Introduction to crystal elasticity and crystal plasticity

Prof Swarup Bag
Mechanical Engineering Department
Indian Institute of Technology Guwahati
Week-05
Lecture-09

Hello everybody!

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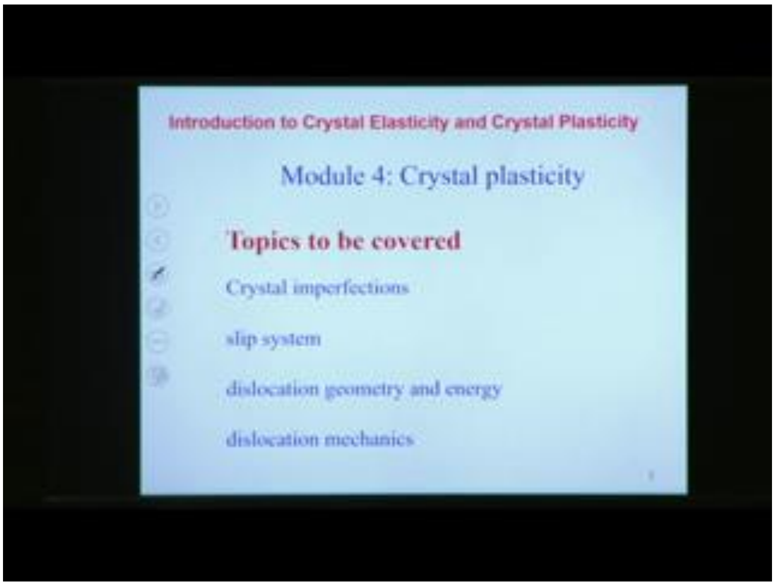

Introduction to Crystal Elasticity and Crystal Plasticity

Module 4: Crystal plasticity

Topics to be covered

Crystal imperfections

slip system

dislocation geometry and energy

dislocation mechanics

Today we will discuss the next module crystal plasticity for the course Introduction to Crystal Elasticity and Crystal Plasticity. So, so far we have discussed the continuum plasticity model specifically for isotropic and anisotropy cases. And that plastic behavior of our material, when we try to analyze using the continuum plasticity it may not be directly applicable for crystal plasticity, so this subject actually focus on the plastic deformation behaviour of a single crystal uhh looking into the uhh deformation or motion of the dislocation in a single crystal structure.

So to discuss this crystal plasticity broadly we will try to cover the following topics, first is the crystal imperfection for crystal defects, second is the what are the different slip system generally also found in engineering materials and what are the dislocation geometry and energy and dislocation mechanics. So actually crystal plasticity is more oriented to explain this phenomena using the mechanism of dislocation so basically we will try to understand that what is the dislocations and how it is impactful to analyze the plastic deformation of uhh single crystal strucutre.

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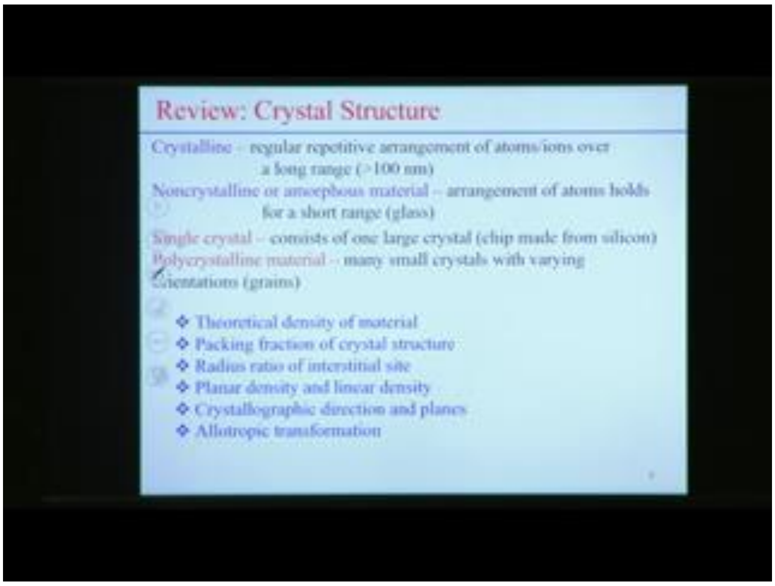

Review: Crystal Structure

Crystalline – regular repetitive arrangement of atoms/ions over a long range (>100 nm)
Noncrystalline or amorphous material – arrangement of atoms holds for a short range (glass)
Single crystal – consists of one large crystal (chip made from silicon)
Polycrystalline material – many small crystals with varying orientations (grains)

- ❖ Theoretical density of material
- ❖ Packing fraction of crystal structure
- ❖ Radius ratio of interstitial site
- ❖ Planar density and linear density
- ❖ Crystallographic direction and planes
- ❖ Allotropic transformation

So let us start with the crystal imperfection or cyrstal defect, so before that we will try to review what we discuss to analyze the crystal structure of different materials, so basic structure for example FCC, BCC and AXP structure. So first what is the crystalline material, regular repetitive arrangement of atoms or ions over a long range which is long range in the sense that it is more than 100 nanometer, then that structure is called crystalline structure.

Non-crystalline structure or amorphous material that is arrangement of the atoms actually hold for a short range maybe be one example is the glass, which is the non-crystalline structure. So in the sense that whether it is long range or short range this is the relative matter depending upon the scale of analysis however focusing to do this crystal structure or to explain the structure or different materials. So single crystal structure consist of one large crystal for example chip made from silicon is one of the single crystal structure, but it may consist of several unit cells.

Polycrystalline material many small crystals with varying orientation and actually we have tried to explain the continuum plasticity model which is the aggregate behavior of the different polycrystalline behavior. Now to analyze the crystal structure uhh we actually cover the following topic first was the theoretical density of the material, if we know what is the basic crystal structure of a material oriented BCC, FCC or HCP, we can find out the theoretical density of the uhh material. Then we discussed the (())(4:10) fraction of the crystal structure that actually within the unit cell, what is the volume of the unit cell occupied by the atoms that actually (())(4:22) the packing fraction of a specific crystal structure.

Then we discussed the radial issue of interstitial side, so within the atoms regularly arrangement of the atoms there will be some interstitial side so that side is very much important uhh in the sense that side by the ratio of the interstitial as well as the outer side which create actually interstitial side the radius of the atoms is important to know and we have discussed that for a different type of crystal structure the radius ratio actually varies and accordingly we can analyze the type of structure of a specific material.

Then we discussed the planar density and the linear density of the atoms along one plane or maybe along one direction, so the planar density actually represents the number of atoms exist one specified plane, linear density is the similar way number of atoms exist one specific directions. These are the only important to parameters to analyze the crystal structure that actually try to uhh characterize for the different mechanical behavior of the materials when you try to focus on the one specific crystal or one specific unit cell of a specific material.

Then we discussed different crystallography direction and planes in terms of the Milar indices of a specific crystal structure and that actually helpful quickly to identify the different plane, (())(6:02) or specific direction of close pack direction. And also we learned about how we can construct the different planes of directions in a unit cell. Last was the allotropic transformation, so one single material can exist different type of crystal structure depending upon the condition whether the temperature range that transformation actually indicates that when there is a change of the crystal structure from one for example BCC to FCC or vice versa then it must be accompanied with the change of the volume because the arrangement of the atoms actually changes from when the crystal structure changes from one to another.

So that allotropic transformation is sometime here to find out what is the change of the volume fraction within the unit cell when there is a change of the allotropic function and how actually it influence the structural form. This actually helpful to understand the plastic deformation behavior when it try to analyze the specifically change of the volume that actually induce some amount of the strain and this is very much (())(7:22) to the analyze within the microstructure of a specific material or maybe polycrystallization of a specific material. So this actually help to understand the crystal structure of materials and it will be helpful for further dislocation or further awareness of the topics.

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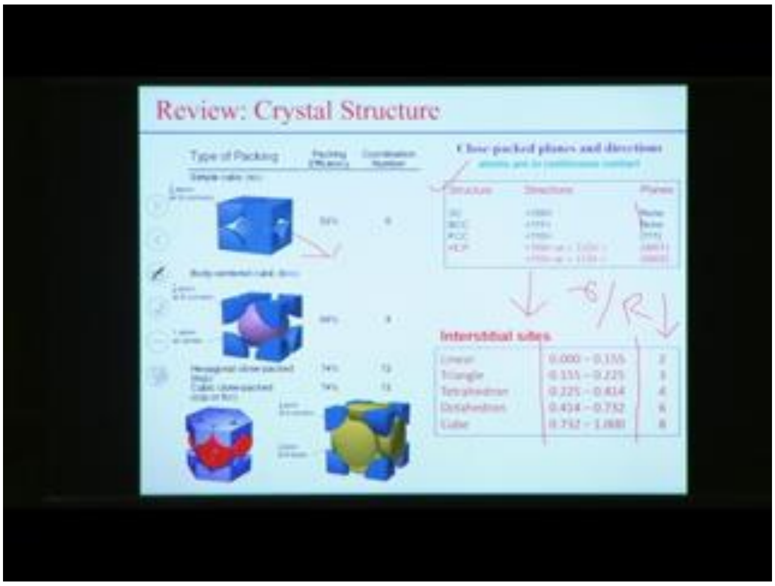

Review: Crystal Structure

Type of Packing

Close packed planes and directions

Interstitial sites

Linear	0.000 – 0.155	2
Triangle	0.155 – 0.225	3
Tetrahedron	0.225 – 0.414	4
Octahedron	0.414 – 0.732	6
Cube	0.732 – 1.000	8

Now here we are trying to represents that 4 basic crystal structure that FCC, simple cubic, BCC and HCP structure. All this structure there is a I think just to review the different parameters involved in the analysis of the crystal structure, for example simple cubic structure that exist some 8 corner atoms and packing efficiency is 52 percent, packing factor is only 52 percent and coordination number is correspond to the if we focus on atoms within the unit cell, how this atom is continuous conduct with so many atoms that actually decides the coordination number of a specific material, or specific crystal structure.

So simple cubic structure is having coordination number, 6 only. If you look into the body central cubic structure when there one atom exist under body along with the corner atoms, so it is having packing efficiency 68 percent and the coordination number is 8 here. But if we look into the hexagonal close packed structure or cubic close packed structure or we can say the phase center cubic structure, these two structure is having the packing efficiency 74 percent as well as the coordination number of 12.

So this FCC and HCP actually having some kind of uhh close relationship so that we have tried to explain that 4 axis system is used in case of hexagonal close packed structure and 3 axis is used for the cubic structure and the correlation can be possible, so that means the representation of the 4 axis system in terms of the 3 axis system was possible in this case. Now if we look into that specific arrangement of the atoms then we can explain what are the close packed planes and directions that we already investigated in case of simple cubic structure, uhh BCC structure, FCC structure and HCP structure all these cases the closed packed.

First we look into the closed packed planes, actually there is no (())(10:02) closed packed plane in case of the simple cubic structure and BCC structure, but FCC there is 111 plane is having close packed plane and HCP also having the closed pack plane 0001 or 0002. So in case of simple cubic and BCC structure the closed packed direction is 100 and BCC is having 111 direction, basically the 111 direction is the body diagonal direction and HCP is equal to 110 direction that actually represents the phase diagonal direction.

So if we look into that different structure and their corresponding closed packed planes and closed packed direction we can represent or we can use this (())(10:49) form to know about the closed packed planes and closed packed directions of different structure, but if we see that HCP and BCC structure actually there is no having well defined closed packed plane as compared to the FCC and HCP structure but still they can be analyze their several other we can construct the slip when it happens for the several other different planes, we will try to invest it later on, what are the slip and how the slip planes we can consider and how the deformation may happen in the different planes and the different directions in case of simple cubic and BCC structure.

Apart from that we have discussed the interstitial side that is important and we have tried to represents here the range of the radius ratio, actually the radius ratio here are small r, the side of the interstitial and capital R the side of the atom surrounding the interstitial side so that r by R ratio is the variation for the linear triangle tetrahedron and octahedron cubic this as a radius range, we have already discussed and if we see right hand side this actually represent the coordination number so that coordination number of the interstitial side, so that interstitial side is accompanied by the surrounding number of atom, for example in the cubic side it is having coordination number 8 and we and directly say the simple cubic structure and the center point we can fix one cubic side and then cubic side is surrounded by the H coordinate, so here the coordination number of this cubic side is 8.

Similarly we can analyze the octahedron and tetrahedron sides that we have already discussed and this octahedron and tetrahedron sides actually exist in case of FCC and BCC in both type of crystal structure. So this was just a review of this, the crystal structure.

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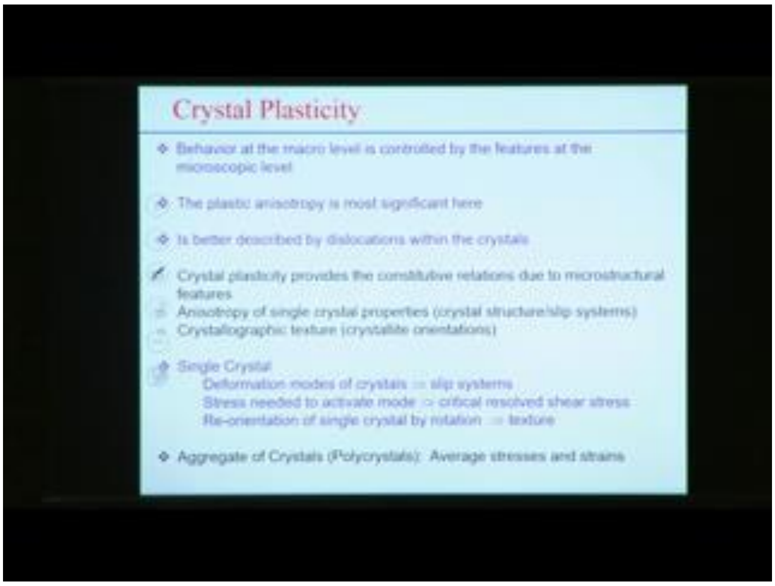

Crystal Plasticity

- Behavior at the macro level is controlled by the features at the microscopic level
- The plastic anisotropy is most significant here
- Is better described by dislocations within the crystals
- Crystal plasticity provides the constitutive relations due to microstructural features
  - Anisotropy of single crystal properties (crystal structure/slip systems)
  - Crystallographic texture (crystallite orientations)
- Single Crystal
  - Deformation modes of crystals => slip systems
  - Stress needed to activate mode => critical resolved shear stress
  - Re-orientation of single crystal by rotation => texture
- Aggregate of Crystals (Polycrystals): Average stresses and strains

Now we will start to the actual the crystal plasticity, what we mean by the crystal plasticity and why it is necessary. One thing is that behavior at the macro level is actually controlled by the features of the microscopic level. So when you try to analyze precisely the what is the deformation behavior is explained in the microscopic level and then that microscopic level behavior actually influence the microscopic behavior, most of the case of the microscopic behavior is represented by averaging the behavior which happens in the microscopic level.

So now we will try to focus what are the deformation behavior at the microscopic level so to do that one most important thing is that plastic deformation also happens in the single crystal structure but here the deformation is little bit different as compared to the microscopic level, so here the plastic deformation that means most aligned or oriented to the plastic anisotropy condition. So it is important or here it is very much significant when you try to analyze the microscopic level of deformation, you need to consider the anisotropy deformation behavior of the material.

