we consider one segment, so that segment that can start from one note to another note and that note actually the meeting point of the several dislocations. So this is the first significant point where three or four dislocation lines meet that can be considered as a node point.

Second important point is that at a node two dislocations with Burgers vector b1 and b2, they can combine to produce a resultant dislocation and having a Burgers vector b3. But how b1, b2, b3 can be linked or can be represented in terms of the mathematical equations. First thing is that it should satisfy that the resultant dislocation is uhh a vector sum of the two dislocation that is b1 and b2 in this case. Of course dislocation with Burgers vector equal to one lattice spacing each generally consider as a dislocation of unit strength, so this can be we can remind that basically when you try to represents the edge dislocation in that case that uhh we explain the Burgers vector simply shifting of the shortest repeat dislocation of the atoms, so that shortest repeat distance is represented is a unit strength of the dislocation.

Because of the energy considerations, definitely when we try to analyze the association, dissociation of the different reaction of the dislocations, it is associated with the amount of the strain energy and during the reaction how there is a energy balance can be done in this case. So because of the energy consideration, dislocation with strength large than the unity or generally unstable, so that means the dislocation length of the more than unit strength is generally unstable practically and it actually dissociated into two or more dislocations of relatively lower length. But what maybe the level of the energy when there is a reaction of the dislocation whether association or dissociation of the dislocation, we will try to look into that part.

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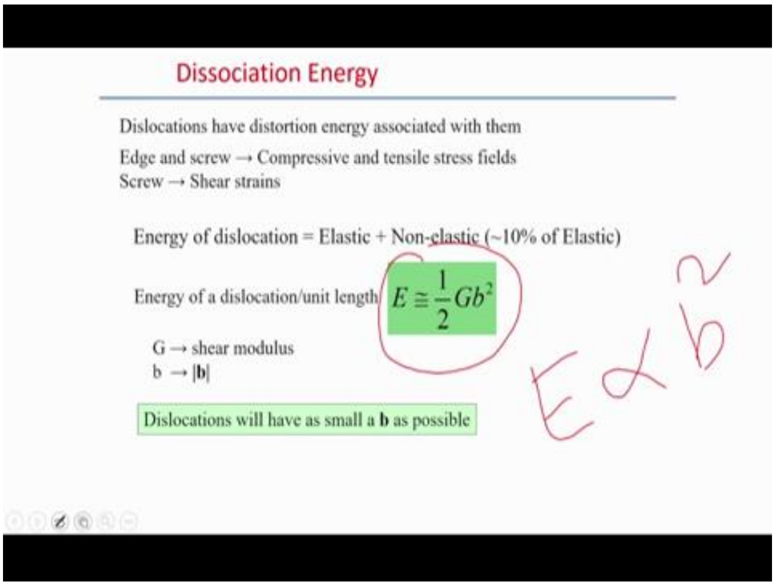

Dissociation Energy

Dislocations have distortion energy associated with them

Edge and screw → Compressive and tensile stress fields
Screw → Shear strains

Energy of dislocation = Elastic + Non-elastic (~10% of Elastic)

Energy of a dislocation/unit length $E \cong \frac{1}{2}Gb^2$

G → shear modulus
b → |**b**|

Dislocations will have as small a **b** as possible

$E \propto b^2$

Now we come back to the very basic things, that we have discussed the two basic elements of the dislocation that is edge dislocation and screw dislocation and we are trying to represents that all actual dislocation reaction in terms of the edge dislocation and screw dislocation, so dislocation have distortion energy associated with them, we have already estimated that what is the amount of the strain energy associated with either edge dislocation or screw dislocation and here we can see that edge dislocation and screw dislocation actually creates the amount of the compressive for stress field even when there is a effect of the another adjacent dislocation is there, accordingly it can create the stress field whether it is compressive or tensile and accordingly they can attract or they maybe the repulsion between the two dislocations, that we have already discussed.

Now we can summarize from the analysis of the dislocation energy associated with the basic element of dislocation, we can find out that screw dislocation is basically we have observed that exist only on the shear strain and one shear stress. And then we found that the energy of the dislocation we divide into two components, one is the elastic and another is the non-elastic energy exist within the core of the dislocation and we have defined the side of the core of a dislocation and normally that energy associated with the core is around 10 percent of the elastic energy of the dislocation.

So in general we can represent the energy of the dislocation per unit length using this equation E equal to half of Gb square, b is the here the Burgers vector and of course dislocation always tend to have the Burgers vector as minimum as possible and G is the shear modulus so we can say that energy per unit length is basically proportional to the square magnitude of the square of Burgers vector.

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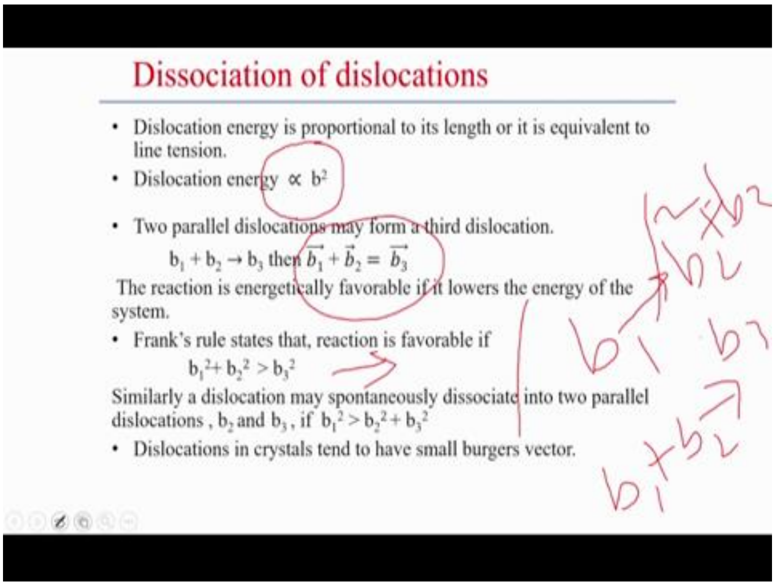

Dissociation of dislocations

- Dislocation energy is proportional to its length or it is equivalent to line tension.
- Dislocation energy ∝ b^2
- Two parallel dislocations may form a third dislocation.

$b_1 + b_2 \rightarrow b_3$ then $\vec{b_1} + \vec{b_2} = \vec{b_3}$

The reaction is energetically favorable if it lowers the energy of the system.

- Frank's rule states that, reaction is favorable if

$b_1^2 + b_2^2 > b_3^2$

Similarly a dislocation may spontaneously dissociate into two parallel dislocations, b_2 and b_3, if $b_1^2 > b_2^2 + b_3^2$

- Dislocations in crystals tend to have small burgers vector.

Now with this we can further analyze the dissociation of the dislocation in the sense that dislocation energy, the total energy is actually proportional to its length, so far we have discussed that energy per unit length is half of G into b square, but in this case total energy is basically l into half of G into b square, so we can say that the total energy of the dislocation is proportional to its length or it is equivalent to the line tension. We have shown that energy per unit length is basically equivalent to the line tension in case of the dislocation.

And another significant point we can find out that dislocation energy is actually proportional to the b square. Now when their existence of the different parallel dislocations the two parallel dislocations can form another third dislocation, when it can satisfy this equation that means vector sum or two dislocation is the third the resultant dislocation, so in this case the reaction is energetically favorable if it lowers the energy of the system, but that feasibility of this reaction can be explained by using the Frank's rule of statement.

It states that the reaction is favorable if b1 square plus b2 square greater than b3 square, that means basically it is trying to represents the energy level and we have already shown that dislocation energy is proportional to the b square and other terms shear modulus terms is a constant for all these cases, so if it is satisfied then this reaction is favorable, reaction means it is basically association of the two dislocation b1 plus b2 we will try to form the b3 if it actually lowers the energy level during this reaction.

Similarly our dislocation may spontaneously dissociate into two parallel dislocation that means if b1 tends to form b2 plus b3, so in this case the b1 square, the energy of the dislocation is more than that of the energy of the two partial dislocations, so in this case the reaction will be the favorable or that means dissociate into points, when they satisfy the state of the energy level according to the Frank's rule. So dislocation in crystals always tends to have the small Burgers vector.

