**Mechanical Behaviour of Materials**
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**Lecture - 14**
**Introduction to Dislocations - II**

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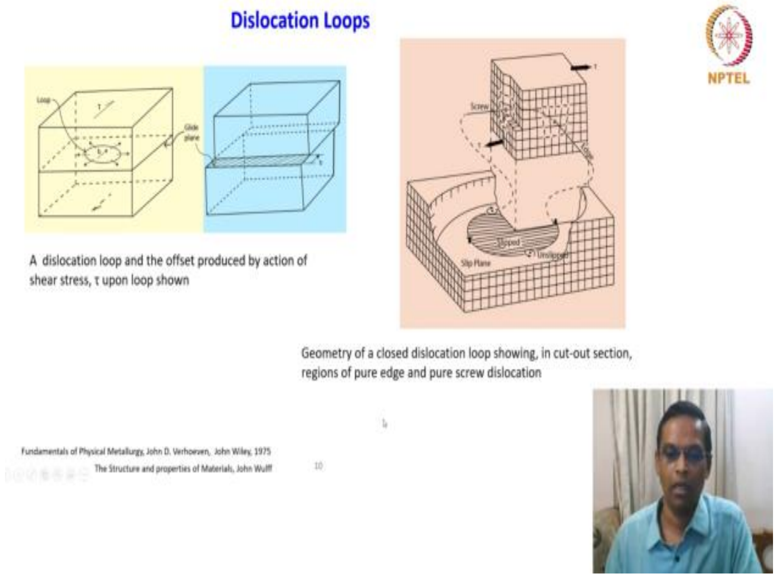


Hello, I am Professor S. Sankaran in the Department of Metallurgical and Materials Engineering. And it is not that types of geometries alone there is something called dislocation loops which is more realistic. And suppose if you see that the crystal contains a dislocation look like this how do we understand this suppose this is a glide plane. Glide plane we know now, where the dislocation moves easily.

So, this is a shear stress direction but suppose this is a loop and then how do we understand this Burgers vector here? The Burgers vector is marked like this. So, at least one point you can think of since we know the Burgers vector with this orientation with respect to dislocation line we will be able to clearly say that suppose if it is parallel to this, this could be a screw character and if it is perpendicular to this b could be an edge character and in between we know the mixed character.

So, that is how we should understand this loop. Suppose if we the completely you know the loop is generated inside this crystal like this crystal unit once this the unit the dislocation loop comes out of this unit cell then it will leave the slip line like this a slip region in the crystal like this of course that is a glide plane. So, a dislocation loop and an offset produced by action of shear stress $\tau$ upon loops what is shown here.

See the other schematic what is shown here will give you much more again clarity in terms of you know suppose you imagine that huge chunk of a crystal unit as being taken out from the larger crystal something similar to this which has got a dislocation loop in it and how do we understand this loop with respect to the screw and edge character that is what is shown here is the same idea.

But, as we have done with the previous slides like we are taking some extra schematic to describe and get more clarity similarly, we can do that here. So, what is shown here this is a slip region inside the crystal unit and this is the cut-out unit from that which is already slipped which is exhibiting as screw character as well as edge character and somewhere in between a mixed character that we know what to do.

So, now, what is shown here is the loop in the opposite ends will have the dislocations of opposite sign that is one important character. So, I just mentioned here it is about whether it is a screw or edge with respect to b orientation, that is what I just mentioned, but within that edge dislocation if these opposite sides will have opposite sides. So, this is positive edge dislocation this is negative edge dislocation.

So, similarly, this is positive screw dislocation this is negative screw dislocation and we have to make sure that in terms of you know geometrical understanding we just look at this the clockwise Burgers circuit which shows the Burgers vector b, b is here this is a b and it should be the same Burgers vector in the other side also even if you do it in a anti clockwise the Burgers vectors of both the sides should be similar. So, these are some of the simple points but important points to remember if you want to keep the track of dislocation line orientation Burgers vector and so on. So, that is about the dislocation loop description.