But this behavior is better explained by the dislocation or motion of movement of the dislocation within the crystals, for example when you try to analyze the continuum plasticity in this case we started with the deformation behavior from a single tension test data or relation between the stress and strain and accordingly we can decide whether it is deformation within elastic meet or plastic slip. But in this case we will try to focus on the how slip will happen in the single crystal structure and when there is a start of the deformation, plastic deformation within the single crystal so that will try to get it from this overall crystal plasticity, different theories of the crystal plasticity.

So crystal plasticity actually provides the constitutive relations due to the microstructural features okay, so anisotropy of single crystal properties actually depends on the crystal structure of the specific material and what are the slip system exist within that materials. Secondly the crystallographic section that is basically the crystalline orientation actually brings the anisotropy behavior and that is very much related to the crystal plasticity so that behavior will try to explain by looking into the basic mechanism that means the dislocations and the slip mechanism and the motion of the dislocation and finally the hardening behavior of this material simply by explaining the mechanism of dislocation.

So single crystal the mode of deformation actually related to the slip system within the unit cell, secondly we will focus on that stress needed to activate the mode of deformation that is related to or that is define in terms of the critical resolve shear stress, so basically shear stress actually induces the amount of the shear strain and that introduces the slip within the crystal structure. And finally reorientation of the single crystal by rotation that actually is from the structure. But aggregates of the crystal basically polycrystal we will try to explain all these things, averaging the stress and strain we try to explain the plastic deformation of the materials.

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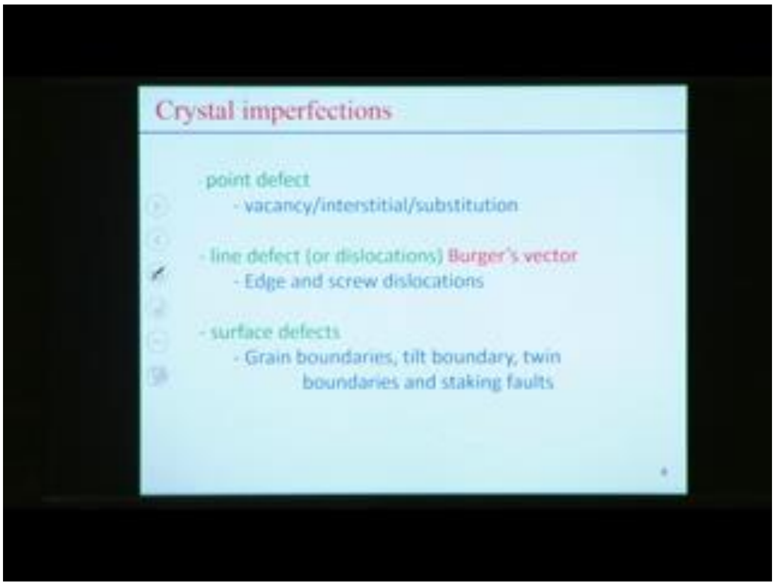

Crystal imperfections

- point defect
    - vacancy/interstitial/substitution
- line defect (or dislocations) Burger's vector
    - Edge and screw dislocations
- surface defects
    - Grain boundaries, tilt boundary, twin boundaries and staking faults

So now to start with that crystal plasticity first step is to analyze the what are the crystal defects, so practically if we look into uhh the structure of the material and if we focus on single crystal it maybe consist of the several defects can be divided into three components one is the point effect, then line effect or in other way line effect can be called as a dislocation and finally the surface defect, so first we will look into the point defect and existence of the point defect within a regular arrangement of the atoms of a single crystal structure.

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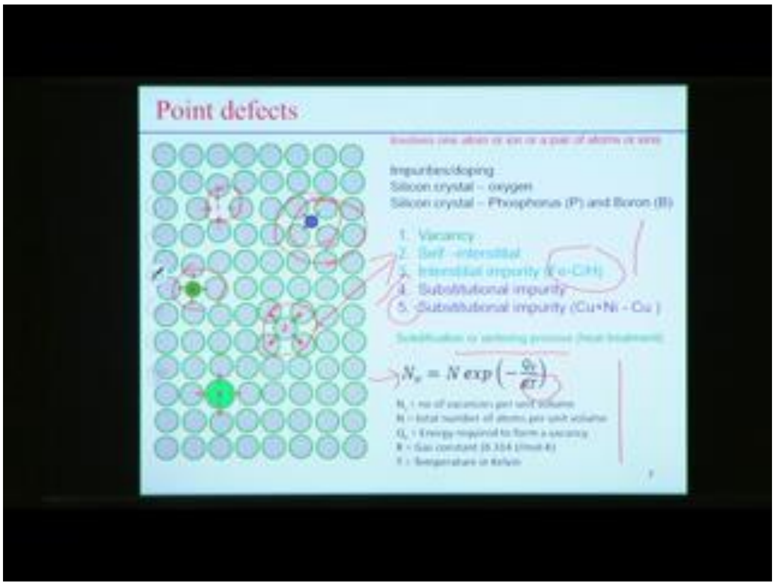

Point defects

Impurities/doping

Silicon crystal – oxygen

Silicon crystal – Phosphorus (P) and Boron (B)

1. Vacancy
2. Self -interstitial
3. Interstitial impurity
4. Substitutional impurity
5. Substitutional impurity (Cu+Ni - Cu)

$$N_v = N\,exp\left(-\frac{Q_v}{RT}\right)$$

So point defects it involved one atom or ion or pair of atoms or ions, so normally if we look into silicon crystal so normal impurities in this silicon crystal exist as oxygen, so that is that happens actually natural so that oxygen existence of the oxygen between the single crystal structure can be consider as a defect exist and that defect exist for the point defect. Now if we look into the silicon crystal but if we add intentionally the phosphorous or boron to improve the electrical conductivity of this material that can consider as defect of that, this type of defect is beneficial or two orient the single crystal to bring some specific properties of (())(19:07) some properties for a single crystal structure.

But basically how we can categories the different type of point defects so that actually point represents in terms of the space of a specific atom or interstitial side here, so first one type of defect is that is called vacancy, so if we look into the vacancy it is a simply the point one actually represents the defect line vacancy so here simply missing of the atoms from the regular arrangement of the atoms, so that type of defect is vacancy. Second is the sell interstitial, if we look into the point 2, here that the interstitial sides, that means we do try to regular arrangement of the atoms and if uhh interstitial position is occupied by the similar kind of atom then it will create a defect that is called self interstitial and this type of defect is that similar type of atoms will try to occupy that position and which create amount of strain or stress field surrounding circuit area.

Now interstitial impurity, for example point 3, in this case that the interstitial side occupied with another atom but that is smaller in size, so for example carbon and hydrogen can take that position in case of uhh when you try to react with the iron. So basically the low carbon strain for example, the carbon acts as a impurity so that carbon will try to take always the interstitial position but size of the atom in this case is smaller as compared to the parent atoms, in this case with respect to iron atom so this type of impurity or self or interstitial impurity, both type of defects happens in case of normal material.

Now if you look into the fourth point that corresponds to the substitution impurity, here in this case the actual atom is actually replaced by the other atom or it is substituted by the other atoms so this type of defect actually called the substitution impurity and if you look into that fifth position that is also substitutional impurity but in this case the substitutional impurity size specifically bigger as compared to the parents atoms here. For example while making it alloy copper and nickel, copper actually crate this kind of impurity in the regular structure of a crystal.

So now the different types of point defects can be observed during the solidification of the centering process or sometimes heat treatment we can observe the this all this types of point defects. Now number of vacancies per unit volume so which is very much related to the point defect so that vacancy of number of vacancy creation is depends on the total number of atoms per unit volume and some energy you can form the vacancy as well as the temperature. So if we look into this expression here n, v actually represents the number of vacancies per unit volume and where A is the total number of atoms per unit volume and it depends on exponential of minus QV by RT.

So QV is the energy required to form one vacancy and R is the gas constant and t is the temperature. So actually the number of vacancy is very much dependent on this parameter that is temperature. So using this temperature we can roughly estimate the number of vacancies created in one specific material depending upon one specified temperature.

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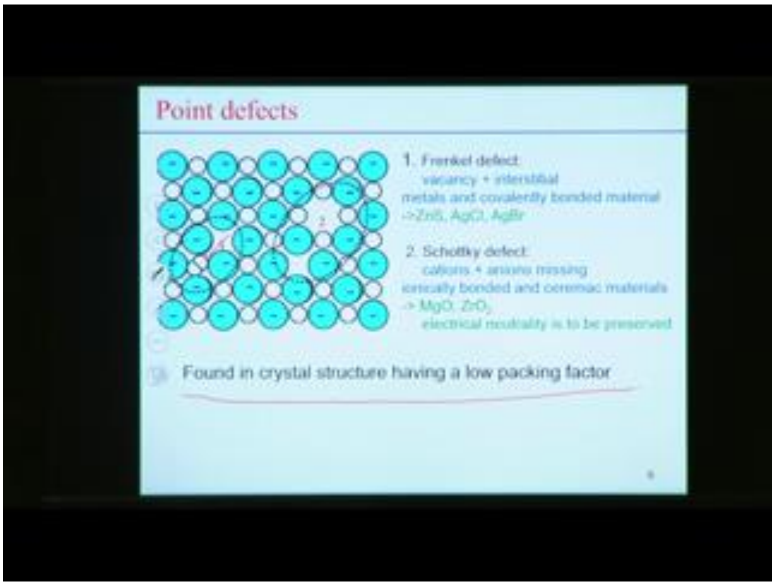

Point defects

1. Frenkel defect
   vacancy + interstitial
   metals and covalently bonded material
   ->ZnS, AgCl, AgBr

2. Schottky defect
   cations + anions missing
   ionically bonded and ceramic materials
   -> MgO, ZrO_2
   electrical neutrality is to be preserved

Found in crystal structure having a low packing factor

So there is also another point like we call the Frenkel defect that in that case point 1 actually it creates the one anion per cation, in this case that is uhh creation of the vacancy the same time the similar ion will take the interstitial position, so displacing forces the interstitial position. This type of defect is generally called Frenkel defect. And metals and covalently bonded materials having this type of general defect, for example zinc sulfate, AgCl, AgBr, that are the typical compound where we observe Frankel defect.

Similarly Schottky defect also, here the cations and anion actually missing, so in this case the both cation and anion miss one position so that type of defect is called Schottky defect and specifically ironically bonded and ceramic materials, these types of defects are observed examples are Magnesium oxide, ZrO2, but in this case of course it always try to maintain the electrical neutrality but this type of defect actually found in the crystal structure having low packing factor material.

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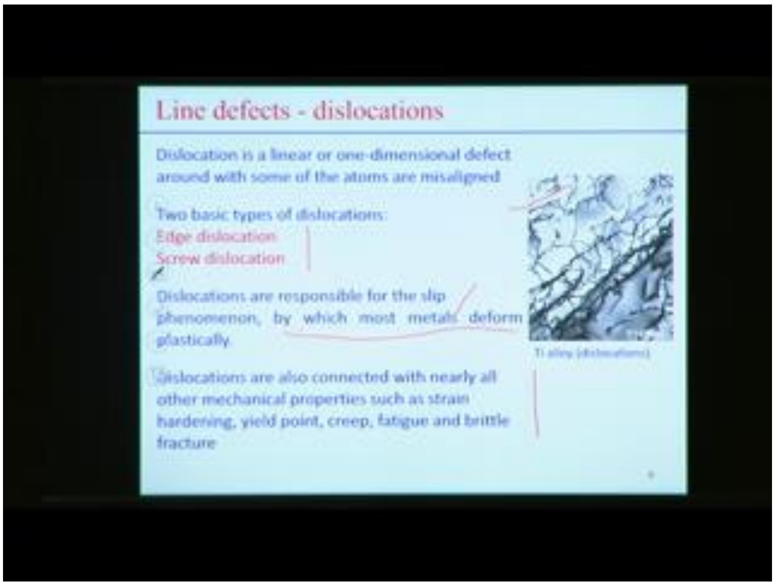

Line defects - dislocations

Dislocation is a linear or one-dimensional defect around with some of the atoms are misaligned

Two basic types of dislocations:
Edge dislocation
Screw dislocation

Dislocations are responsible for the slip phenomenon, by which most metals deform plastically

Dislocations are also connected with nearly all other mechanical properties such as strain hardening, yield point, creep, fatigue and brittle fracture

Ti alloy (dislocations)

Now we see it to the line defect or we can say the line defect as a dislocation. Dislocation is a linear or 1 dimensional defect around with some of the atoms are misaligned. So two basic types of dislocations, edge dislocation and screw dislocation, that is the representation of the dislocation, while if you look into that right hand figure here see for titanium alloy, the dislocations are observed, so uhh dislocation is basically uhh we can say that simply misalignment of the atoms for number of atoms and that actually disturbs the regular arrangement of the atoms, so several dislocation and that dislocation can be generated, dislocation can move from one point to the another point.

So this is a one typically representation of the defects that is specifically represent the dislocation in terms, that is called line defect, so basically we represent the dislocation in terms of the unit of the length. Now dislocation actually responsible for the slip phenomena by which most of the metals deform plastically. So we can better explain by looking into the basic mechanism of the dislocation, the slip phenomena or plastic deformation behavior of the material.

Dislocation are also connected to nearly all other mechanical properties, for example such as strain hardening, yield point, creep, fatigue and brittle fracture, all this phenomena can explained using the concept of the dislocation, so it is necessary to understand the, what are the dislocations and how it represents the dislocation here. So typical two basic types of dislocation that means edge and screw dislocation, we will discuss further that what are the edge and screw dislocation.

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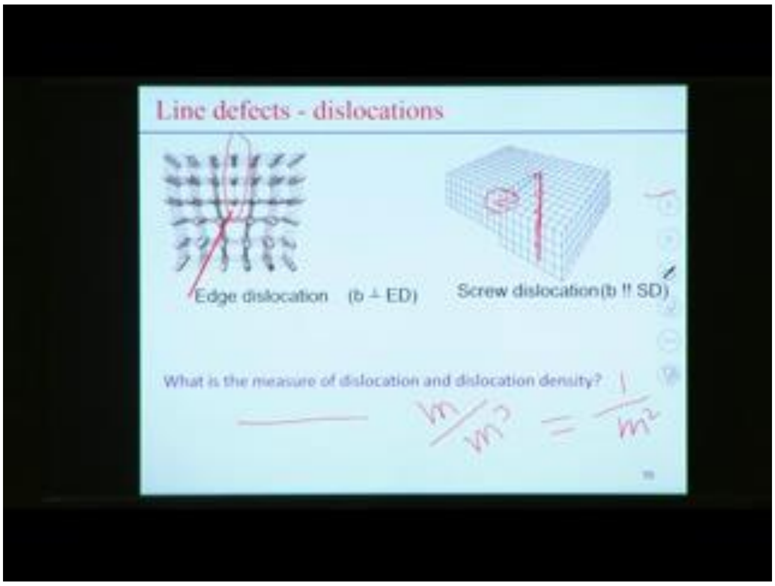

Line defects - dislocations

Edge dislocation (b ⊥ ED)

Screw dislocation(b ‖ SD)

What is the measure of dislocation and dislocation density?