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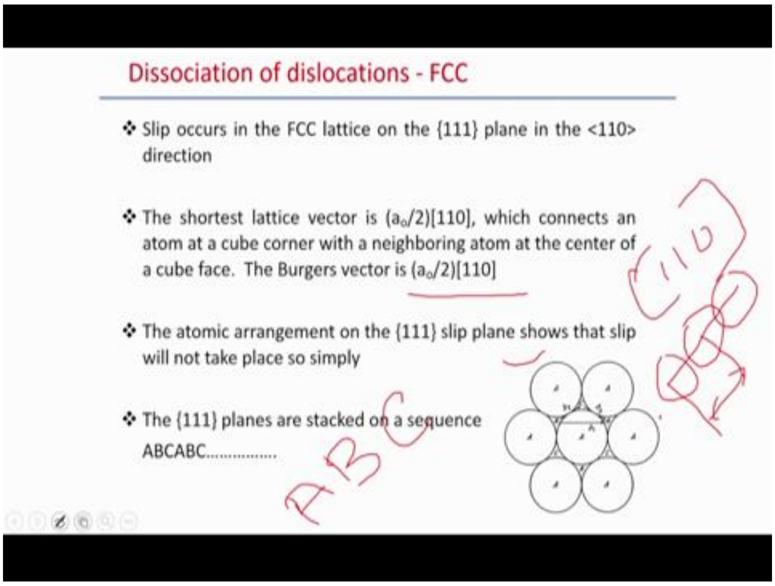

Dissociation of dislocations - FCC

- Slip occurs in the FCC lattice on the {111} plane in the <110> direction
- The shortest lattice vector is $(a_o/2)[110]$, which connects an atom at a cube corner with a neighboring atom at the center of a cube face. The Burgers vector is $(a_o/2)[110]$
- The atomic arrangement on the {111} slip plane shows that slip will not take place so simply
- The {111} planes are stacked on a sequence ABCABC................

Now we try to analyze that how dissociation of dislocation may happen in case FCC crystal structure, to do that we know that in FCC crystal lattice the slip plane is define by this 111 plane, so it is basically the 111 plane that can be constructed like that it is along the x, y, z axis. If we add these three extreme point then we can find out the this is the plane of the 111 in case of FCC structure. Now we know the shortest lattice vector is represented by a0 by 2, 110. What does it means?

It means that 110 basically shows the direction of the face diagonal and this face diagonal, along the face diagonal there is the arrangement of the atoms is like this and the repeat distance is half of the face diagonal and that we can represents the Burgers vector along the face the diagonal is by this, a0 by 2, 110, so a0 is the lattice parameter in case of FCC structure. Now if we look into that atomic arrangement of 111 plane, it shows the figure that the stacking sequence of the sequence of the atoms is like that first there is a layer, all the layer there is nothing, layer A specific sequence of the atom.

Then next layer is the, it follow another sequence of the atoms B, and another layer sequence of the atom is C, so it follow like that A, B, C kind of stacking sequence, now figure also shows the tracking sequence and we can see that how slip will happen on this plane but remember that this stacking sequence ABCABC like that on FCC structure is actually normal to that 111 plane. So along this tracking sequence we will try to explain that how the slip may happen in case of FCC structure or we try to represents the dissociation of the dislocation.

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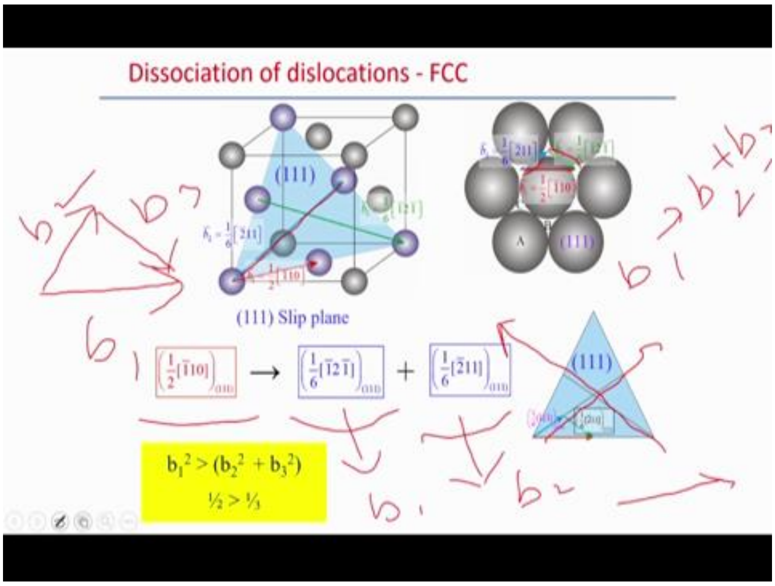

Dissociation of dislocations - FCC

$$\left(\frac{1}{2}[\bar{1}10]\right)_{(111)} \rightarrow \left(\frac{1}{6}[\bar{1}2\bar{1}]\right)_{(111)} + \left(\frac{1}{6}[\bar{2}11]\right)_{(111)}$$

$b_1^2 > (b_2^2 + b_3^2)$

½ > ⅓

Now if focus on this figures, we see this figure source, actual atomic arrangement of the unit cell in FCC structure, corner atoms are there, face atoms are there. Now here we define 111 plane, so this plane actually define the 111 plane, and on this 111 plane if we see that how other reaction will happen here, so this is the actual Burgers vector of the dislocation that means the dislocation associated with the FCC structure, so this dislocation the atoms may slip along the direction from this point to that point.

So this actually the arrow the red color, this actually represents the full dislocation, or that is represented in terms of the dislocation of the unit strength, so that dislocation of the unit strength actually consist of the two partial dislocations that how to represent this two partial dislocation in this case if we look into right hand side figures, so there is a displacement of the atoms or layer of the atoms from one point to another point and that is the full dislocation or dislocation of the unit strength.

Now the dissociation of the dislocation can follow some other path, it can follow the other two paths like this, from this point to that point and from here that point to another point and it comes back to the position so it is like that the if this arrow indicates the actual dislocation or dislocation of the full strength then this part can consist of the another two path, this is one path and it is another path. So if we say that if it is b1, Burgers vector and it consists of the two partial b2 and b3, then the dislocation reaction b1, b2 plus b3 how, we want to physically how we can explain this happening of the favorable condition of the reaction of this dislocation.

Here we see that it consist of the two partial dislocation, and that two partial dislocation is basically represented along this direction, one is along 121 direction and another is 211 direction, so here the 121 direction is basically this direction, that means on a 2 dimensional it is represented along this is the 121 direction and another 211 is another direction and finally it is the path, the reaction is b1 and this is corresponding to b2 and another is corresponding to b3. So the partial has represented by the two different partials I think it is in the same plane but two different directions.

Now we will look into that whether this reaction is feasible or not. Now if we look into analyze this thing from the Frank's rule that b1 square is greater than b2 square plus b3 square, we can easily estimate the Burgers vector from the this uhh from this looking into the uhh reaction. So this is corresponding to b1, corresponding to b2 and you can investigate this thing that b1 square is 12 and b2 square plus b3 square is 13. That means if it is follow this direction path or along the full dislocation then energy level is more as compared to the other two paths that means b2 plus b3.

So definitely in this reaction there is a decrease of the energy level so that actually indicated the favorable condition so that we can say that this kind dislocation, dissociation is possible in case of FCC structure.