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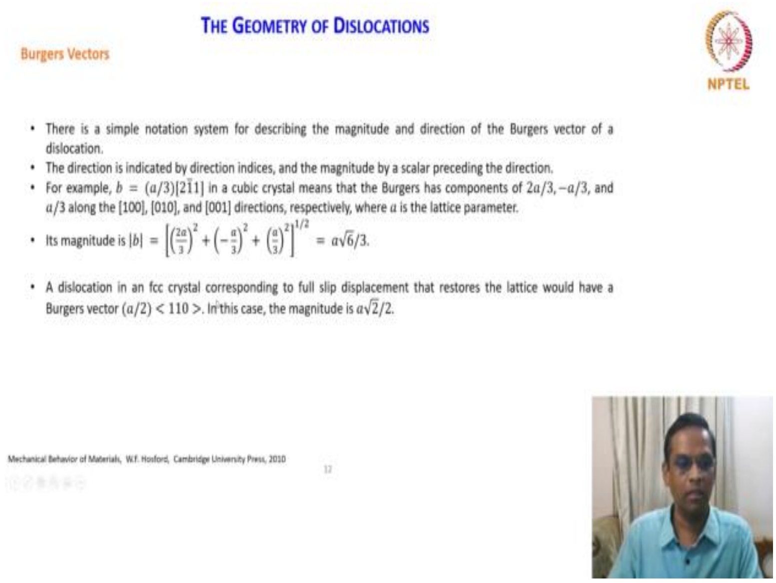


So, now let us spend some time on Burgers vector which is also very important how do we mark this circuit. So, this is the lattice which has got a dislocation extra half plane is inserted here then I have the dislocation core here which is marked by this and here it is positive dislocation if it is inverse symbol of this it will be negative the dislocation line is perpendicular to this which is going inside I mean perpendicular to this plane. So, how do we mark and what is the rule for this making a circuit?

Dislocations are characterised by Burgers vector, consider an atom to atom circuit in the figure that would close on itself if made in a perfect crystal, suppose, you start counting. Suppose, you leave this core first line and go to the second line start counting the displacement 1, 2, 3, 4, 1, 2, 3, 4, 1, 2, 3, 4, 1, 2, 3, 4 that is it and then this particular gap it is failing to close. So, that means, this is that is a defect that is a measure of defect which is here it is a Burgers vector or failure gap whatever you may call it.

So, wherever if you do it the same thing in a perfect crystal it will close so, if it is around the dislocation it will not close. The closer failure is the Burgers vector denoted by b. Burgers vector can be considered a slip vector because its direction is the slip direction and its magnitude is the magnitude of slip displacement caused by its movement of the dislocation. So, this is very important because Burgers vector describes you know the slip direction as well as its magnitude of slip displacement that is why it is very important.

A location may wander through a crystal with its orientation changing from place to place, but its Burgers vector is the same everywhere this is something you have to remember this is exactly we have just shown in the previous slide, whether it is you know, we are looking at a cut-out crystal block we have measured the beam, but that is same everywhere whether you measure it clockwise, anticlockwise whether you measure in a screw dislocation side or edge dislocation side or mixed dislocation side the magnitude is same.

If the dislocation branches into two dislocations the sum of the Burgers vectors of the branches equals its Burgers vector. So, this point we will just we can qualify after a few slides we will look at later. So, there is a simple notation system for describing the magnitude and direction of Burgers vector of a dislocation the direction is indicated by the direction indices and the magnitude by a scalar proceeding the direction so, how to give a kind of notation system? So, this is a kind of notation system.

For example, if the b is given like this (a /3) [2 $\bar{1}$ 1] direction in a cubic crystal means that the Burgers has the components of 2a/3, -a/3 and a/3 along the [100], [010] and [001] directions respectively. Where a lattice parameter, very important do not get confused with this symbolism **a** you know lattice parameter and you know how to mark a direction in a crystal.

So, planes and you know miller indices we would have seen it. So, you do the same thing, so, direction and the magnitude is given. So, all the Burgers vectors will have this kind of notation, how much magnitude in terms of the lattice parameter and what is the direction. Its magnitude is |b| so, which is you can square and square root of this the direction components in this case it is

$$a\sqrt{6}/3$$

A dislocation in an fcc crystal corresponding to full slip displacement that restores the lattice would have the Burgers vector a/2 in <110> direction in this case the magnitude is

$a\sqrt{2}/2$

Suppose, what is shown what is mentioned in this point is suppose in an fcc crystal has got a slip displacement it has slipped to restore that slip region that the Burger vector has to move this amount in this direction that is what it says.