$\frac{m}{m^3} = \frac{1}{m^2}$

So this leaves us in the simplest schematically representation of uhh edge dislocation and here if you see the schematic representation of the screw dislocation, so it can be explained like that, for example there is a regular arrangement of the atoms, now if you look this here, this extra plane of the atoms actually disturb the regular arrangement of the atoms, but it happens during the metal crystal, so when there is a existence of the extra plane of atoms in such a way that actually create the edge dislocation, so this type of dislocation, so is with respect to this point, so edge dislocation that (())(27:59) to this plane represents the dislocation line.

But in this case dislocation is characterized in terms of the Burger’s vector, we will come later on. So this type of if configuration of the atoms is like this so there is a extra plane of atoms from the upper side otherwise we can see there is a missing of the atoms from the bottom plane, then that actually produces the uhh dislocated the actually arrangement of the atoms and this type of dislocation we can call as edge dislocation.

Now screw dislocation actually uhh when regular arrangement of the atoms is disturbed by (())(28:46) by the shear respect to that center point. So that center point and this is the, actually this point we can find out that (())(29:00) to that point, regular arrangement of the atoms and this (())(29:03) representation of the screw dislocation and of course this screw dislocation also characterized by the Burger’s vector. Now point is that what is the measure of dislocation and actually and what is the dislocation density. So basically the measure of dislocation is the measure of length so simply we represent the dislocation by a line, what is the length of the dislocation that is the uhh measure of the one dislocation.

Now dislocation density, so dislocation density probably if you consider the SI unit, so length of the dislocation for example it is, meter. Now density, what is the total number of dislocation or total length of dislocation within the crystal structure itself, so it simply add all the dislocations and that representation of the total length divide by the volume, for example in SI unit it maybe meter cube. So finally the dislocation density is basically unit is 1 by meter square for example. So these are the measurement of the dislocation and dislocation density will further discuss on that topic.

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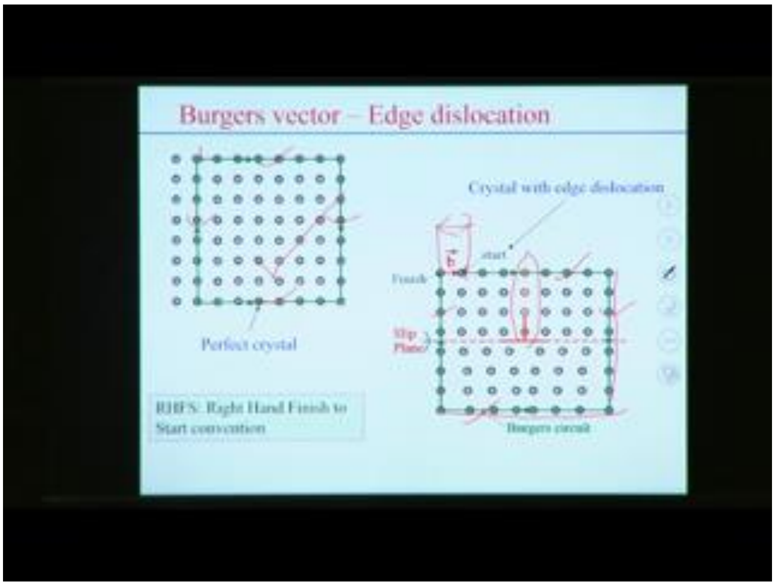

Burgers vector – Edge dislocation

RHFS: Right Hand Finish to Start convention

Now what is the, we characterize the dislocation in terms of the Burger’s vector but how we can represent the Burger’s vector and how to find out the Burger’s vector. If we look into that left hand side figure, this figure, her we see, this figure that it represents the regular arrangement of the atoms and if we start from one point from this point and if we make it close circuit that representation of the perfect crystal, so close circuit in the sense the total number of atoms covered in the upper side, covers the vertical line, along the vertical line or the numbers along the horizontal line, these are the number of shape, upper shape and lower shape is the same number of atoms it is covering this thing and it is for the perfect crystal we making this close circuit.

Now if there is introduction of the one extra plane of the atoms, here if we see this extra plane of the atoms actually disturbs the regular arrangement of disturb the perfect crystal structure.

So in this case if we follow the same circuit what we consider for the perfect crystal and if we start from this point we count this number, if we count this number, so uhh that is like a this count on the line, the total number, the total number is same similarly this side and this is same and we gain at this point.

So this here actually represents the Burgers vector for this specific configuration of the crystal structure. So Right Hand Finish to Start the convention so that we follow it and we can find out the start and finish point is the total number of (())(32:45) balancing, but there is a gap, this gap actually represent the Burger’s vector, so that is corresponds to, so this structure actually corresponds to the edge dislocation structure and this is edge dislocation structure, actually this is the representation of the Burger’s vector but in this case dislocation line actually if we go back to the previous, in this case the dislocation actually represents the Burger’s vector like this, but dislocation line is perpendicular to this plane of this spin.

So that dislocation Burger’s vector actually perpendicular to the edge dislocation line in this case. Similarly for the screw dislocation actually this represent the Burger’s vector but dislocation lies in center, so in this case the screw dislocation, the Burger’s vector actually parallel to the screw dislocation line.

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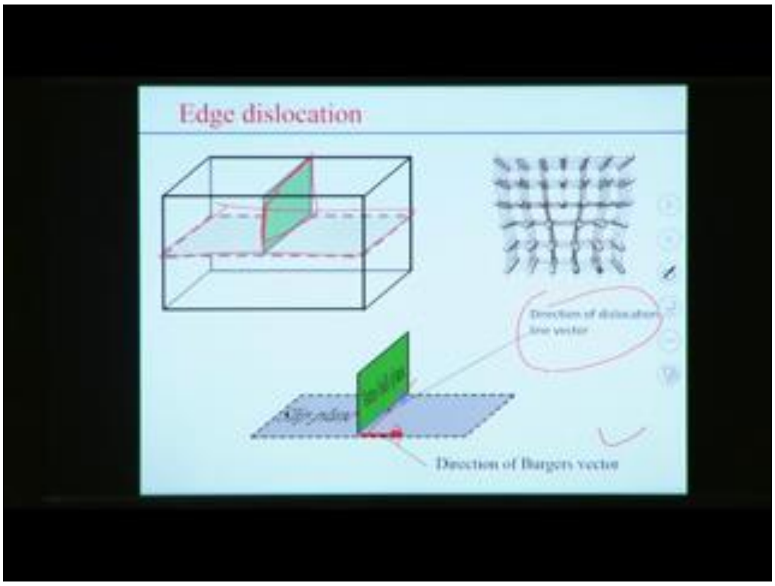

Edge dislocation

Now it will be better understood that how it represents the edge dislocation, so if we see that this is the extra plane of the atom, this define in this figure, and that extra plane of atom maybe presence or existence from the upper side, so in this case the extra plane of the atoms and this plane is considered as the, in case of edge dislocation considered as the slip plane, because slip will happen along on this plane and this extra half plane, due to the presence of the extra plane this is the representation of the direction of the Burger's vector.

But at the same time, the normal to the on this plane, normal to this plane that actually represents the direction of the dislocation line vector, so here is the dislocation line vector and it is Burger's vector so in case of specifically for edge dislocation this dislocation line vector and the Burger's vector perpendicular with each other.

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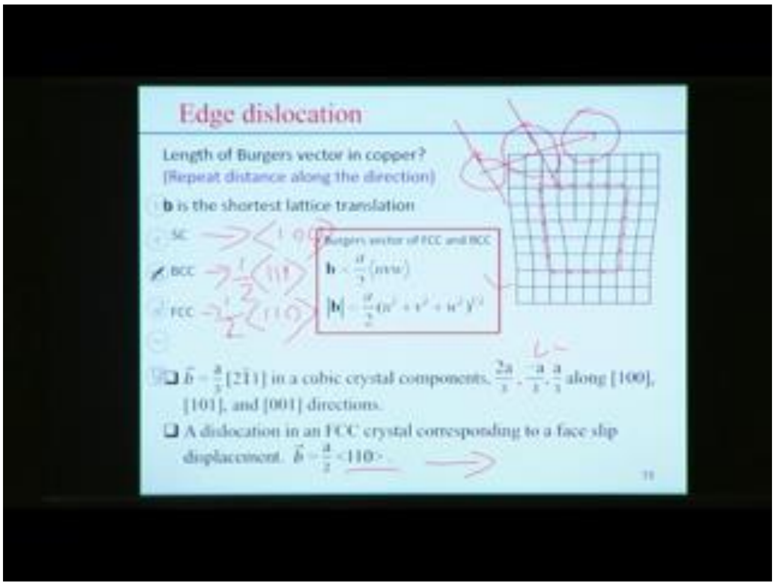

Edge dislocation

Length of Burgers vector in copper?
(Repeat distance along the direction)

b is the shortest lattice translation

- SC → <100>
- BCC → $\frac{1}{2}$<111>
- FCC → $\frac{1}{2}$<110>

Burgers vector of FCC and BCC

$\mathbf{b} = \frac{a}{2}\langle uvw \rangle$

$|\mathbf{b}| = \frac{a}{2}(u^2+v^2+w^2)^{1/2}$

- ❑ $\vec{b} = \frac{a}{3}[2\bar{1}1]$ 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, what maybe the length of the Burger's vector for a specific material how we can estimate this things. Actually the Burger's vector representation in the repeat distance along the direction, repeat distance is the shortest distance of the atomic arrangement so other ways b is the shortest lattice translation. For example, in case of simple cubic structure actually the shortest repeat distance means when you consider the atomic arrangement along one specific direction so in this case the discharge from one atom to the next atom, uhh that distance what is the possible combination of the, several possible combination of the direction which is the unit cell or that direction exist several combination of the plane.

So on that plane on the specific direction what is the shortest distance between the two atoms that can be consider as a full dislocation, or that can be consider as a measure of the Burger's vector. So in case of simple cubic structure the shortest distance actually exist along the edge, so that means the direction maybe we can say 100, but in case of BCC structure or FCC structure we can see that BCC structure Body central structure the shortest distance along the body diagonal, so along the body diagonal there are the arrangement of the atoms is like this, the corner atom, body atom and the another next corner atom.

So representation of the Burger's vector in this case it is the this division. So half of the, we can say the half of the body diagonal, so we can represents this direction is uhh BCC 111, but this is the, this represents the direction of the body diagonal but repeat distance is the half of that. So half of 111 actually represents the Burger's vector in case of BCC structure. Now what happens in case of FCC structure, in case of FCC structure the shortest distance actually exists between the two atoms along the face diagonal, so along the face diagonal also similar arrangement of the atoms, so it is the one corner atoms and it is the another corner atom and there is between the face atoms.

So similarly FCC also the half of face diagonal 110 that is the 110 actually represents the face diagonal so half of that represent the shortest lattice structure distance so that is the representation of the Burger's vector, so in general for Burger's vector for FCC and BCC can be represented by a by 2 and uvw represents the (())(38:36) of a specific directions, so specific direction in the case here is the closed pack direction. So the magnitude of that Burger's vector can be represented like this a by 2, this curve plus this curve of root. This is the general way to find out the Burger's vector or a specific crystal structure.

So if we know the lattice parameter of for a copper and copper actually follows the FCC structure so then we can easily find out the length of the Burger's vector in case of copper. Now if we represents the Burger's vector in other way, for example Burger's maybe represented, a by 3 to 11 in a cubic crystal component, so component can be represented like that in terms of coordinate 2 a by 3 minus a by 3 a by 3 along 100 direction along the x axis, first component, second component is along 101 y axis for example and third component say 001 directions. So this is the other way some representation of the Burger's vector.

Now a dislocation in a FCC crystal structure corresponding to the face slip displacement, so in this case the FCC structure corresponding face slip displacement, in this case the Burger's vector will be represented along the compact direction so b is the representation of the a by 2 110, a is the lattice parameter in this case, so 110 actually this direction, it is a family of directions, so 110 represents the face diagonal direction. So these are the typical representation of the Burger's vector.

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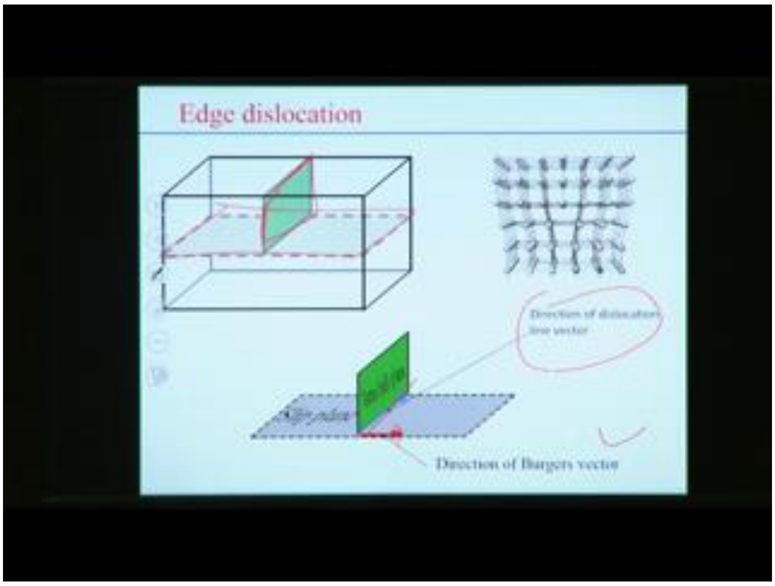

Edge dislocation

And here we have discussed the representation of the dislocation line. Point is that this represents the dislocation line and this represents the Burger’s vector.

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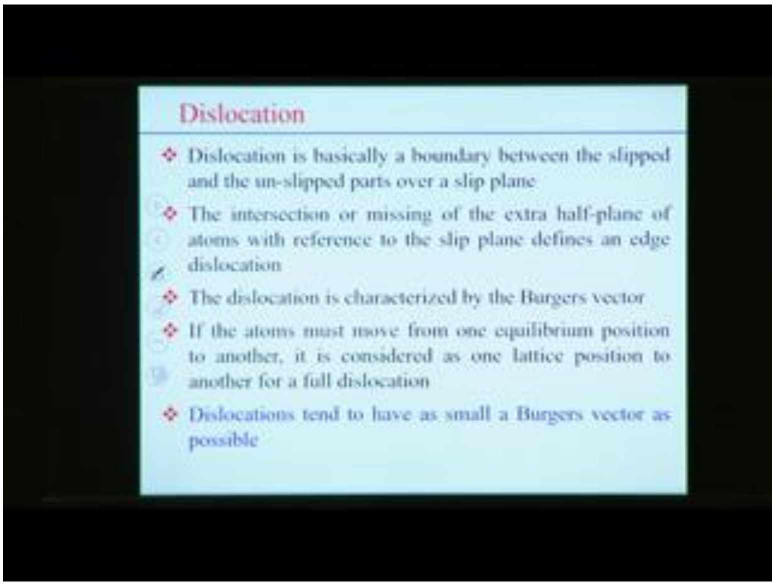

Dislocation

- Dislocation is basically a boundary between the slipped and the un-slipped parts over a slip plane
- The intersection or missing of the extra half-plane of atoms with reference to the slip plane defines an edge dislocation
- The dislocation is characterized by the Burgers vector
- If the atoms must move from one equilibrium position to another, it is considered as one lattice position to another for a full dislocation
- Dislocations tend to have as small a Burgers vector as possible

Now we come to that point dislocation, how we can define the dislocation, actually dislocation is basically a boundary within the slipped and un-slipped parts over a slip plane. So it actually distinguish between the slipped and the un-slipped part, that is the representation of the dislocation, the interaction or the missing of the extra half-plane that we have already discussed of with reference to a slip plane actually defines an edge dislocation. The dislocation is characterized by the Burger’s vector. If the atoms must move from one equilibrium position to another then it is considered as one lattice position to another for a full dislocation.