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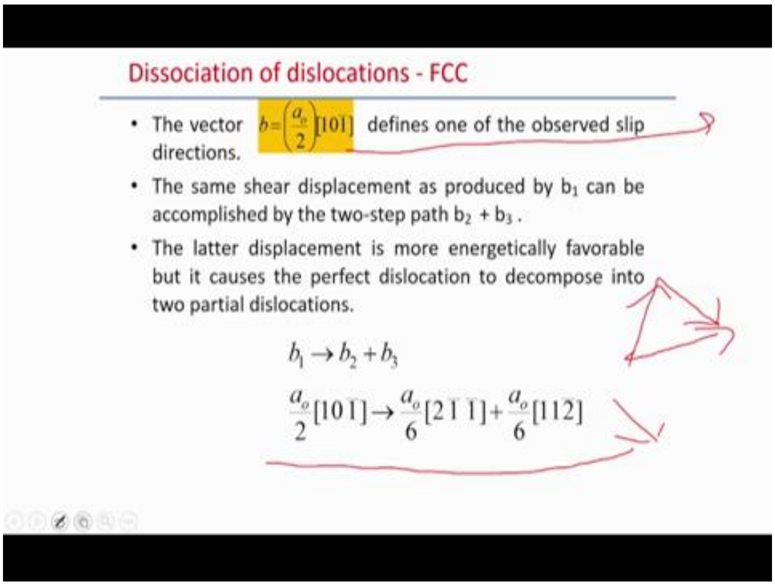

Dissociation of dislocations - FCC

- The vector $b=\left(\frac{a_o}{2}\right)[101]$ defines one of the observed slip directions.
- The same shear displacement as produced by b_1 can be accomplished by the two-step path $b_2 + b_3$.
- The latter displacement is more energetically favorable but it causes the perfect dislocation to decompose into two partial dislocations.

$$b_1 \rightarrow b_2 + b_3$$

$$\frac{a_o}{2}[10\bar{1}] \rightarrow \frac{a_o}{6}[2\bar{1}\bar{1}] + \frac{a_o}{6}[112]$$

Now in general we can say that from the dissociation of the dislocation in case of FCC structure and we find out that definitely there is another way that b Burgers vector represents this defines one of the observed slip direction in FCC structure and the same shear displacement as produced by b1 can accomplish by the two partial or two step path so that means b2 and b3. So what does it mean, the same path can be represented by another two path, b2 plus b3. The latter displacement is more energetically favorable but it causes the perfect dislocation to decompose into two partial dislocation that we have already observed that it is energetically favorable and we can find out that b1 is consist of the b2 plus b3. So this reaction can be represented this way, so this is the actual reaction where 1 full dislocation is dissociated in two partials in case of FCC structure.

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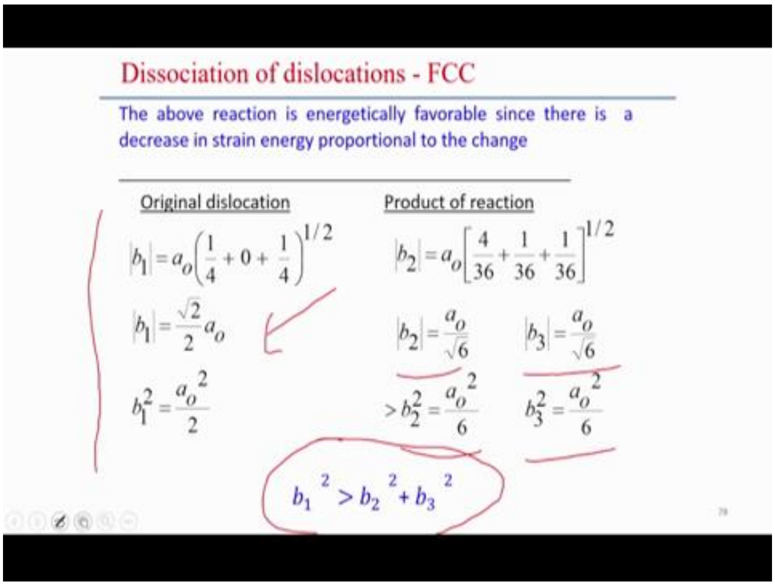

Dissociation of dislocations - FCC

The above reaction is energetically favorable since there is a decrease in strain energy proportional to the change

Original dislocation

$$|b_1| = a_o\left(\frac{1}{4}+0+\frac{1}{4}\right)^{1/2}$$

$$|b_1| = \frac{\sqrt{2}}{2}a_o$$

$$b_1^2 = \frac{a_o^2}{2}$$

Product of reaction

$$|b_2| = a_o\left[\frac{4}{36}+\frac{1}{36}+\frac{1}{36}\right]^{1/2}$$

$$|b_2| = \frac{a_o}{\sqrt{6}} \qquad |b_3| = \frac{a_o}{\sqrt{6}}$$

$$> b_2^2 = \frac{a_o^2}{6} \qquad b_3^2 = \frac{a_o^2}{6}$$

$$b_1^2 > b_2^2 + b_3^2$$

And of course we can observe whether it is energetically favorable or not so if we look into that there is a first original dislocation or maybe the dislocation of the unit strength is represented like this b1, we have estimated the Burgers vector by looking into that reaction and we found out that b1 square is equal to a0 square by 2, a0 is the lattice parameter and for that reaction that means two partials in this case, b2 and b3 we can found out and finally we can say that b1 square greater than b2 square plus b3 square, that means that reaction is the energy level actually in favor to cause of this dislocation reaction.

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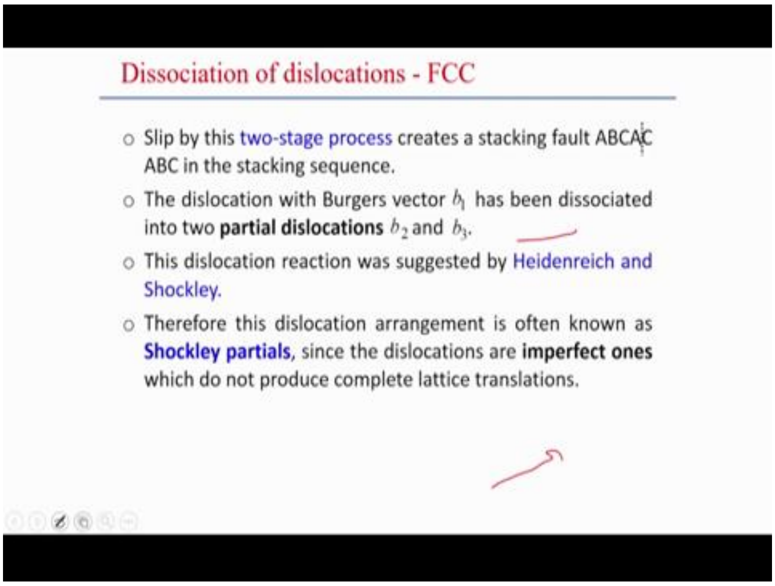

Dissociation of dislocations - FCC

- Slip by this two-stage process creates a stacking fault ABCAC ABC in the stacking sequence.
- The dislocation with Burgers vector b_1 has been dissociated into two **partial dislocations** b_2 and b_3.
- This dislocation reaction was suggested by Heidenreich and Shockley.
- Therefore this dislocation arrangement is often known as **Shockley partials**, since the dislocations are **imperfect ones** which do not produce complete lattice translations.

We can further make uhh conclusion that dislocation and dissociation in case of FCC structure that slip by this two stage process creates actually the stacking fault uhh that means ABCA that is the missing of the layer of the B then C, again ABC is the stacking sequence. Actually with a partial dissociation of the dislocation is link with the creation of the stacking fault and we will try to link that the dislocation reaction or dissociation of the dislocation in terms of the stacking fault and how we can link and what are the energy level and we can estimate.

Now if we look that dislocation with Burgers vector b1 has been dissociated in the two partial b2 and b3, we have observed the dislocation reaction actually suggested by the Heidenreich and Shockely so therefore this kind of dislocation arrangement is actually know as the Shockley partials. So since it is the one full dislocations consist of the two partials and it is a imperfect ones that is why it is called the partial dislocation and which do not produce the complete lattice translations, that we have observed that it does not complete the complete lattice translation so it is called partial, so that means one full dislocation can be dissociated into the two partial dislocation.