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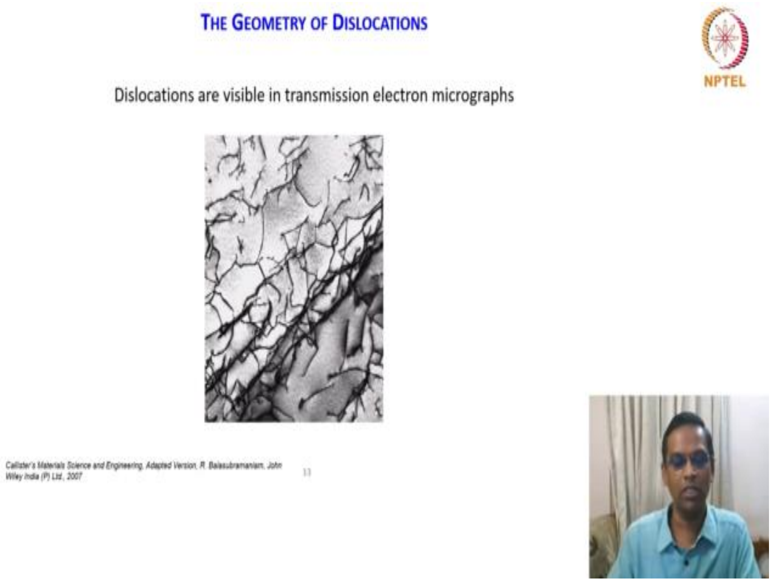


How do we see these dislocations? Dislocations are visible in transmission electron micrographs. So, what you are seeing here is your bright field transmission electron micrograph typically the dislocations are visualised in this manner with a dark contrast what it exhibits dark lines, this is how it looks like at least if you want to get into avoid appearing dark and how you are seeing this is a loop and other things it requires much more knowledge of microscopy and diffraction contrast theory so, on.

Probably you can just take the help of some characterization course to get into the details, but this is just an example how it in reality what do you see all you see because we just said that edge, screw and loop and this does not give that kind of a feeling it gives much more chaotic. So, to get into this kind of suppose if you want to analyse some of this lines like you know, whether it is a loop suppose whether it is the edge character or screw character and this requires further analysis.

But it can be done that is a different field itself analysis of a dislocation in TEM. So, for time being it just you know the message here is we can visualise dislocation in a TEM to understand their behaviour and I mean at least look at their morphology density how much where it is formed? Whether it is formed near grain boundaries? Whether it was formed near any second phase particles or interface boundaries? It is very useful at least whether you involve yourself in analysis of dislocation that is a different question, but at least we are able to see them.

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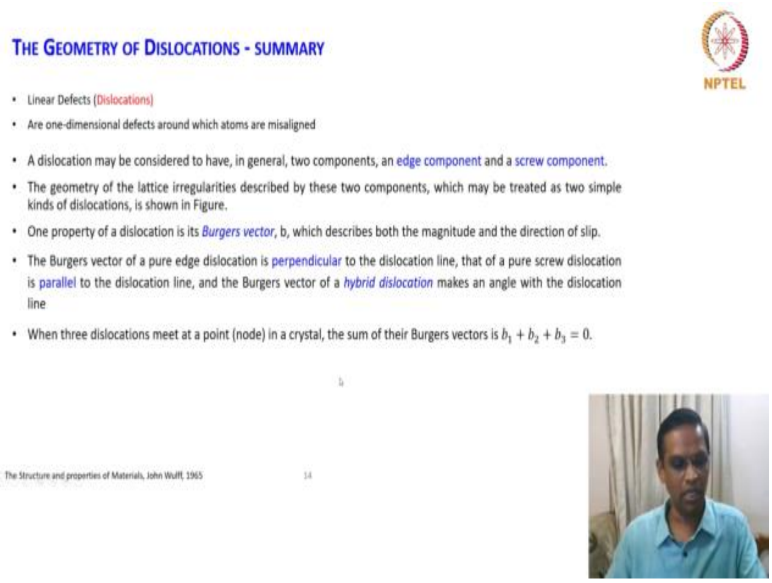