So if one complete transformation of the one lattice point to the another translation that is corresponds to a full dislocation. But it is also possible to partial dislocation that we will discuss later on. Now dislocations actually always tend to have the small Burger's vector as possible, so that is corresponds to the created, can be created in such way that always he will try to follow the short repeat distance that means that's was repeat distance actually exist for common material in terms of closed packed direction.

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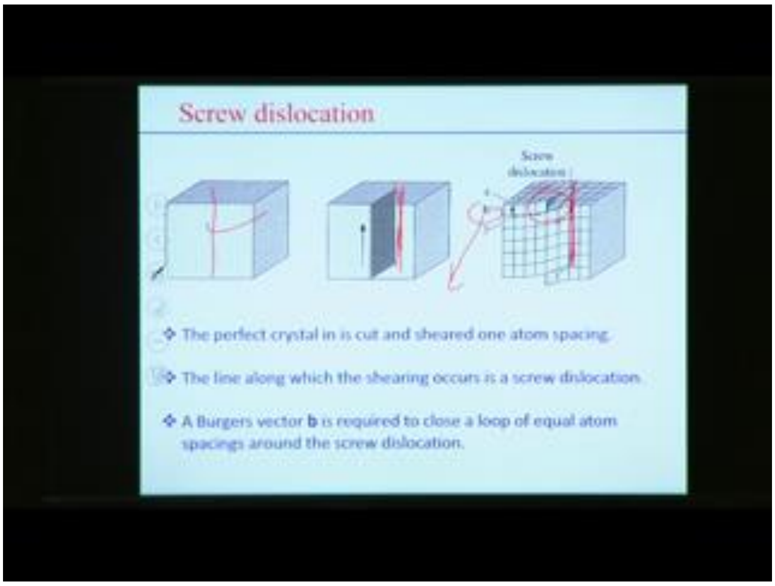

Screw dislocation

- The perfect crystal in is cut and sheared one atom spacing.
- The line along which the shearing occurs is a screw dislocation.
- A Burgers vector **b** is required to close a loop of equal atom spacings around the screw dislocation.

Now we will shift to the dislocation of the screw dislocation. So in screw dislocation if we look into that, first figure actually represents perfect crystal and then it is cut and sheared one atoms spacing. So it is cut in certain position and there is a sheared action between this, on this cardiac plane and if we see the line along with the shearing occurs in a screw dislocation. So with respect to one line the shifting of the one lattice point, that actually represents the screw dislocation and if we see the Burger's vector is represented that one lattice translation point so that is corresponding to the b, so this amount is b just very much clear from the figure itself.

But in this case the dislocation line actually was screw dislocation like is a (())(43:23) plane found here, the screwing start with respect to the plane with which the shear actually happen, so this is line actually representation of the screw dislocation line which is little bit different from the edge dislocation line. Now the Burger's vector b is required to close a loop of equal atom spacings around the screw dislocation. So similar if we put it here the close circuit, according to the definition of the Burger's vector then we find out there is a gap of the one atomic spacing and that gap actually represents the Burger's vector in case of screw dislocation.

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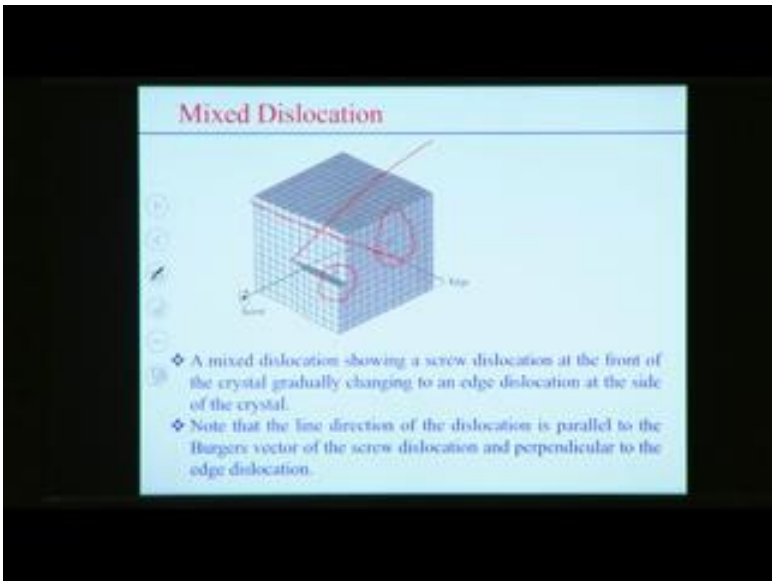

Mixed Dislocation

- A mixed dislocation showing a screw dislocation at the front of the crystal gradually changing to an edge dislocation at the side of the crystal.
- Note that the line direction of the dislocation is parallel to the Burgers vector of the screw dislocation and perpendicular to the edge dislocation.

So both edge and screw dislocation both actually represents in terms of the or characterize in terms of the Burger's vector and, when it is corresponds to the full dislocation then we can say it is corresponds to the one lattice point translation in this case. Now practically there maybe the possibility of the existence of the mixed dislocation, so existence both screw as well as the edge dislocation. So our next dislocation showing a screw dislocation at the front of the crystal gradually change screw dislocation and then the dislocation line is with respect to that direction and this is the representation of the Burger's vector.

But if we look into the at the same time the direction of the dislocation is parallel to the Burger's vector only screw dislocation but in case of edge dislocation we see this is the extra plane of the atoms actually adding here and that produces some amount of the dislocation here, edge dislocation, that edge dislocation actually perpendicular to the dislocation, the Burger's vector. So edge dislocation actually exists this internally this direction and screw dislocation is exit actually internally this direction and Burger's vector is direction parallel to the screw dislocation but edge in this case, the edge dislocation which is perpendicular to the Burger's vector, which is perpendicular to the edge dislocation in this case.

So that mixed dislocation can also be produced or sometimes it is observed there is the existence of the mix dislocation consistently edge and screw. So this are the some basic idea about the edge dislocation and screw dislocation and how to represent dislocation in terms of the Burger’s vector. Now we will shift to the next surface defects within the crystal structure.

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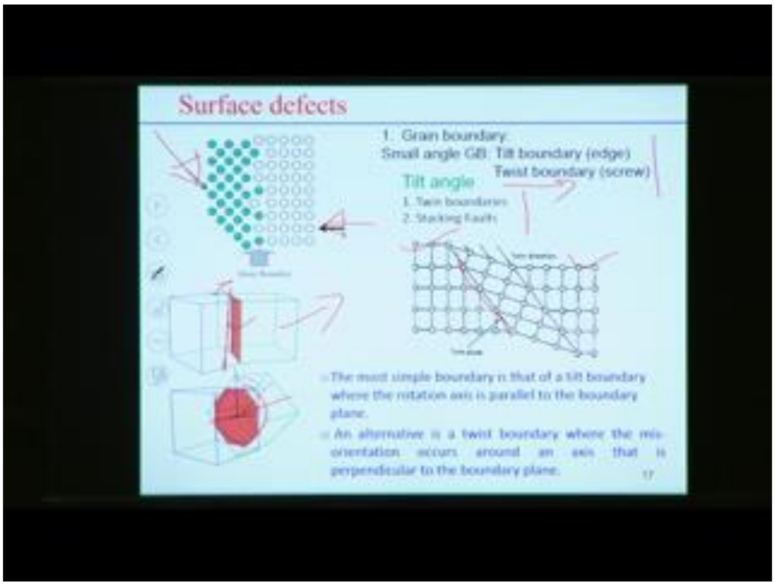

Surface defects

1. Grain boundary
Small angle GB: Tilt boundary (edge)
Twist boundary (screw)

Tilt angle

1. Twin boundaries
2. Stacking Faults

- The most simple boundary is that of a tilt boundary where the rotation axis is parallel to the boundary plane.
- An alternative is a twist boundary where the mis-orientation occurs around an axis that is perpendicular to the boundary plane.

Surface defect normally if we find out that if there is a difference in the orientation of the atoms uhh, so orientation of the crystals basically, that actually define a boundary between these two. So if we look into that the orientation of the atoms, orientation of the crystals this direction and in this the way the orientation of the atoms is this direction. So then there must be some clear distinguish boundary between these two orientations, that boundary is actually called as the grain boundary. One grain is having one orientation and another grain have another orientation, so this grain boundary were the typical translation generally used in the grain boundary that is small angle grain boundary, so orientation difference may not be very high.

So small orientation difference can be consider as the small angle grain boundary so if orientation difference angle form is very high then it is high angle of grain boundary can be consider. Now the small angle grain boundary you get having the tilt boundary, we can define the twist boundary whether tilt boundary actually in terms of the edge dislocation representation of twist boundary we can represent the correlate in terms of the screw dislocation. So now we need to find out what is tilt angle, next part I will focus on how to find out the tilt angle.

And twin boundaries and stacking faults are the other kind of defect generally we observe, so here if we see that uhh tilt boundary, the most simple boundary is the tilt boundary where the rotation axis is parallel to the boundary of the plane. If you look into this figure, here if you see that the tilt boundary the rotation axis is parallel to the boundary plane, so we define this as a color form, that is the boundary plane and if there is a movement or angle from small angel form is there, uhh that angle actually represents the tilt angle so this type of typical boundary is considered as a tilt boundary or the rotation axis parallel to the boundary plane.

So basically with respect to the rotation axis, so here it is the rotation axis, rotation axis is actually parallel to the boundary, so this type of boundary is called the tilt boundary. But twist boundary whether miss orientation occurs around an axis that axis is perpendicular to the boundary of the plane, so if this is the boundary, by rotation axis is perpendicular to the boundary and there is a twist between the, we can say that between the two grains so that kind of boundary is called the twist boundary.

Twin boundaries if we look into that orientation of the grain of orientation of the atoms in such a way that one part, another part they actually the mirror image with respect to each other, with respect to certain plane so that type of plane is basically called the boundary, that is called the twin boundary and this plane I think is define as the twin plane and this direction actually basically represents the twin direction. So this are the different types of main which is the surface defect that exist within the crystal structure.

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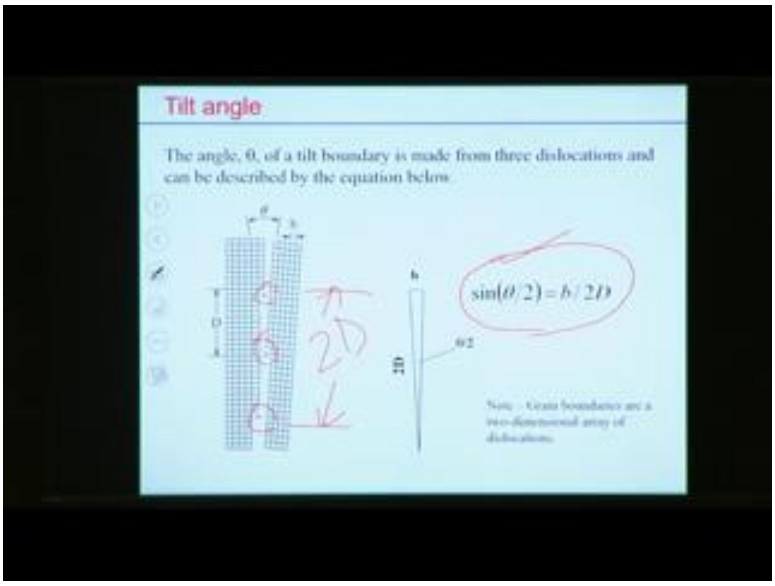

Tilt angle

The angle, θ, of a tilt boundary is made from three dislocations and can be described by the equation below

$$\sin(\theta/2) = b/2D$$

Note – Grain boundaries are a two-dimensional array of dislocations.

Now we are look into the tilt angle, how we can find out the tilt angle, for example the angle theta of a tilt boundary is made from three dislocation and can be described by the equation below. So this is the three dislocation, so represents in the three edge dislocation here, tilt angle or tilt boundary is corresponds to the edge dislocation. So in this case that if these are distance between the dislocations and we represents the Burger's vector here, now if there exist three dislocations so we can find out the angle theta but all the three dislocation but it is total corresponds to this to this, actually basically distance is 2D.

So that 2D, b is the Burger's vector and this angular form is the symmetric with respect to only theta by 2, so this relation holds to the sin theta by 2 equal to b Burger's vector or magnitude of the Burger's vector divide by 2D. So this is the relation of representation of the tilt angle. Now actually grain boundaries are 2 directional array of dislocations and what we have discussed that we can correlate this edge and screw dislocation in this case, representation of the 2 dimensional array of the edge at screw dislocation depending upon the type of the grain boundary, whether it is a tilt boundary or whether it is twist boundary.

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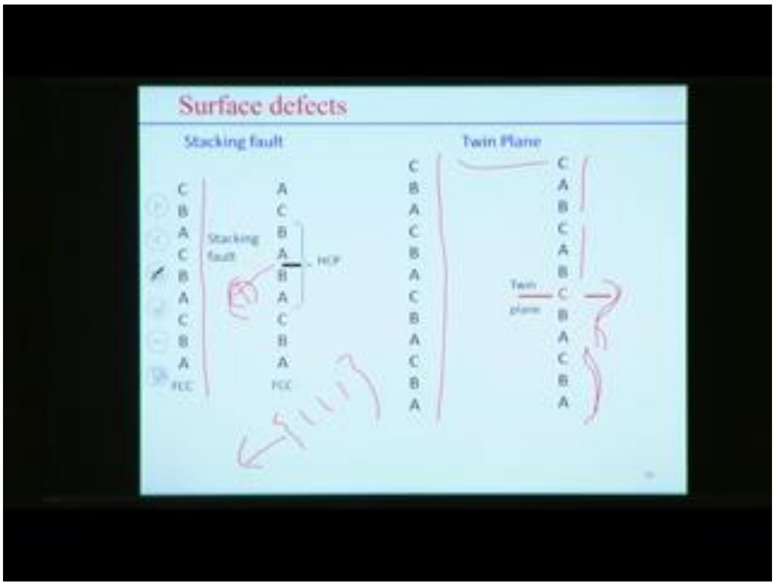

Surface defects

Stacking fault

Twin Plane

Now another surface defect that is called the stacking fault or twin plane. Stacking fault we understand the we have discussed the stacking sequence in case of FCC structure and we have discussed the stacking sequence of the HCP crystal structure. The atomic arrangement with the crystal structure exist. If we simply se the HCP structure on the base plane there is a follow specific arrangement of the atoms if we see to the next plane, they exist on the three atoms and if you see the next upper plane of the HCP crystal structure if we look the repetition of the base plane structure so that sequence of the atoms can be represented like is that one the form of A, for example next layer we consider this different arrangement of the atoms b, and let us, there again if it is of the base plane so that we can consider another A.

So in case of HCP structure the stacking sequence can be consider like that A, B, AB, AB like that, or in case of FCC structure and if we consider the FCC structure stacking sequence or atomic arrangement of the different plane, so that plane is basically normal to the 111 plane, so 111 plane if we consider the three, if we define the in case of FCC structure, if we define the 111 plane and if we consider the stacking sequence normal to that plane it follows like that A, B, C and similarly sequence of the arrangement ABC, ABC this are the typical stacking sequence in case of FCC structure.