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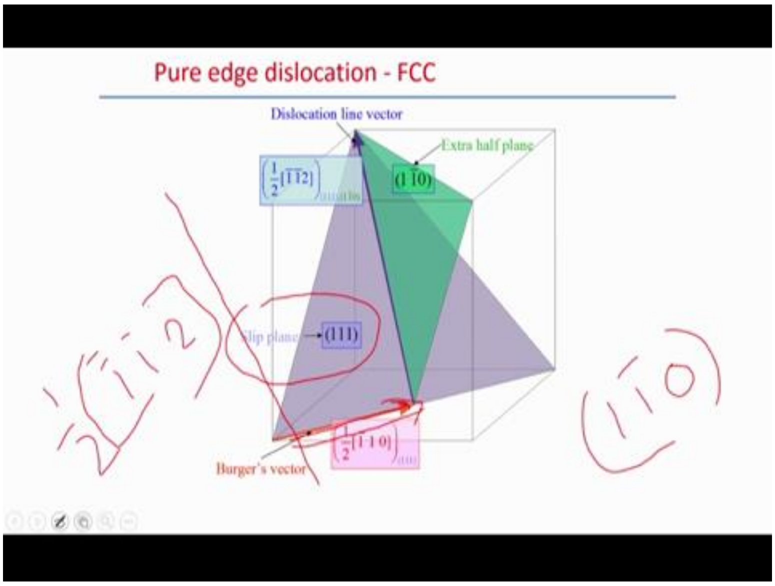

Pure edge dislocation - FCC

So we look into the further dislocation reaction in case of FCC structure but in the, if we consider the pure edge dislocation, how it happens in case of the FCC structure. Now edge dislocation means we have explained that there is a displacement of the one layer of the atoms and that or if there is a extra half plane with the regular arrangement of the atoms is inserted then the displacement actually happens and that the displacement of this repeat distance is considered as a Burgers vector in the case of edge dislocation and of course in case of edge dislocation the Burgers vector is perpendicular to the dislocation line.

Now how we represent this dislocation in a unit cell of the FCC structure, so it is obvious that 111 slip plane is define here and we consider that 1 minus 10 actually the extra half of the plane and with a extra half of the plane there is a displacement of the atoms so if we consider there is a another layer of the atoms parallel to this and if we found out that it is the actually this shifting of the one layer of the atoms from one point to another point along the shortest repeat distance that is the Burgers vector in case of edge dislocation of FCC structure.

Now this is the Burgers vector half of minus 110 on 111 plane, this is because of the extra half of the plane and the dislocation line is here half of 1 minus 1 minus 12, so this represents the dislocation line vector and the Burgers vector if you see that Burgers vector and the dislocation line vector they are perpendicular to each other and the plane 1 minus 10 actually represents the extra half plane, if we look into the very basic structure of the edge dislocation that we have already discussed.

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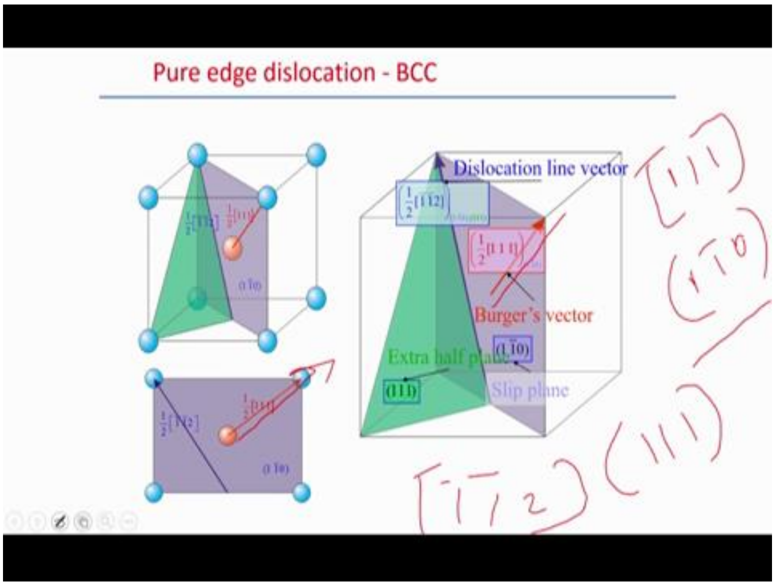

Pure edge dislocation - BCC

Now we can look into that edge dislocation in case of BCC structure. So there are slip planes in case of BCC structure as well but here we try to see that extra half of the plane is represented by here 111 plane and if we see that the other plane so it is the 1 minus 10, so when there is a sum 0 plane that means that plane is actually paralle to the 1 of the axis so here it is parallel to the z axis so 1 minus 1 plane having inclined the unit length along x and y direction but it is parallel to the z direction and if we see that on this plane, 1 minus 10 plane the extra half of the plane is inserted 111 plane and that actually represent the uhh system of the edge dislocation and we can compare with a very basic structure of the edge dislocation in case in a unit, uhh in case of the BCC structure.

We see that here the Burgers vector represent along this direction so that is the 111 direction so basically 111 direction is the along the body diagonal direction and this is the schematic representation of the uhh edge dislocation in case of BCC structure and we can see further how we can represents, we can represent one plane and the perpendicular to the plane there is a edge dislocation happen and dislocation line we represent here in this case is the 1 minus 1 minus 12 this is the direction of the dislocation line vector. And if we look into that 2 dimensional figure here you can see that this is the Burgers vector in case of pure edge dislocation of BCC structure and here the dislocation line and Burgers vector is actually perpendicular with each other.

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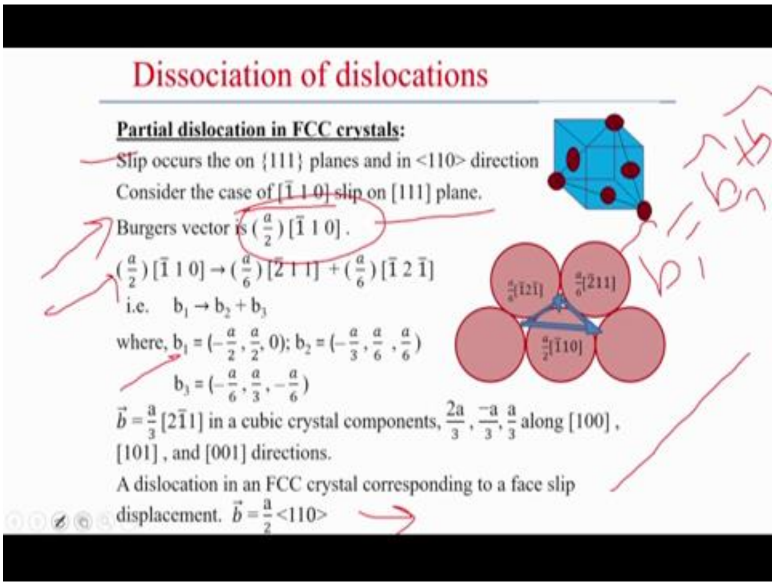

Dissociation of dislocations

Partial dislocation in FCC crystals:

Slip occurs the on {111} planes and in <110> direction

Consider the case of $[\bar{1}\,1\,0]$ slip on [111] plane.

Burgers vector is $(\frac{a}{2})\,[\bar{1}\,1\,0]$.

$(\frac{a}{2})\,[\bar{1}\,1\,0] \rightarrow (\frac{a}{6})\,[\bar{2}\,1\,1] + (\frac{a}{6})\,[\bar{1}\,2\,\bar{1}]$

i.e. $b_1 \rightarrow b_2 + b_3$

where, $b_1 = (-\frac{a}{2}, \frac{a}{2}, 0)$; $b_2 = (-\frac{a}{3}, \frac{a}{6}, \frac{a}{6})$

$b_3 = (-\frac{a}{6}, \frac{a}{3}, -\frac{a}{6})$

$\vec{b} = \frac{a}{3}[2\bar{1}1]$ in a cubic crystal components, $\frac{2a}{3}, \frac{-a}{3}, \frac{a}{3}$ along [100] , [101] , and [001] directions.

A dislocation in an FCC crystal corresponding to a face slip displacement. $\vec{b} = \frac{a}{2}<110>$

Now we just simply summarize the dislocation of the, dissociation of the dislocation in case of FCC structure and we are representing this structure in a different way that slip occurs on 111 plane and 110 direction in case of FCC structure. Now from the group of plane or from the group of direction we can pick up one specific plane and one specific direction and we can found out the Burgers vector is represented is a by 2 minus 110, so this Burgers vector actually along that we have already explained, along that specific direction this is the shortest repeat distance consecutive dislocation between the uhh 2 atoms that is represented by a by 2 minus 110 and this is the reaction, so one full dislocation can be dissociated into two partials in terms of b1 consist of the b2 plus b3.