But stacking sequence actually exists normal to the 111 plan, now with the regular arrangement of the stacking sequence, if there is an absence of any layer sequence then this actually creates some amount of the stacking cover. For example in FCC structure there is a missing of the one layer, so A, C, B, so A, C and B, like that C actually missing here. So since this missing of the here actually creates one of the defect that is called the stacking point. Actually BA BA within that layer these actually follow the sequence of the HCP structure, because HCP structure only two stacking sequence is generally follow and repetition of the same afterwards.

Now if we look into that twin plane, there is the regular arrangement is like that CBA is the perfect arrangement, CBS, CBS and CBA like that. Now if the deformation, if the sequence of the stacking is like that CAB but at the same times other CBA and CBA so this actually with respect to that plane they actually create the twin plane according to the sequence of the atoms and this actually happens in most of the case, the plastic deformation during the plastic deformation. So these are the stacking sequence grain boundary or stacking (())(55:13) all is considered as a surface defect so that means the defect actually happens over the area, this type of defects.

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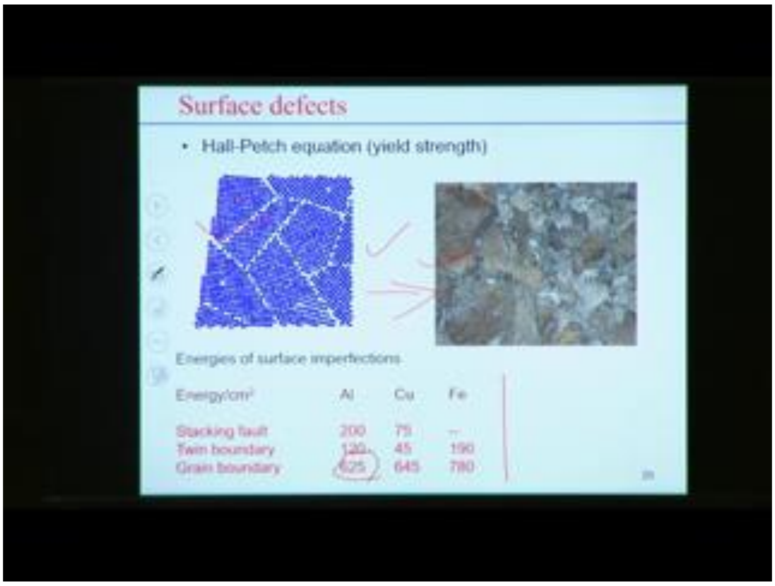

Surface defects

- Hall-Petch equation (yield strength)

Energies of surface imperfections

Energy/cm^2	Al	Cu	Fe
Stacking fault	200	75	--
Twin boundary	120	45	190
Grain boundary	625	645	780

Now we can find out this see we can see the actual structure of a material, if you see the one grain is separated by the grain boundary and then grain boundary is consider as our defect, so that defect mostly representation in terms of the dislocation. If you look into this figure also that schematically representation of the grain boundary, so orientation of the grin boundary, so orientation of the grains are different, that orientation is separated by one specific boundary.

So these are the representation of the WhatsApp, explanation of difference kind of defects exist whiten the crystal structure itself. Now if you look into that comparison of the different energy associated, definitely when it is associated uhh some amount of defect, and that defect (())(56:24) break some amount and associated with some amount of the energy in the crystal structure. Now if we compare the different type of defect exist in the crystal and what are the energy associated with the defect, they will get some idea what is the contribution of the different defects here.

So for example stacking fault in for example in aluminum stacking fault energy for (())(56:45) are is 200, example twin boundary is 120 and grain boundary 625, so grain boundary is energy is more important here in this case, and most all the other materials also if we look into the energy associated with the different surface defect then we can find out grain boundary energy is more amount of energy stored within the material itself. So that means the when metal is associated some defect and that defect is associated to some amount of the energy so more defect exist within the material is associated with the more amount of energy is actually deposited or maybe more amount of energy actually involved in the crystals.

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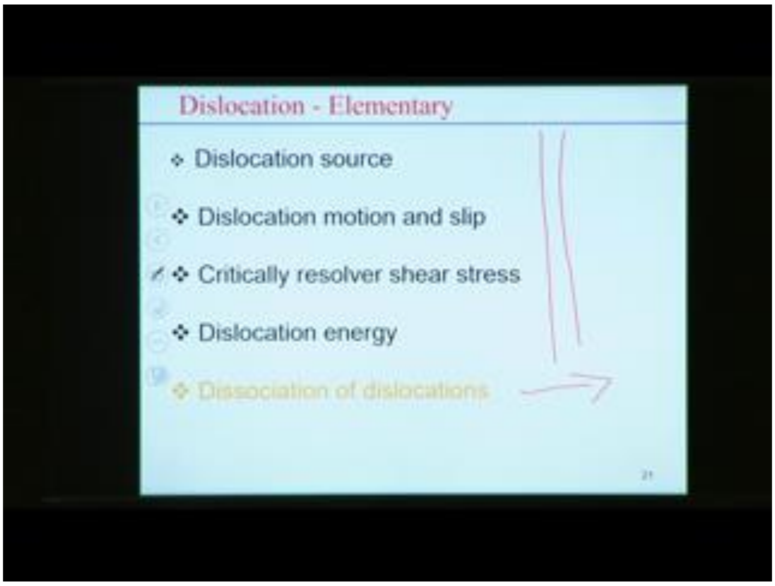

Dislocation - Elementary

- ❖ Dislocation source
- ❖ Dislocation motion and slip
- ❖ Critically resolver shear stress
- ❖ Dislocation energy
- ❖ Dissociation of dislocations

Now we will come to that point the dislocation, elementary discussion of the dislocation from the surface defect, basically we have discussed the surface defect now we will shift to the dislocation and elementary dislocation in that we will try to cover the basic idea about the dislocation source, dislocation motion and slip critically reserve shear stress and dislocation energy, all this compressive dislocation and probably with the next class we will, next class or next module probably we will discuss the dissociation of the dislocation.

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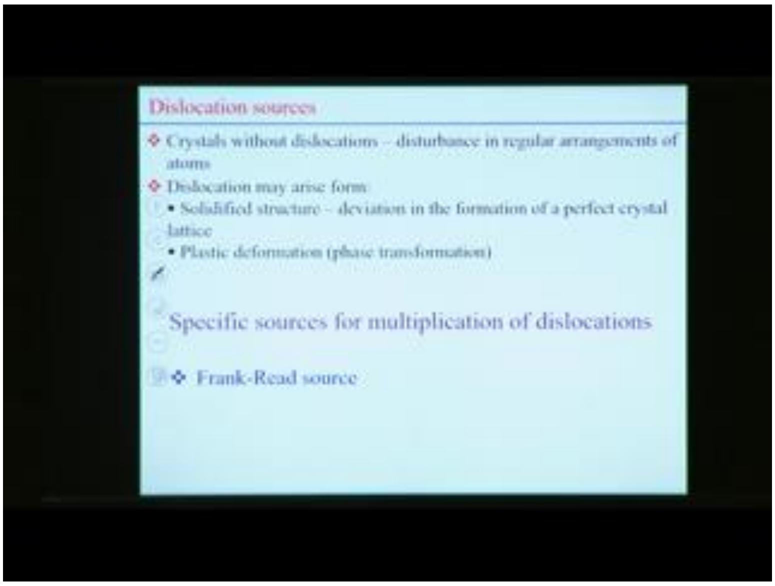

Dislocation sources

- ❖ Crystals without dislocations – disturbance in regular arrangements of atoms
- ❖ Dislocation may arise form:
  - Solidified structure – deviation in the formation of a perfect crystal lattice
  - Plastic deformation (phase transformation)

Specific sources for multiplication of dislocations

- ❖ Frank-Read source

So first we will try to focus on the dislocation source, crystal without dislocation is difficult to form. So disturbance in the regular arrangement of the atoms is simply representation of the dislocation, so there exist some amount of the dislocation in any kind of structure. Dislocation may arise, dislocation can be increased or dislocation can be formed from a solidified structure, so in the solidified structure deviation in the formation of the perfect crystal lattice so when you solidify structure form there is automatically form of the some at least some amount of the dislocation within the structure itself.

Then dislocation can be incorporated through the plastic deformation and even there is a solid state phase transformation and with the second phase particles that actually introduces some amount of the disturbance during the microstructure, so there are several ways to introduce the different types of crystal structure and sometime the when you try to form a material through the any kind of manufacturing process for example either melting solidification or through the metal process so that materials is subjected to by some amount of the dislocation or in terms of the motion of the dislocation.

So dislocation is always associated this thing and that dislocation is very much representative of the material or maybe very much representative of a crystal defect, what is associated with the always some associated with some amount of the energy. Now there are several ways to analyze the dislocation that means how we can dissociate into dislocation of crystal structure and how the different dislocation can interact with edge and form the new dislocation.

So, so far we have discussed the edge dislocation and screw dislocation but the edge dislocation can be, can be represented like that positive and negative and similarly screw dislocation can be represented easily at left hand screw or right hand screw dislocation and when they interact with each other they can, sometimes they can energy can be balanced depending upon the nature or type of the dislocation of interacting, and sometimes the dislocation can dissociated into small partial dislocation that we would discuss later.

Now if we try to focus on this specific dislocation and here we will try to explain that, what are the specific sources for the multiplication, basically addition of the dislocation. So one is that is the Frank – Read source that mechanism actually explain how we can multiply the amount of the dislocation during the plastic deformation.

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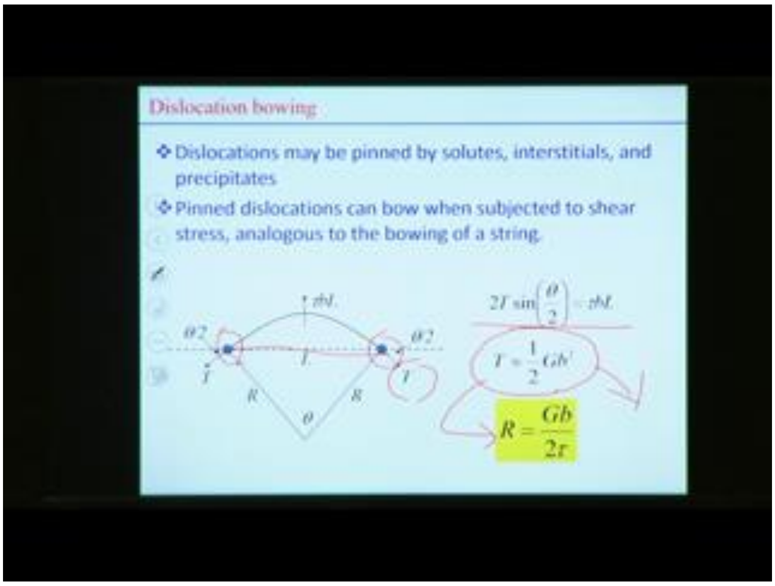

Dislocation bowing

- Dislocations may be pinned by solutes, interstitials, and precipitates
- Pinned dislocations can bow when subjected to shear stress, analogous to the bowing of a string.

$$2T\sin\left(\frac{\theta}{2}\right)=\tau bL$$

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

$$R=\frac{Gb}{2\tau}$$

So that one mechanism is called dislocation bowing. If we consider maybe the path of the dislocation, maybe the the part of the actual dislocation, actually pinned by the solutes, presence of the solutes, presence of the interstitials and presence of the precipitates. Now if we consider one small segment but that is pinned between the two point, so that if we consider this is the one part of the dislocation and pinned by these two points, that two points can come from the solutes, some interstitials or some precipitates.

Now if it is subjected to (())(62:06) of the shear stress then it will bowing, like bowing of a string, so it deformation or can be represented that bowing of the dislocation of a string. Now we try to mathematically explain this express the amount of the energy associated with this, for example if we consider the force is like t, here at the pinned l, for example it is making the angle theta and radial distance is R is define and the length of the segmented dislocation is l in this case. It is subjected to amount of the force that is shear stress into B is the dislocation, B is the Burger's vector and l is the length of the dislocation.

Now here with a configuration we can find out the directly 2T sign theta by 2 is equal to tau bl. So T can be again represented in terms of the energy dislocation, dislocation energy so that we will discuss later, what is the amount of energy is associated with dislocation of edge dislocation and whether it is screw dislocation, roughly estimate the amount of the energy, energy part dislocation and that can be represented by half of Gb square, G is the shear modulus of the material b is the Burger's vector. So from here we can find out that R equal to simply Gb by 2 tau, tau is the shear stress.

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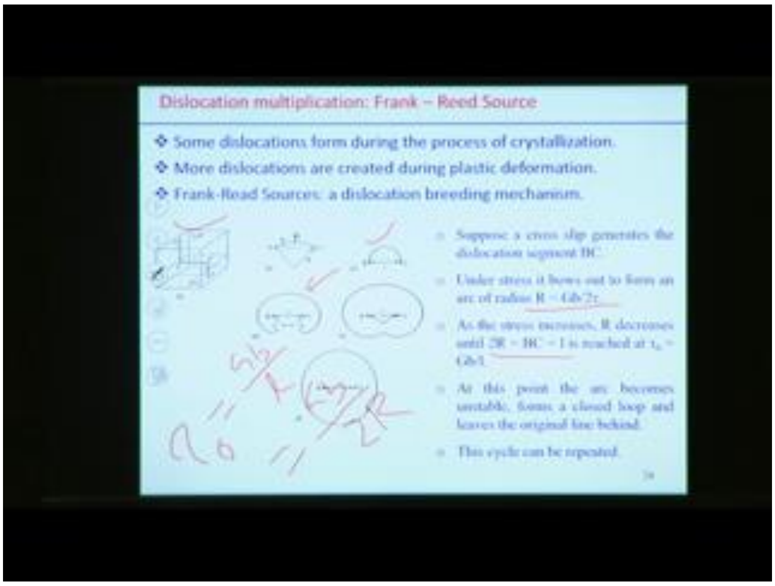

Dislocation multiplication: Frank – Reed Source

- Some dislocations form during the process of crystallization.
- More dislocations are created during plastic deformation.
- Frank-Read Sources: a dislocation breeding mechanism.

- Suppose a cross slip generates the dislocation segment BC.
- Under stress it bows out to form an arc of radius R = Gb/2τ
- As the stress increases, R decreases until 2R = BC = l is reached at τ_c = Gb/l
- At this point the arc becomes unstable, forms a closed loop and leaves the original line behind.
- This cycle can be repeated.

Now Frank – Reed explain that some dislocations form during the process of the recrystallization is very much related to any kind of metal for big process and that happens, this recrystallization actually happens that the recrystallization temperature which is below the melting point temperature of the material, so more dislocations are created during the plastic deformation and Frank – Reed source actually explains a dislocation (())(64:09) mechanism.

So let us see how it works the Frank – Reed source of dislocation, this mechanism how we can explain it. Say for example BC is the segment of the, if we look into this figure, this is the segment of the dislocation of length and it is subjected to a shear stress tower. Now suppose a cross slip generated the dislocation segment BC, now under stress it bows out to form an arc of radius, say for example R. So R can be represented Gb by 2 pi so that segment radius R, so this radial distance segmented R can be represented like Gb by 2 pi.

Now stress increases then R decreases until and unless take 2R equal to BC equal to l that means when actually the this segmented R is the semi-(())(65:08) takes the exactly the semi-circular form. So when you take the semi-circular form then shear stress is equal to basically Gb by l, so R we can say Gb by l equal to 2R exactly that take the semi-circular form. So at this point the R becomes unstable with the further straining and form a closed loop and leaves the original line behind.

So after slip this is the next step with the further straining, actually it creates the movements of the dislocation is the line is like this, and after that it form the closed loop and finally, it actually forms the closed loop and that if we look there is a closed loop of initial, what was the initial length l it is created, so again that means with this mechanism it is explained that similar what we start from the segmented length of the dislocation BC and we are getting the segmented BC which is surrounded by this, so this is the simply generation of the dislocation. So by using the Frank – Reed source of dislocation generation mechanism we can explain that there is a generation of the dislocation during the deformation of the material.

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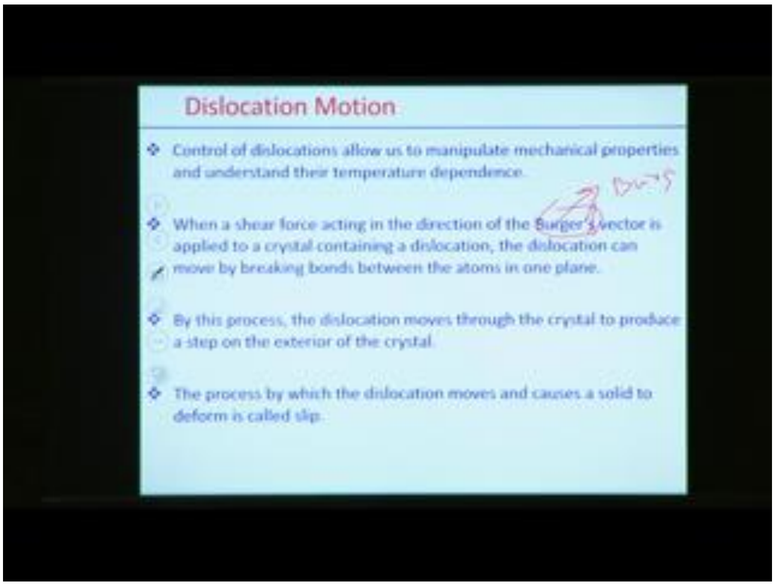

Dislocation Motion

- Control of dislocations allow us to manipulate mechanical properties and understand their temperature dependence.
- When a shear force acting in the direction of the Burger's vector is applied to a crystal containing a dislocation, the dislocation can move by breaking bonds between the atoms in one plane.
- By this process, the dislocation moves through the crystal to produce a step on the exterior of the crystal.
- The process by which the dislocation moves and causes a solid to deform is called slip.

Now next step we try to discuss the dislocation motion, so actually the controlled of dislocation allow us to manipulate different mechanical properties and understand their temperature dependence, so when the shear force is acting in the direction of the Burger's vector, so this is actually wrong, this Burger's vector, actually BURGERS vector is applied to a crystal containing a dislocation, the dislocation can move by breaking bonds between the atoms in one plane. So basically to break the bonds between the atoms of the plane we need to apply the uhh the amount of the strength so that there is a movement of the dislocation happens.

By this process the dislocation moves through the crystal to produce a step on the exterior of the crystal. So the process by which the dislocation moves and cause a solid deform is called slip. So the process by which the dislocation movies and causes a parallel, actually initially the deformation of the material of a single crystal that process is called actually slip. We will try to explain the slip metals.

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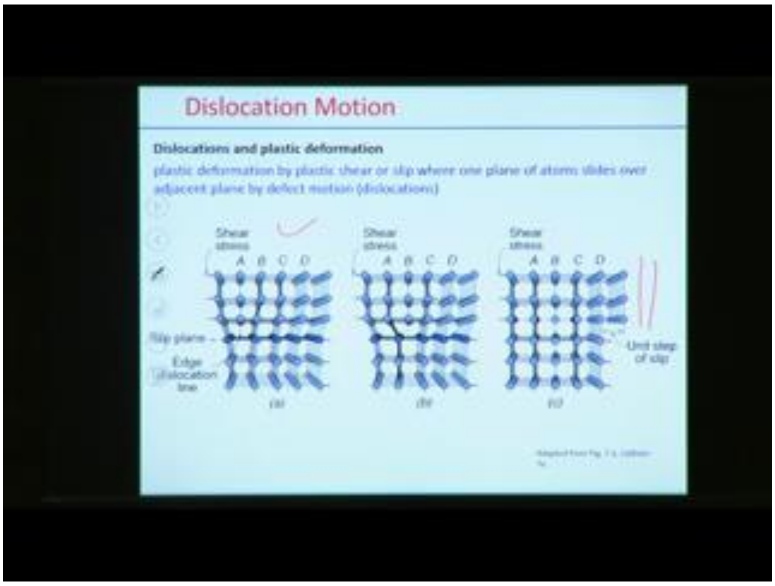

Dislocation Motion

Dislocations and plastic deformation

plastic deformation by plastic shear or slip where one plane of atoms slides over adjacent plane by defect motion (dislocations)

So let us look into that how we explain this thing, so dislocation and plastic deformation, so this is the represent of the atoms atomic arrangement of the atoms and their exist on the one edge dislocation there. So extra plane of the atoms A at point A actually the extra plane of the atoms and that represents the, that bring the one edge dislocation with this arrangement of the atoms. Now with the application of the amount of the shear stress, we will look into that shear stress and then there is a gradual movement of the plane of the atoms ABCD, it leaves like that ABCD transition and it will produce the unit step of the slip.

So there is a extra plane of the atoms actually brings the other right hand side to application of the shear stress. So this process actually, with this process we can say there is a movement of the dislocation from one point to another point that means the movement of the dislocation from on the plane of A then it moves to point plane B, and gradually moves to C, gradually moves to D and finally it brings out. So there is a that slip mechanism actually explain through the movement of the dislocation in this case and that finally produce the unit step of slip.

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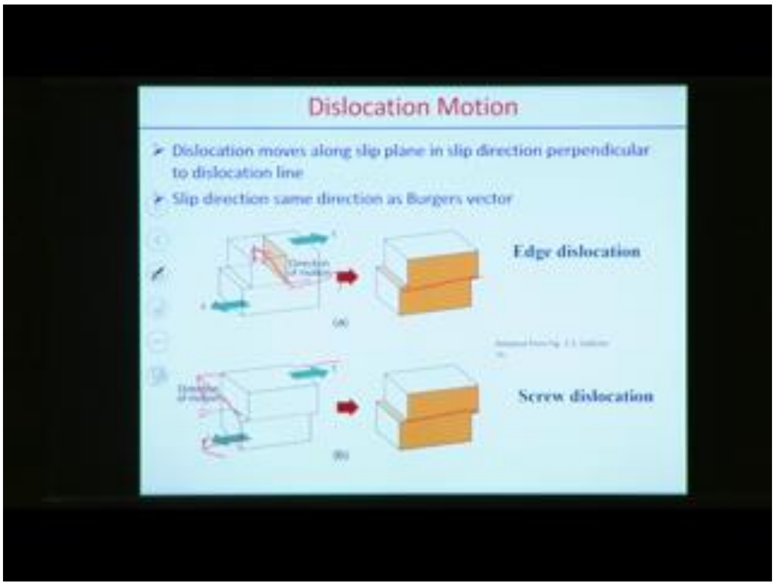

Dislocation Motion

- Dislocation moves along slip plane in slip direction perpendicular to dislocation line
- Slip direction same direction as Burgers vector

Edge dislocation

Screw dislocation

Let us look into the further explanation of this thing, dislocation motion, so actually dislocation moves on the slip plane in the slip direction perpendicular to the dislocation line, so let us look into that and slip direction is the same direction as the Burgers vector. Here if you see in case of edge dislocation so there is a uhh slip plane is defined on this, if here you see the vertical plane here and direction of the slip surface simply movement of the edge dislocation from one point to another point which direction actually the shear stress is acting.

So this representation of the shear, actually this plane represents the shear plane and from bottom and upper layer there is a movement of the atom with respect to each other, so this is correspond to the edge dislocation and if you see this is the direction of motion is also give, and slip plane is also defines uhh and dislocation line is also defined. So in this case if you see the slip plane is the uhh along the slip plane, the slip direction is actually perpendicular to the dislocation line. So this is the slip direction and dislocation line in this case is this, so perpendicular with each other in case of edge dislocation.

But if you look into the screw dislocation also here you will see similar kind of things or shear stress is acting and direction of the motion actually shear stress is acting but direction of the motion is this and this plane, the horizontal plane, actually represents the slip plane and dislocation in this case, the dislocation line is on the slip plane itself.

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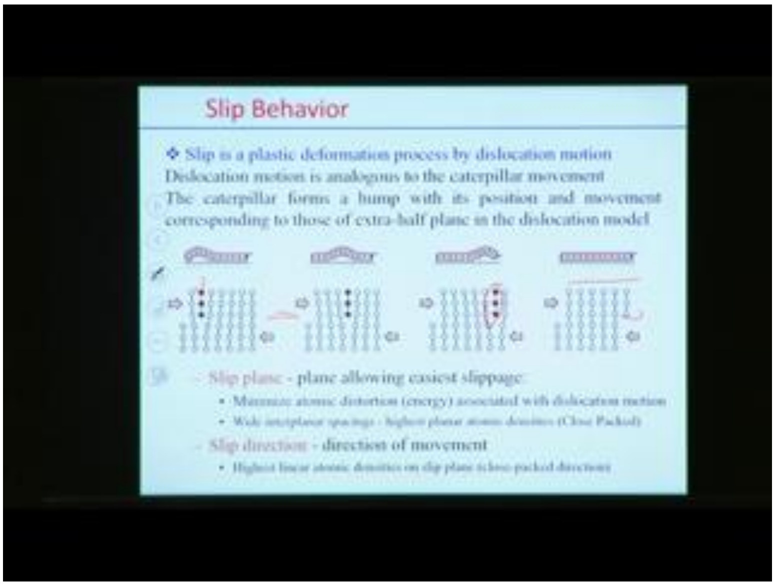

Slip Behavior

- Slip is a plastic deformation process by dislocation motion

Dislocation motion is analogous to the caterpillar movement

The caterpillar forms a hump with its position and movement corresponding to those of extra-half plane in the dislocation model

- Slip plane - plane allowing easiest slippage:
  - Minimize atomic distortion (energy) associated with dislocation motion
  - Wide interplanar spacings - highest planar atomic densities (Close Packed)
- Slip direction - direction of movement
  - Highest linear atomic densities on slip plane (close-packed directions)

So by dislocation movement we can represents the slip mechanism but a slip can be represents other also to that that means here we are trying to represent the slip and the plastic deformation by the dislocation motion but taking some other example, so dislocation motion is analogous to the caterpillar movement, if we look into this thing, the caterpillar actually forms a hump with its position and movement corresponding to this extra half plane in this dislocation model. So let us look into this dislocation model, it is like that only.

So this is the arrangement and there is a one case dislocation exist extra plane of the atoms so it assumes this is the creation of the hump by this caterpillar, so next step network the hump actually shift so that means the extra plane of the atoms shifting corresponding to the edge dislocation also shift to some other point. Similarly with further movement the hump actually of the caterpillar actually shifting to the right hand side according to the shifting this thing, extra plane of the atoms or we can say the shifting to the dislocation line in this case so finally to take the shape, so it is the completely movement of the dislocation line to the right hand end.

So this way through the movement of the caterpillar by forming a hump we can explain the motion of the dislocations, and that motion of the dislocation is basically try to represent the complete details, with this movement we can represents the complete separation of the atoms uhh from when it is shifting from one position to the another position, so that slip form is actually represented by the motion of the dislocation. Now slip plane, the plane allowing the easiest slippage.

So in actually in the crystal structure the slip plane is consider as the plane allowing the easiest slippage, so minimize atomic distortion is corresponds to the minimized atomic distortion energy, so that is associated with the dislocation motion and the same time why the inter planar spacing or closed pack density of high planar atomic density that is corresponds to the closed packed plane.

So slip will happen mostly in the closed packed plane and slip direction also happen in the direction of the movement, the highest linear atomic densities on the slip plane, the shortest that is translation point that is the closed pack direction. So we can conclude from that slip behavior of the materials that slip will actually happens in the closed packed plane, on that closed packed plane in the closed packed direction.

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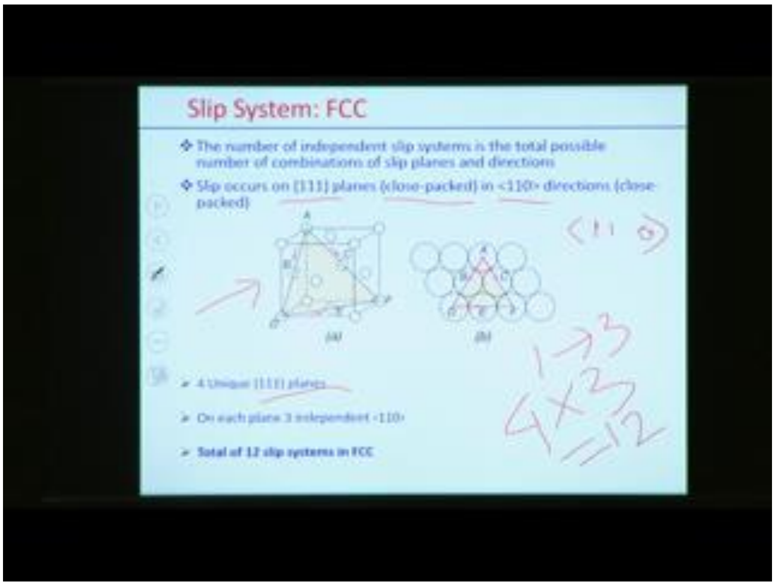

Slip System: FCC

- The number of independent slip systems is the total possible number of combinations of slip planes and directions
- Slip occurs on {111} planes (close-packed) in <110> directions (close-packed)

- 4 Unique {111} planes
- On each plane 3 independent <110>
- **Total of 12 slip systems in FCC**

Now if we look into the slip system in case of FCC structure that number of independent slip system in the total possible number of combination of the slip planes and direction, so in FCC structure the slip often occurs actually 111 plane that is the close packed plane in this case and on that closed packed plane that is the 110 direction that is the close packed direction, so if we try to represents that slip plane in this case that FCC structure, so that ADF, if we define that plane, that plane actually defines the slip lane in case of FCC structure and on that plane specifically on that plane the direction 1110.

So basically it is a family of directions, so 1110 it represents the several other direction, so that is corresponds to the three different direction say along the direction D, along the direction C and along the direction E, so one plane there is a possible three directions but in this case this is the plane, family of the plane actually represents 111 plane but within the unit cell we can constitute the four different types of 111 plane, four unique different types of plane. So what maybe the total of possible directions so one direction is corresponds, one plane corresponding to three different directions, so then 4 plane corresponds to total twelve direction. So total twelve slip system in FCC structure is possible, so that means the slip system consists of the twelve possible slip direction in case of FCC structure.