Now here in terms of the coordinate maybe you can represent b1 minus a by 2, a by 2 0 b2 is like that, and b3 also in the similar way, and we can found out that uhh in FCC corresponding to the face slip displacement is b equal to a by 2 11 that is the full, so in this case what is the uhh, how we can decide that feasibility of the reaction so to do that we need to consider the two points, first point is that when the 2 reaction will happen then that we will try to make should be the vector sum of the resultant or just vice versa also, if one dissociated into the two partial or 2 partial dislocation can associated in the one dislocation, so in both the cases it should satisfy the vector sum or one single dislocation is vector sum of the two partial.

And second thing we need to check the feasibility of the energy level whether it is decreased or whether it is increased, accordingly we will decide whether reaction will happen or not. So with this dissociation of the dislocation or association of the dislocation actually it is more or less associated with the stacking fault of the crystal structure. Stacking fault means we understand that stacking fault is there is a missing of the simply one layer of the atoms so it may not follow the sequence in case of the different structure.

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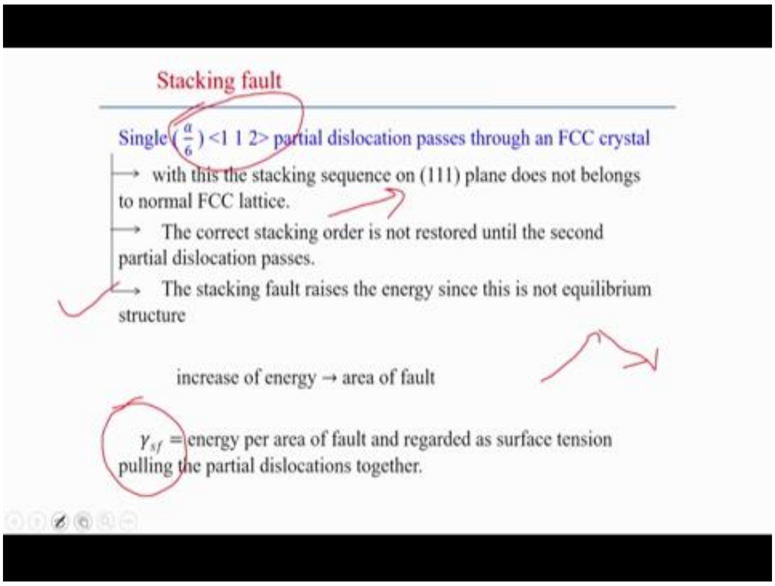

Stacking fault

Single $(\frac{a}{6})$ <1 1 2> partial dislocation passes through an FCC crystal

→ with this the stacking sequence on (111) plane does not belongs to normal FCC lattice.

→ The correct stacking order is not restored until the second partial dislocation passes.

→ The stacking fault raises the energy since this is not equilibrium structure

increase of energy → area of fault

γ_{sf} = energy per area of fault and regarded as surface tension pulling the partial dislocations together.

Now come to that point, we will try to link the association or dissociation of dislocation with the stacking fault. Let us see how it links with the stacking fault energy in case of the simple cubic structure. Now that we have observed a by6 112, actually one of the partial dislocation generally observed in case of the FCC structure, so with the presence of this partial this stacking sequence on the 111 plane actually does not belong to the normal FCC lattice, we will try to explain this things with the presence, so there is maybe the stacking sequence actually change with the presence of this partials, so it may be shift to the HCP structure.

Second point is that correct stacking order is not restored until the second partial dislocation passes that means presence of the one partial uhh may not be the very stable cases until and unless the second partial exist accordingly then the correct sequence of the stacking may not be the restored. But with the presence of this partial the stacking fault presence of the partial that means creation of the stacking fault actually the increases the energy level since this is not an equilibrium structure. But this amount of the energy increment depends on the area of the fault, that means area of the stacking fault.

Now it can be like that, that if gamma sf actually represents the energy part area of the stacking fault and regarded as surface tension pulling the partial dislocations, we can consider this amount of energy and that we can estimate for the different kind of crystal structure.

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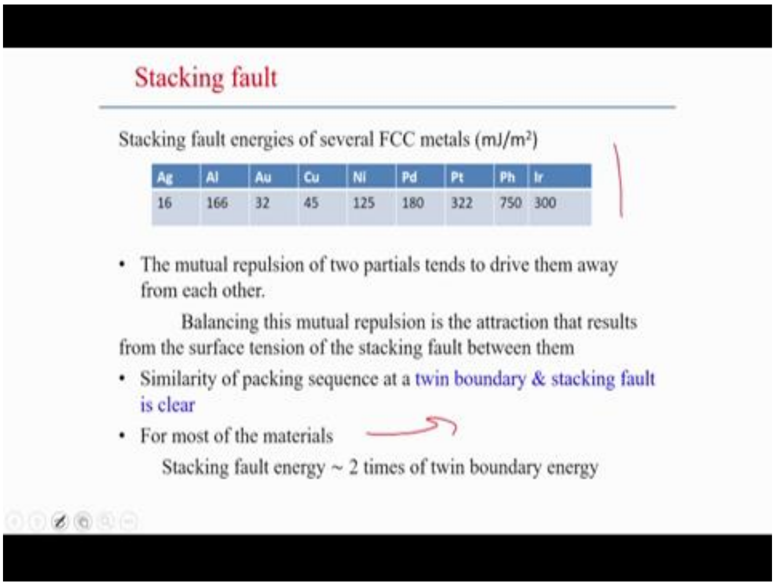

Stacking fault

Stacking fault energies of several FCC metals (mJ/m^2)

Ag	Al	Au	Cu	Ni	Pd	Pt	Ph	Ir
16	166	32	45	125	180	322	750	300

- The mutual repulsion of two partials tends to drive them away from each other.

Balancing this mutual repulsion is the attraction that results from the surface tension of the stacking fault between them

- Similarity of packing sequence at a twin boundary & stacking fault is clear
- For most of the materials

Stacking fault energy ~ 2 times of twin boundary energy

And it has been shown that cases that stacking fault energies of the several FCC metal in terms of uhh miliJoule per meter square. If you see that silver, aluminum, gold, copper is basically most of the common materials, we see aluminum is having very high stacking fault energy as compared the other materials. Now this is the simply statistics of the stacking fault energy. Now from this stacking fault energy of the different type of materials we can conclude the several statement here, first thing is that the mutual repulsion of the two partial tends to drive them away from each other, therefore balancing this mutual repulsion is the attraction that actually results from the surface tension from the stacking fault between them.

Similarly similarity of the packing sequence at a twin boundary and stacking fault is very much clear from the figure that we will try to explain from the next slide. But most of the materials found the stacking fault energy is actually two times of the twin boundary energy so that means presence of the stacking fault can create the twin boundaries.

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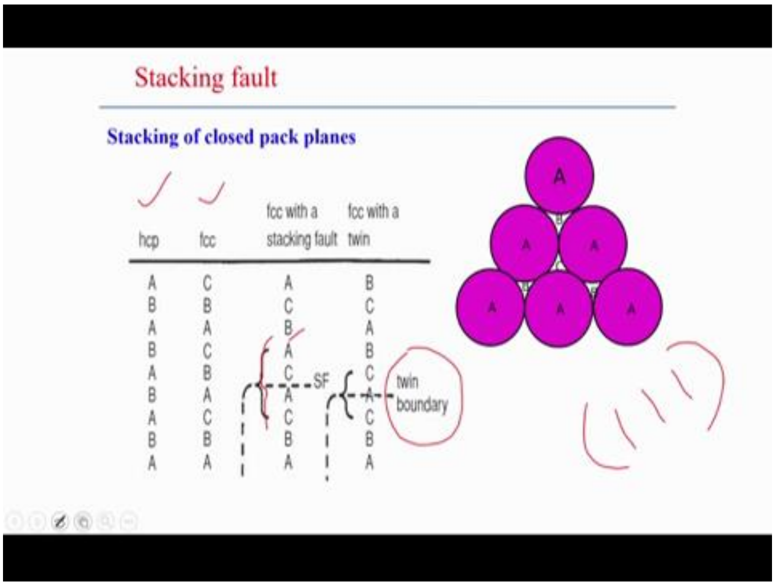

Stacking fault

Stacking of closed pack planes

hcp	fcc	fcc with a stacking fault	fcc with a twin
A	C	A	B
B	B	C	C
A	A	B	A
B	C	A	B
A	B	C	C
B	A	A	A
A	C	C	C
B	B	B	B
A	A	A	A

We will try to look into things, so this is the simply stacking of the closed packed plane and assuming that this is the closed packed plane of the FCC structure and that plane actually this plane is actually exist on FCC structure on 111 plane. Now stacking up the closed packed planes we know, the stacking sequence of the HCP crystal structure is like that ABAB in that sequence that means there is a two layer and the repetition of the layers in case of the FCC structure CBACBACBA like that that means there is a three different layers sequence of the atoms and there is a repetition of the sequence of the atoms.