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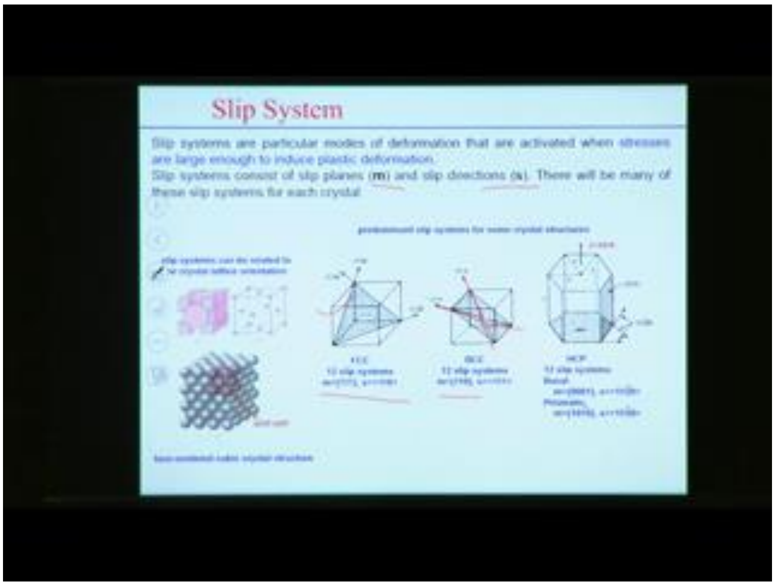

Slip System

Slip systems are particular modes of deformation that are activated when stresses are large enough to induce plastic deformation.

Slip systems consist of slip planes (m) and slip directions (s). There will be many of these slip systems for each crystal

Similarly we can investigate for all other crystal structure different slip system, so slip system actually particular most of deformation that are activated when stresses are large enough to induce the plastic deformation. So slip will happens one specified plane, one specified direction but when the applied stress exit some amount of critical stress value that actually induce the plastic deformation on that plane, now in that sense we can define the slip system of the with respect to the slip M and slip direction s.

So there are many of this slip system for each crystal so it is like that only, slip system can be related to the system lattice orientation definitely so that why crystal lattice orientation of the symmetry measure of the crystal lattice orientation, if we look into that so slip can occur in the several orientation, and what with the regular arrangement of the atoms we can represents that one repetitive one representation of the characteristic of the geometric arrangement of the atoms that is represented by the unit cell here.

Now within the unit cell this is the first figure if we look into that FCC structure we have discussed that FCC structure the plane is defined the slip plane and corresponding the slip direction so corresponding total pure slip system is possible. Similarly in case of BCC structure already mentioned that BCC structure is not having exactly the very well defined closed packed plane like FCC structure so possible number of slip systems is more in case of BCC structure, so one of that is the m equal to 11, that slip lane is 110 plane and slip direction is 111.

So on that slip lane there is a, so it is defined as the slip plane, one of the possible slip plane and direction is 111 that basically the 111 direction is simply the body diagonal direction, this as the uhh BCC structure this is the slip system, but in BCC structure the other slip system also exist, we will discuss later on. In HCP also twelve slip system exist basically that to slip plane is the base plane, one of the prismatic plane also we define this is as the possible slip plane at possible direction also indicated.

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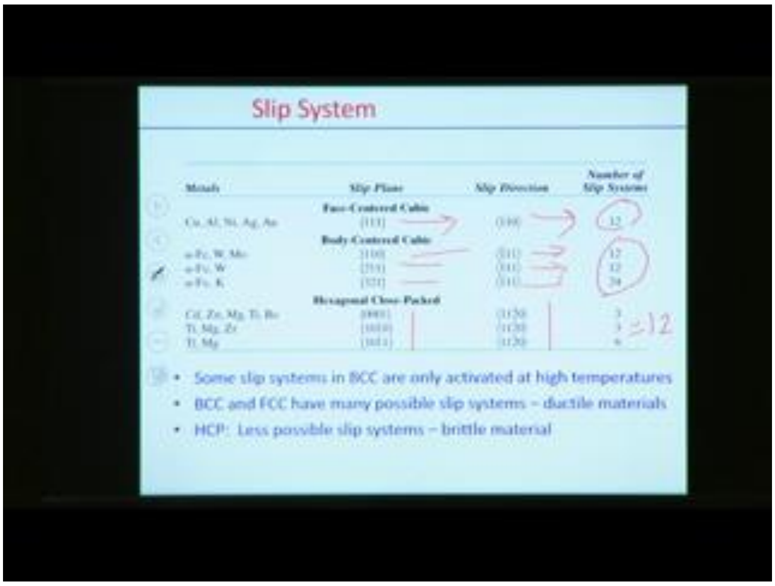

Slip System

Metals	Slip Plane	Slip Direction	Number of Slip Systems
	Face-Centered Cubic		
Cu, Al, Ni, Ag, Au	{111}	⟨110⟩	12
	Body-Centered Cubic		
α-Fe, W, Mo	{110}	⟨111⟩	12
α-Fe, W	{211}	⟨111⟩	12
α-Fe, K	{321}	⟨111⟩	24
	Hexagonal Close-Packed		
Cd, Zn, Mg, Ti, Be	{0001}	⟨11$\bar{2}$0⟩	3
Ti, Mg, Zr	{10$\bar{1}$0}	⟨11$\bar{2}$0⟩	3
Ti, Mg	{10$\bar{1}$1}	⟨11$\bar{2}$0⟩	6

=12

- Some slip systems in BCC are only activated at high temperatures
- BCC and FCC have many possible slip systems – ductile materials
- HCP: Less possible slip systems – brittle material

When summary if we look into that slip system of the different crystal structure, for example FCC structure, this is the plane and this is the corresponding direction but total number of slip system is twelve here. BCC structure several plane slip may occur and on the, on that plane is the direction 111 direction, actually slip occurs. So total possible number of the slip shifting in case of BCC structure is actually 48 which is more than respect to the FCC or HCP structure. Similarly HCP structure this as a plane and here if you see the slip direction also happen and we can find out the total twelve number of slip system exist in case of HCP structure.

So in summary we can say the some slip system BCC are only activated at high temperature and BCC and FCC have many possible slip system that we already possible slip system so that is why this metal is basically the ductile in nature but in the materials having less possible number of slip systems the nature is generally the brittle, in that cases the brittle material. So if there is a several possible slip system, the possibility of uhh deformation can be oriented in any direction. But if there is restricted number of slip system then possible number of deformation happens within the restricted itself, so then it is the (())(81:08) or maybe of the plastic deformation in this with the restricted number of slip system is less so that type of material is actually brittle in nature.

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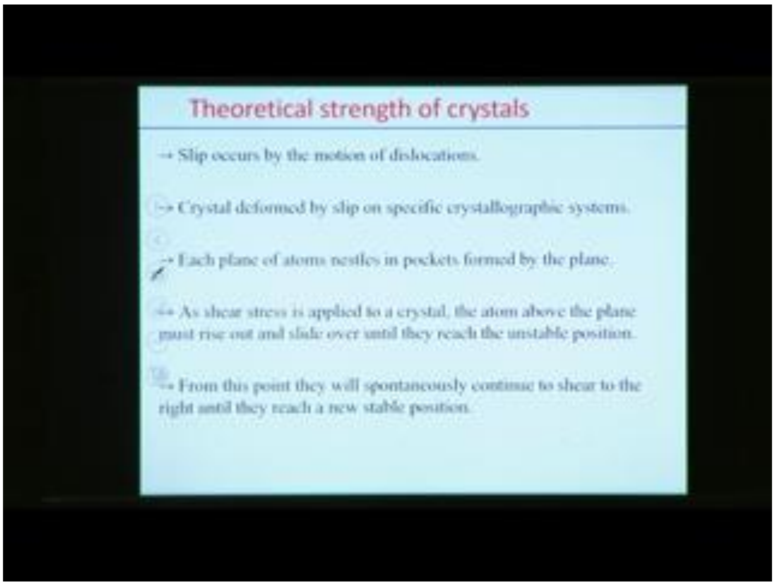

Theoretical strength of crystals

→ Slip occurs by the motion of dislocations.

→ Crystal deformed by slip on specific crystallographic systems.

→ Each plane of atoms nestles in pockets formed by the plane.

→ As shear stress is applied to a crystal, the atom above the plane must rise out and slide over until they reach the unstable position.

→ From this point they will spontaneously continue to shear to the right until they reach a new stable position.

Now when it say, when it try to explain the slip system exist in the material and this is the this can be linked with the motion of the dislocation, but at the same time when the slip is activated, when it is cross some amount of the strength of the material, so that can represent in terms of the physical amount of the shear stress is required to initiated the slip system, so that we can, it is possible to plastically deform the material. So to do that first we look into the theoretical strength of the uhh material by looking into that slip occurs by the motion of the dislocation.

First crystal system by slip on the specific crystallographic system that we already discussed that each plane of the atoms nestles in pockets formed by the plane and as shear stress is applied to a crystal atom above the plane must rise out and slide over until they reach the unstable position, so from this point they will spontaneously continue to shear to the right until they reach to a new stable position, so based on this things we can find out the theoretical strength of the crystals.

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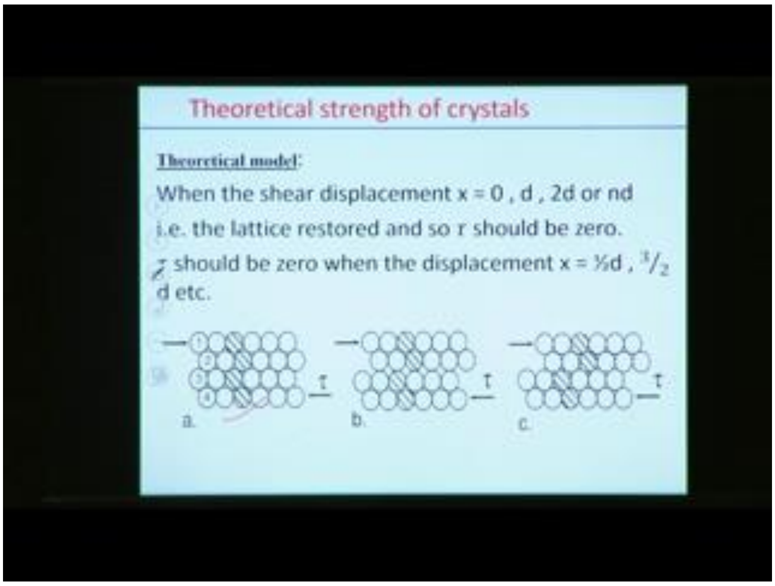

Theoretical strength of crystals

Theoretical model:

When the shear displacement $x = 0$, d , 2d or nd

i.e. the lattice restored and so τ should be zero.

τ should be zero when the displacement $x = \frac{1}{2}d$, $^{3}/_{2}$ d etc.

So look into that we consider one specific model, theoretical model, for example this is the arrangement of the atoms, now with the application of the shear stress there is a position of the atoms changes of slip, so after slip there is a arrangement, atoms will take the new equilibrium position, to explain this phenomena we see that when shear displacement, basically the shear stress is (())(83:08) this direction, what is the movement of this thing, displacement, x can be represented like that X can vary, x can be zero, d means complete one atomic space movement 2d or nd.

So that means the lattice restored and so that tau should be zero. So that means when it is reaching the after with a continuous application of the shear stress when the atomic distance is equilibrium position then we can assume the shear stress this to 0. But tau should be zero when the displacement can also be half d 3 by 2 d etcetera.

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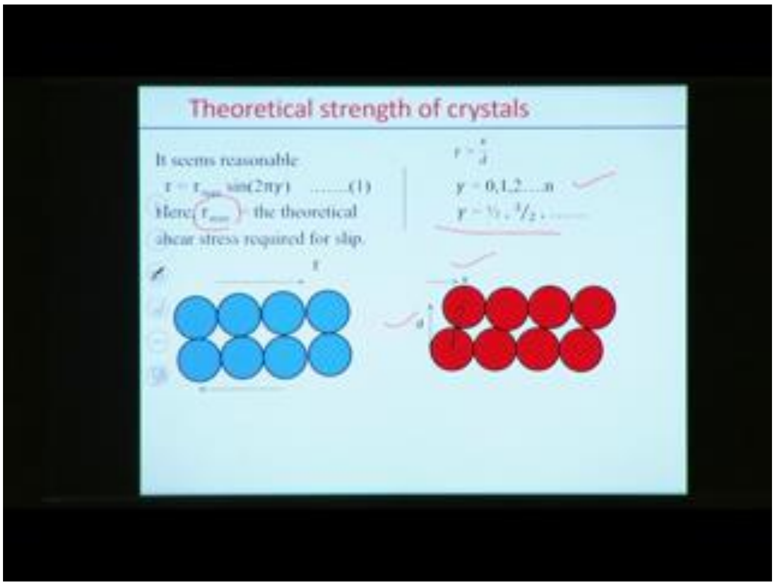
Theoretical strength of crystals

It seems reasonable

$\tau = \tau_{max} \sin(2\pi\gamma)$ ....(1)

Here τ_{max} = the theoretical shear stress required for slip.

$\gamma = \frac{x}{d}$

$\gamma = 0,1,2....n$

$\gamma = \frac{1}{2}, \frac{3}{2}, ...$

So this model is better, it seems to most reasonable expression of this equation of (())(84:12) like that tau equal to tau max into sin 2 pi gamma. So this is the representation of the shear stress and if we see there is a one maximum value tau max, the theoretical shear stress require for slip, that is the maximum value in this case, and if we look there is a shear displacement x and the distance is d and shear displacement is x here, so shear stress can be represented by x by d. So that shear stress corresponding to the zero 1 to n, and gamma is corresponding to the half of half 3 by 2, it is the measure of what we will be define the x here, the displacement here. So accordingly the shear stress will be liked that.

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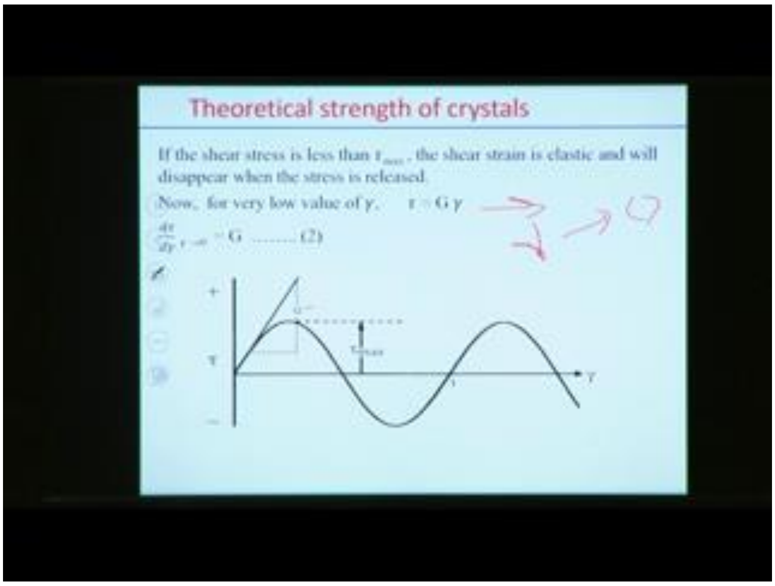
Theoretical strength of crystals

If the shear stress is less than τ_{max}, the shear strain is elastic and will disappear when the stress is released.