But FCC with a stacking fault, how it can create, so if we see there is a missing of the one layer due to the stacking fault then we can see the AC again AC, so then up to that ACAC that actually (())(39:37) the stacking sequence of the HCP structure. So presence of the one partial that creates the stacking fault with the FCC structure in that part actually which is equivalent to the stacking sequence of the HCP structure. Now if the stacking sequence or partials dislocation exist in such a way that the stacking is like that BCABCACBA so that means this part actually represents that BCACBCA and ACB that means with respect to the stacking sequence or layer A there is a mirror image between that or symmetrical in the upper side or lower side, BC again CB. So that type of sequence actually creates the twin boundary.

Now we have observed that presence of the stacking fault in case of FCC structure the energy is associated with the can be same from the level and we can get some idea that what is the amount of the energy and the relative amount of the energy between the two metals uhh exist in terms of the stacking fault.

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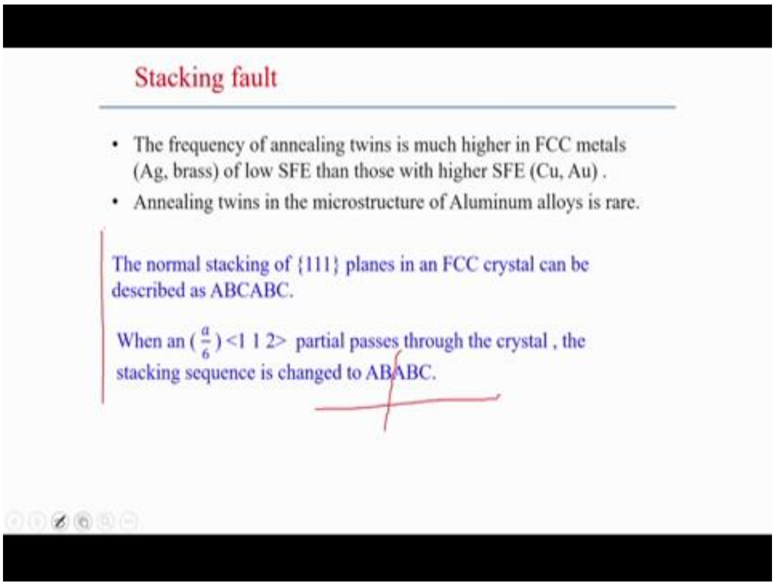

Stacking fault

- The frequency of annealing twins is much higher in FCC metals (Ag, brass) of low SFE than those with higher SFE (Cu, Au) .
- Annealing twins in the microstructure of Aluminum alloys is rare.

The normal stacking of {111} planes in an FCC crystal can be described as ABCABC.

When an $\left(\frac{a}{6}\right)<1\ 1\ 2>$ partial passes through the crystal , the stacking sequence is changed to ABABC.

Now if we look into further analysis on the stacking fault, the frequency of the annealing twins that means face twins is the one kind of the fault is much higher in FCC metals of low stacking fault energy than that of higher stacking fault energy so of course the stacking fault energy between the silver and copper aluminum is not much but relative to the low stacking fault energy the frequency of the annealing twins we observed much in FCC metals.

Annealing twins in microstructure of aluminum alloy is rare because in aluminum the stacking fault energy is actually very high so in this case the twins generally rarely observed in case of aluminum alloy. So if we summarize this thing the normal stacking sequence the 111 plane in FCC crystal, can be described that ABCABC, so this is just to remind this part the stacking sequence we have explained in case of FCC structure that is the normal to that plane 111. Second one partial a by 6 112 actually it is one of the partials that can dissociate from the full dislocation in case of FCC structure, in this uhh stacking sequence is changed to ABABC, so that means there is a absence of the layer of the sequence C, so this stacking sequence changes due to the this partial in case of the FCC structure.

So here we have tried to the basic understanding of the dislocation reaction happens in case of FCC structure and BCC structure and basically how we can uhh how we can expel the reaction will be possible in terms of the energy level during the reaction and whether there maybe the association of the two partial and whether dissociation of the one full dislocation and how uhh they can interact with each other, that actually becomes more complex, so we just focus only on the basic understanding on the dissociation of the dislocation and from this elements now we will try to shift in the next topic for the dislocation mechanics.

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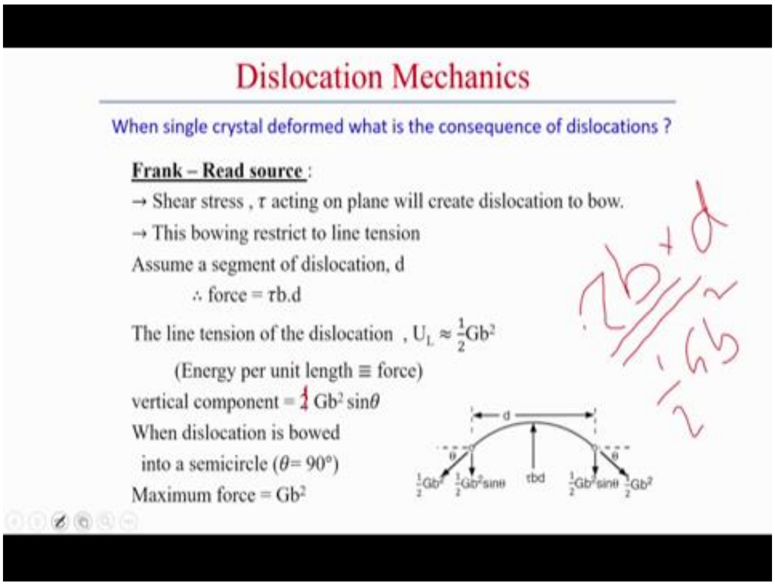

Dislocation Mechanics

When single crystal deformed what is the consequence of dislocations ?

Frank – Read source :

→ Shear stress , τ acting on plane will create dislocation to bow.

→ This bowing restrict to line tension

Assume a segment of dislocation, d

$\therefore$ force = $\tau b.d$

The line tension of the dislocation , $U_L \approx \frac{1}{2}Gb^2$

(Energy per unit length ≡ force)

vertical component = $\frac{1}{2} Gb^2 \sin\theta$

When dislocation is bowed into a semicircle ($\theta = 90°$)

Maximum force = Gb^2

$\tau b \times d$

$\frac{1}{2} Gb^2$

So we have the idea now that different dislocations and the basic types of dislocations that edge and screw dislocation and how the, what is the amount of the energy associated with the dislocation and when they react with each other what maybe the stress field it can create and what type of stress is subjected to in edge and screw dislocation, all look into to the basic ideas or basic understanding on this thing, we will try to explain that different dislocation mechanics with this background.

Let us look into that first question, when single crystal deformed what is the consequence of the dislocation. If single crystals, plastically we deform one single crystal what will happen to the dislocation, what maybe the changes of the dislocation, their movement, their change of the energy level or how they interact with the surrounding dislocation or is there any increment or is there any generation of the dislocation with a further plastic deformation of the materials, that will try to link with the deformation and what happens to the dislocation during the plastic deformation of a single crystal structure.

So first already we have discussed the Frank – Reed source, this is the dislocation generation mechanism and we can explain using the Frank – Reed source mechanism. So here it can be like that, so suppose shear stress is acting on a plane will create the dislocation to bow, so for example this the length of the dislocation and that segment of the dislocation we can consider length d between the two node points. And if we see what are the uhh forces acting on this thing, so we have already estimated tau, tau b is the frictional resistant movement per unit length, so this is the tau b is the amount of the force. When we multiply by length d actually this indicated the total force acting on the dislocation.

Now at the node point what maybe the reaction forces in this case, so we have already explained that half Gb square can be considered ast he line tension and if we look into that it is line tension and it is equivalent to the force here. So at two node points the line tension is acting actually half of the Gb square on this dislocation. Now here this dislocation at this node of point actually this we consider the equivalent force equal to the energy per unit length on this nodal point which is equivalent to the force here.

So if we consider the vertical component, you can define the angle theta and two vertical components are there, half of Gb square sin theta into 2. So when this dislocation it should be total Gb square sin theta, now when dislocation is bow in such a way that theta becomes 90 degree then in this case the maximum force acting equal to Gb square here.

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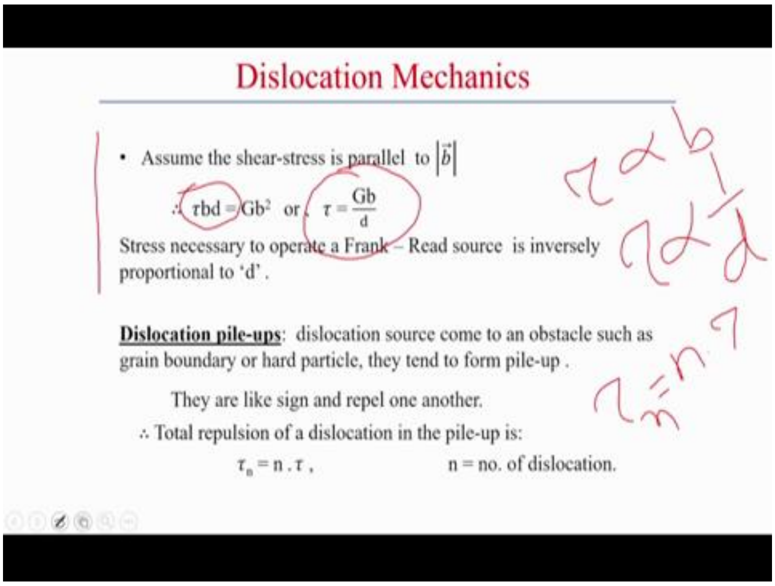

Dislocation Mechanics

- Assume the shear-stress is parallel to $|\vec{b}|$

$\therefore \tau b d = G b^2$ or $\tau = \frac{Gb}{d}$

Stress necessary to operate a Frank – Read source is inversely proportional to 'd'.

Dislocation pile-ups: dislocation source come to an obstacle such as grain boundary or hard particle, they tend to form pile-up .

They are like sign and repel one another.

$\therefore$ Total repulsion of a dislocation in the pile-up is:

$\tau_n = n . \tau$, n = no. of dislocation.

$\tau \propto b$

$\tau \propto \frac{1}{d}$

$\tau_n = n\tau$

And we see the of course in this case the shear stress is actually acting to the parallel to the Burgers vector and the if we balance the force total force is the vertical component, we can found out their shear stress equal to Gb by d. That means stress necessary to operate Frank – Reed course is actually inversely proportional to the dislocation segment length d here in this case. So of course in this case proportional to the Burgers vector b and the shear stress proportional to the 1 by d.

So with this mechanism actually there is a creation of the dislocation and uhh this is just to show the calculation when there is a bowing happens actually at 90 degree but if we do further plastic deformation of a single crystal then actually it multiply the dislocation and then act as a or it can be explained as a generation of the dislocation by this mechanism, so that generation of the dislocation by this mechanism we have already discussed, here we can show only the mathematical calculation here.

Second this is that now we turn to explain the basic terminology used that is called dislocation piles ups and that terminology actually happens during the plastic deformation of the movement of the dislocation. Now dislocation source come to an obstacle such as grain boundary or hard particle, they actually tend to form the pile up. So due to the plastic deformation formation when the dislocation will try to move if there exist such kind of obstacle like grain boundary or hard particle then that actually resist the dislocation movement and gradually the dislocation may pile up and in this case the like sign or the same sign signature either positive or negative edge dislocation or we can say the left hand screw dislocation or right hand screw dislocation similar sign dislocation they actually repel with each other and repulsion of the dislocation pile up can be represented like this.

So total shear stress actually can be linked in this case that n number of dislocation in this case and the tau is the corresponding to the shear stress of each dislocation and this is the actual estimation of the repulsion of that dislocation in terms of the shear stress.

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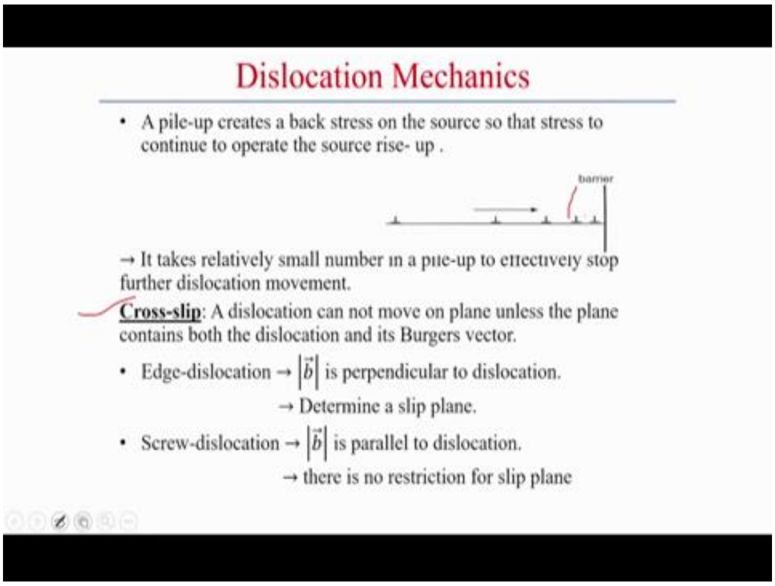

Dislocation Mechanics

- A pile-up creates a back stress on the source so that stress to continue to operate the source rise- up .

→ It takes relatively small number in a pile-up to effectively stop further dislocation movement.

Cross-slip: A dislocation can not move on plane unless the plane contains both the dislocation and its Burgers vector.

- Edge-dislocation → $|\vec{b}|$ is perpendicular to dislocation.
  → Determine a slip plane.
- Screw-dislocation → $|\vec{b}|$ is parallel to dislocation.
  → there is no restriction for slip plane

Now the pile up created actually the dislocation creates some back up stress so that stress to continue to operate to rise up so if there is a exist on a (())(51:00) and we apply for the dislocation moves with certain point and around the barrier there is a resistance of the dislocation and if the resistance of the dislocation actually creates the backup stress and actually creates the total amount of the stress. So this kind of phenomena is generally known as dislocation pileup.

It takes relatively small number in the pile up to effectively stop further dislocation movement that means with a few number of dislocations the piles up can be generated to stop the further dislocation movement. Second thing is the cross slip, this is one of the elementary thing associated with the dislocation movement. Dislocation cannot move on a plane unless the plane contains both the dislocation and its Burgers vector. That is true and in case of edge dislocation we can see that Burgers vector is actually perpendicular to the dislocation and that actually Burgers vector and dislocation line they can create the one or can define the slip plane.

But it is not the case in case of the screw dislocation, because screw dislocation is parallel, the Burgers vector is parallel to the dislocation, so there is no restriction while define slip plane in case of screw dislocation.