Now, for very low value of γ, $\tau = G\gamma$

$\left(\frac{d\tau}{d\gamma}\right)_{\gamma \to 0} = G$ ....(2)

So the model is like that if you graphically represent this thing shear stress versus shear stress is like that that we put in some maximum value the initial slope actually represents the shear modulus G, the zero and the negative value so some it is varies in this way with respect to this thing. Now if the shear stress is less than the maximum the shear strain is elastic and will disappear when the shear stress is released. Now for the every low value of shear strain we can find out the tau equal to shear stress equal to to G2 shear strain. Now (())(85:41) the derivative when very small shear stress value tends to zero then this is corresponding to G.

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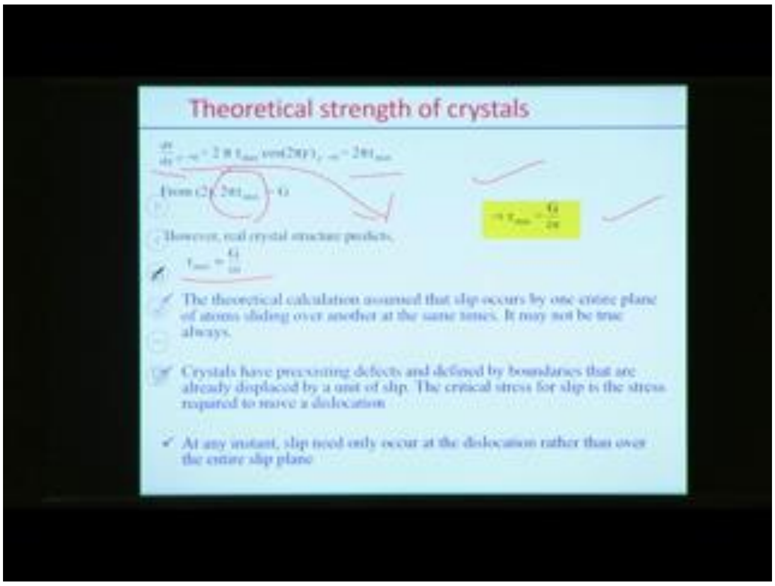

Theoretical strength of crystals

$\frac{d\tau}{dx} = 2\pi\tau_{max}\cos(2\pi x)_{x\to 0} = 2\pi\tau_{max}$

From (2) $2\pi\tau_{max} = G$

$\Rightarrow \tau_{max} = \frac{G}{2\pi}$

However, real crystal structure predicts,

$\tau_{max} = \frac{G}{[illegible]}$

- The theoretical calculation assumed that slip occurs by one entire plane of atoms sliding over another at the same times. It may not be true always.
- Crystals have preexisting defects and defined by boundaries that are already displaced by a unit of slip. The critical stress for slip is the stress required to move a dislocation
- At any instant, slip need only occur at the dislocation rather than over the entire slip plane

Now put it this value, corresponding to (())(85:54) that equation of the relation between the shear stress, shear stress in terms of the shear strain, we can find out the total dow tau by dow lambda is twice pi tau x, so in this case if we see these actually values for this value, that represents the slope at shear strain equal to zero that is the is representation of the shear modulus of a material so that is corresponding to the twice pi tau by equal to G from here we can find out the maximum shear stress equal to G by 2 pi. But this is the theoretical prediction of the maximum shear stress value when there is a if we consider the uhh application of the shear stress, and in one atoms, plane of the atoms is completely displaced then theoretical prediction tells the maximum cells is required in this case equal to uhh it exactly depends on the shear modulus.

But real crystal to the experiment it is observed the real crystal to some extent, the maximum shear stress actually G by (())(87:07) of the crystal. So there is a mismatch actually theoretical prediction of this actual practical values or experimental values. What was the reason for that, actually the theoretical calculations assume that slip occurs by one entire plane of atoms sliding over another at the same times, but it may not be true always. Crystals have pre existing defect and with the define boundaries that already displace by a unit of slip. The critical stress for slip is the stress required to move a dislocation. So at any instant slip need only occur at the dislocation rather than over the entire slip plane so accordingly we can find out that there is a mismatch of the theoretical prediction respect to that.

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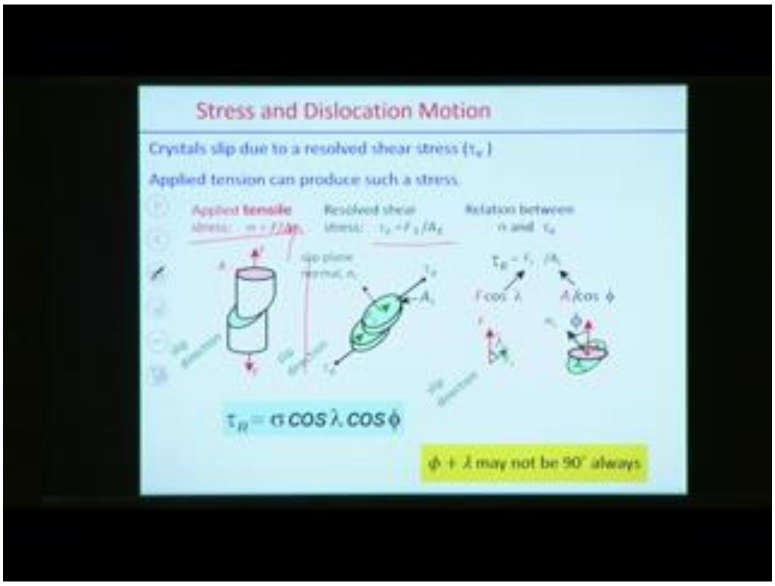

Stress and Dislocation Motion

Crystals slip due to a resolved shear stress (τ_R)

Applied tension can produce such a stress.

$\tau_R = \sigma \cos\lambda . \cos\phi$

$\phi + \lambda$ may not be 90° always

Now if we try to find out the critical values of the shear stress that is required to the movement of the dislocation that is called the critical resolved shear stress tau (())(88:21) and that is the, if we look into that what is the amount of the critical stress is required, we consider on model like that applied stress is phase 1, so in this case the applied stress (())(88:38) this one, and cross section area is A, and the slip will happening in between some layer and if we find that thing things. That resolved shear stress we can find out on a specified plane because on that specified plane is a slip plane at one specified direction which direction slip belong that is the slip direction.

So in this case shear stress can be considered as on the, what is the load is applied on this plane, slip plane divided by area of the cross section that is the representation of the critical resolved stress value, but if we look into that the resolved stress value that Four Square, shear force on that plane that is corresponding to the normal force what is at A cos lambda that lambda is the angle between the shear force and the normal force in between these two and this A is, area of the cross section of the plane that is ratio of the pa by cos phi. So phi is the angle with respect to the direction of the force, normal force f and normal to that slip plane direction between this two the phi is form.

So if we put these things so basically we can find out the resolved shear stress acting on the slip plane, on the slip direction that is sigma cos lambda cos phi, the sigma equal to is the normal stress with the applied of the application of the force f. But with this configuration it is not necessary that phi plus lambda should be always 90 degree.

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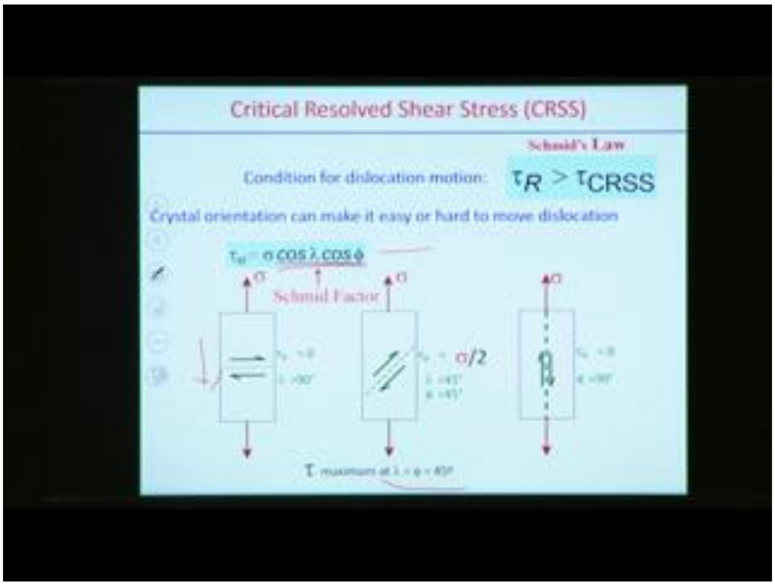

Critical Resolved Shear Stress (CRSS)

Schmid's Law

Condition for dislocation motion: $\tau_R > \tau_{CRSS}$

Crystal orientation can make it easy or hard to move dislocation

$\tau_R = \sigma \cos\lambda \cos\phi$

Schmid Factor

τ maximum at $\lambda = \phi = 45°$

Now physically resolved shear stress which is the condition for the dislocation, so (())(90:31) will start once the applied shear stress will cross some critical value that critical value is called the critical reserved shear stress value, so crystal orientation can make it easy or hard to move the dislocation so that resolved shear stress, if we look into the resolved shear stress value and that cos phi cos lambda actually called the Schmid Factor and this is the position for that, so shear stress equal to zero or in this case the lambda equal to 0. So it will not move.

But when it is considered that phi equal to 45 degree and lambda equal to 45 degree then resolved shear stress or shear stress equal to sigma y2. If we look into this orientation that shear stress equal to 0, phi equal to 90 degree, we can get in the stress value. So the maximum shear stress value will be phi equal to lambda equal to 45 degree. So that maximum amount of the stress to create the dislocation motion that amount of the stress is called critical resolved shear stress value.

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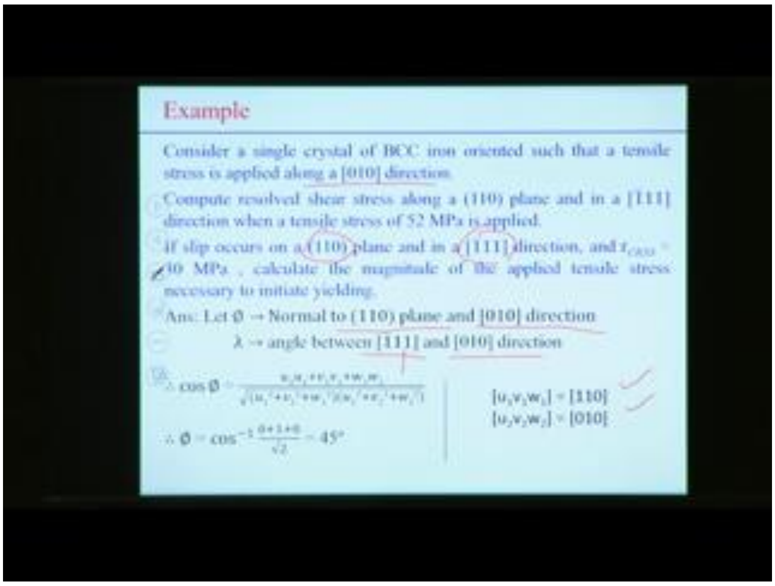

Example

Consider a single crystal of BCC iron oriented such that a tensile stress is applied along a [010] direction.

Compute resolved shear stress along a (110) plane and in a [111] direction when a tensile stress of 52 MPa is applied.

If slip occurs on a (110) plane and in a [111] direction, and τ_{CRSS} = 30 MPa , calculate the magnitude of the applied tensile stress necessary to initiate yielding.

Ans: Let Ø → Normal to (110) plane and [010] direction

λ → angle between [111] and [010] direction

$$\therefore \cos Ø = \frac{u_1u_2+v_1v_2+w_1w_2}{\sqrt{(u_1^2+v_1^2+w_1^2)(u_2^2+v_2^2+w_2^2)}}$$

$$\therefore Ø = \cos^{-1}\frac{0+1+0}{\sqrt{2}} = 45°$$

$[u_1v_1w_1]$ = [110]

$[u_2v_2w_2]$ = [010]

Now if we look into this one example, it will be very clear to that consider a single crystal of BCC ion oriented such that a tensile stress is applied along 010 directions. Now we need to compute the results shear stress along 111 plane in the 111 direction when the tensile stress of 50 megaPascal is applied. Now if slip occurs on 110 plane and in a 111 direction and critically resolved shear stress equal to 30 megaPascal we need to calculate the magnitude of the applied tensile stress necessary to initiate the yielding. Now we consider the similar configuration the phi and lambda.

For example if we look into this, phi and lambda we constitute phi is the normal to the 1110 plane because slip occurs on this plane so phi (())(92:46) normal to this plane and 010 direction, so 010 direction actually the applied stress, so if I consider between these two angles and then lambda between 111 minus 111 direction, 010 direction so this because this is the slip direction, so first one is the slip direction and second one is the direction of this direction the force is acting. So we can easily find out the Miller index, if we put it u1v1w1 and u2v2w2 and you can find out the cost phi between this two directions and that is phi equal to 45 degree.

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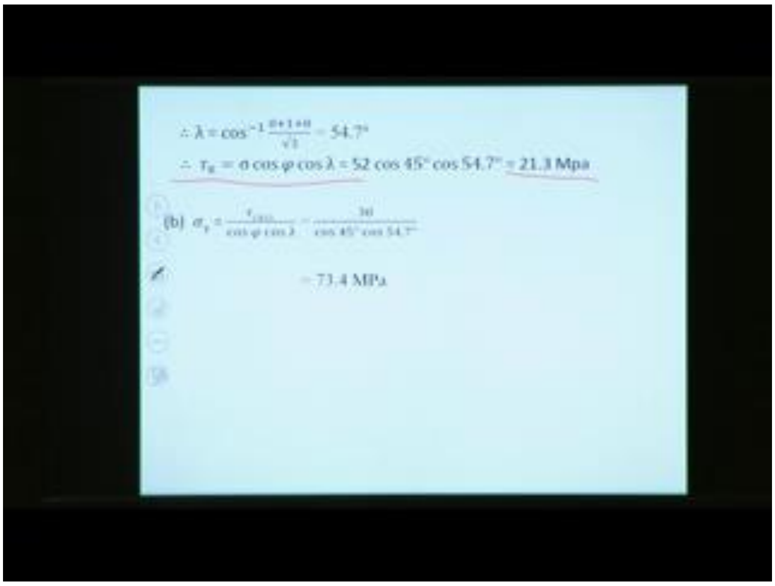

$$\therefore \lambda = \cos^{-1}\frac{0+1+0}{\sqrt{3}} = 54.7°$$

$$\therefore \tau_R = \sigma\cos\varphi\cos\lambda = 52\cos 45°\cos 54.7° = 21.3\text{ Mpa}$$

$$\text{(b)}\ \sigma_y = \frac{\tau_{CRSS}}{\cos\varphi\cos\lambda} = \frac{30}{\cos 45°\cos 54.7°}$$

$$= 73.4\text{ MPa}$$

The similar way we can find out also lambda equal to 54.7 degree and we can find out the reserved shear stress equal to 21.3 megaPascal. Now if we try to initiate the yielding, what maybe the stress value so in that case we initiate the yielding so stress, the normal stress actually equate the critical value of the shear stress to initiate the slip with respect to the cos 45 degree and cos 5, phi and lambda what we have calculated before and here we can find out that 73.4 megaPascal is required actually, maybe we can consider the external load is required to initiate the slip on the specified slip plane and on the specified slip direction.

So thank you very much for your kind attention, now I will start the next class, the remaining part of the dislocation or in broad the remaining part of the crystal plasticity. Thank you.