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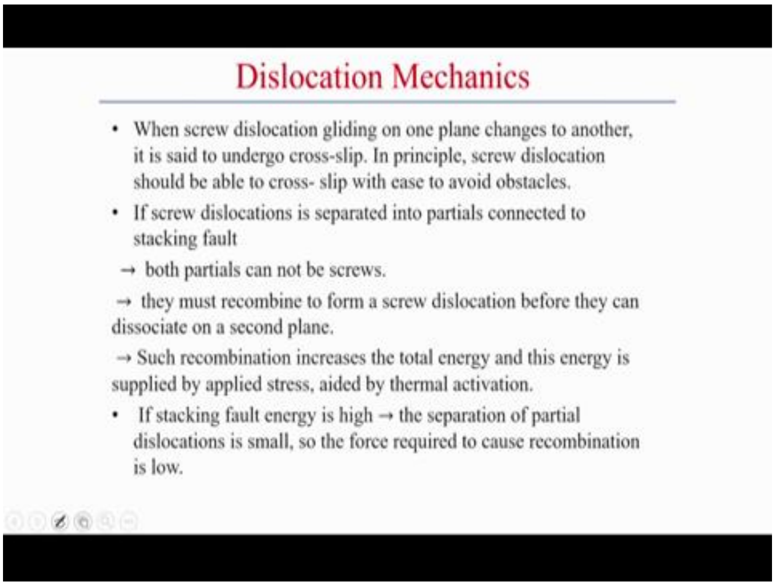

Dislocation Mechanics

- When screw dislocation gliding on one plane changes to another, it is said to undergo cross-slip. In principle, screw dislocation should be able to cross- slip with ease to avoid obstacles.
- If screw dislocations is separated into partials connected to stacking fault

→ both partials can not be screws.

→ they must recombine to form a screw dislocation before they can dissociate on a second plane.

→ Such recombination increases the total energy and this energy is supplied by applied stress, aided by thermal activation.

- If stacking fault energy is high → the separation of partial dislocations is small, so the force required to cause recombination is low.

So in this case when the screw dislocation actually gliding on one plane they can easily change to another and then it is called shift to the cross slip, because in case of the screw dislocation there is no well defined, we cannot define a slip like edge dislocation. So in principal screw dislocation should be able to cross slip with ease to avoid any obstacles. In this case the screw dislocation is actually separated into partial and connected to the stacking fault, if we consider that partial in case of partial of a screw dislocation then fundamentally we can say that both partial cannot be screws and they must be recombine to form a screw dislocation before they dissociate on a second plane.

So that kind of recombination actually increases the total energy level and this energy is supplied by the applied stress and sometimes it is aided by the thermal activation. Now if stacking fault energy is high then separation of the partial dislocation is actually small so force required to cause the recombination is also low.

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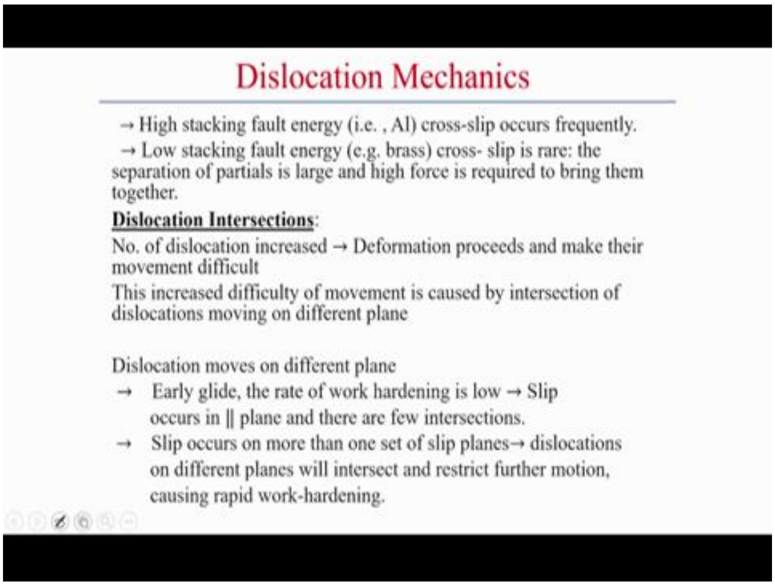

Dislocation Mechanics

→ High stacking fault energy (i.e. , Al) cross-slip occurs frequently.

→ Low stacking fault energy (e.g. brass) cross- slip is rare: the separation of partials is large and high force is required to bring them together.

Dislocation Intersections:

No. of dislocation increased → Deformation proceeds and make their movement difficult

This increased difficulty of movement is caused by intersection of dislocations moving on different plane

Dislocation moves on different plane

→ Early glide, the rate of work hardening is low → Slip occurs in || plane and there are few intersections.

→ Slip occurs on more than one set of slip planes→ dislocations on different planes will intersect and restrict further motion, causing rapid work-hardening.

So from that point we can make some conclusive statement that high stacking fault energy for example, aluminum cross slip occur very frequently but low stacking fault energy actually cross slip is very rare. The separation of the partial is large and high force is required to bring them together. Now we shift to the next elementary topic on the dislocation intersection. Dislocation intersection we simply understand that if there is a number of dislocation increase so deformation process and definitely their movement of dislocation become more difficult, so this increase difficulty of movement is actually caused by the intersection of the dislocation when they are moving on the different planes at different directions.

So dislocation moves on different plane, early glide the rate of work hardening is low and slip occurs in parallel plane and there are few intersection and that happens at the very initial stage. Now when slip occurs or maybe when slip occurs or more than one set of the slip plane in this case dislocation on different plane actually will intersect each other and they actually resist further movement or further motion of the dislocation and in that case they actually cause the rapid work hardening of the material.

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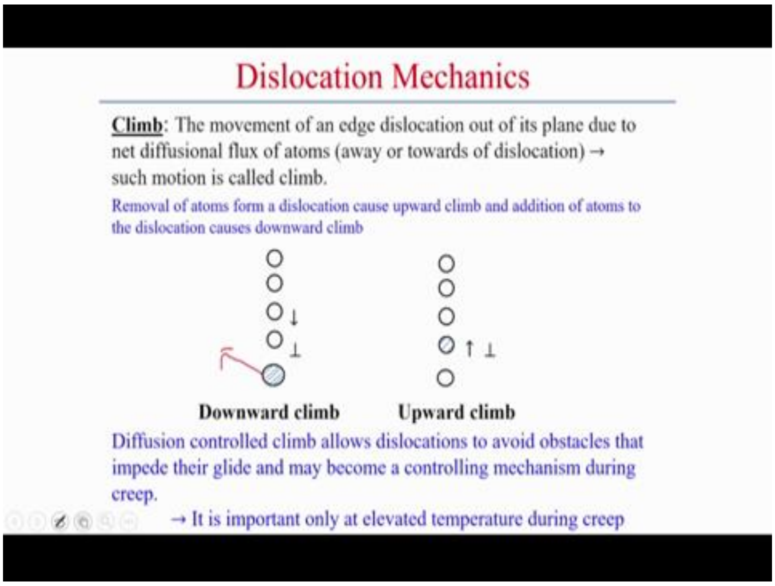

Dislocation Mechanics

Climb: The movement of an edge dislocation out of its plane due to net diffusional flux of atoms (away or towards of dislocation) → such motion is called climb.

Removal of atoms form a dislocation cause upward climb and addition of atoms to the dislocation causes downward climb

Diffusion controlled climb allows dislocations to avoid obstacles that impede their glide and may become a controlling mechanism during creep.

→ It is important only at elevated temperature during creep

Now we come to point of the dislocation that is dislocation climb. You can see the dislocation climb is actually the movement of an edge dislocation out of its plane due to the diffusion flux of atoms. It can come from the array or towards the dislocation, such motion is actually called climb. So it happens removal of the atoms from the dislocation cause upward climb so if we look into this picture removal of the atoms actually caused the dislocation move upward and addition of the atoms to the dislocation actually cause downward climb. So in this case diffusion control climb actually allows dislocation to avoid sometimes to avoid the obstacles that impede their glide motion and may become a controlling mechanism in case of specifically the creep process. So the creep process which is very much important only at the elevated temperature and during the during creep.

So this basic elemental terms of the dislocation mechanics like climb, dislocation intersection, cross slip, and dislocation pile up and Frank – Reed course of the all the typical mechanism of the dislocation movement is actually is very much useful to explain that different mechanism when it is in the mechanism of the plastic deformation of the materials and it help to explain the different phenomena that happens during the plastic deformation of a material. So with this we can conclude the topic dislocation mechanics and uhh as well dislocation intersection and association or dissociation of the dislocation. So thank you very much for your kind attention.