Let us summarise this geometry of dislocation, they are line defects, they are one dimensional defects around which atoms are misaligned. A dislocation may be considered to have in general two components edge component and the screw component the geometry of the lattice irregularities described by these two components which may be treated as two simple kinds of dislocations shown in the figure and one property of dislocation is its Burgers vectors b, which describes both the magnitude and the direction of the slip.

The Burgers vector of a pure edge dislocation is perpendicular to the disruption line that of the pure dislocation is parallel to the dislocation line and the Burgers vector of the hybrid dislocation makes an angle with the dislocation line. When three dislocations meet at a point called node in a crystal, the sum of their Burgers factors is $b_1 + b_2 + b_3 = 0$. So, this particular point we will see as the move along. In a nutshell, this is a complete description of a at least the geometrical nature of this dislocation how they look like.

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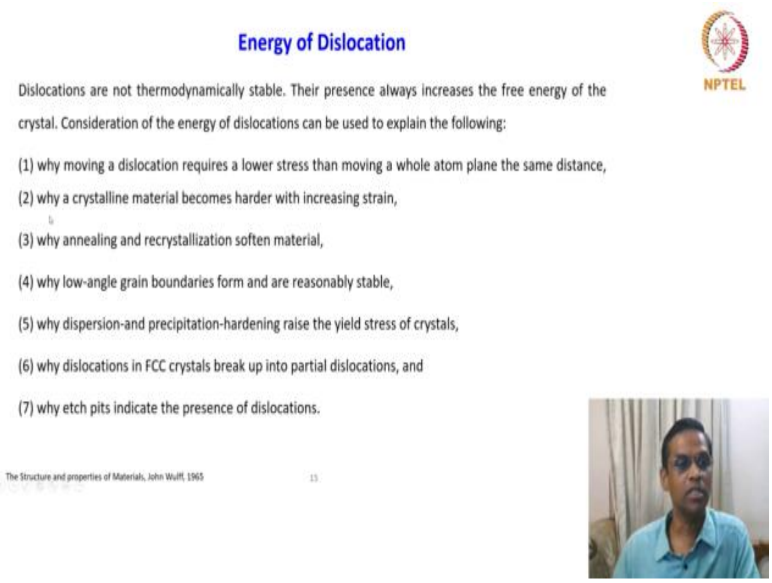


So, now we can move on to the next topic energy of dislocation why are we bothered about this energy of dislocation. Dislocations are not thermodynamically stable, they are presence always increases the free energy of this crystal. So, now, we are giving more information the presence of dislocation increases the free energy of the crystal. Consideration of the energy of the dislocations can be used to explain the following why moving a dislocation requires a lower stress than moving a whole atom plane the same distance?

Why crystalline material becomes harder is increasing strain? So, this is the first two questions are quite relevant to what we have just seen the theoretical estimation of you know bond strength which very high and suppose if we say that denote dislocation is responsible for you know observing the lowest strength and so on. But unless we understand the energy of dislocation itself we cannot explain the other concept. So, that is why understanding of energy is important.

And again, why crystalline material becomes harder with increasing strain? Increasing strain means we are multiplying the dislocation in the crystal system and multiplying crystals multiplying the dislocation in the crystal system it will do so many other things and the systems become complicated and the energy always going to get increased. So, that is why we are thinking about the energy why annealing and recrystallisation softened the material?

So, increasing the strain increases the dislocation it gives a clue increasing the strain increases the dislocation density annealing and recrystallization is going to reduce them a kind of but, we do not know. Why low angle grain boundaries form and are reasonably stable? See, the first statement we say that dislocations are not thermodynamically stable, but here we say that even though it is classified thermodynamically not stable in certain geometrical positions in real time crystals.

A typical low angle grain boundaries formed by this defects we will see them how it forms and why it forms and so on. And the energy concept really helps there and why dispersion and precipitation hardening raise the yield strain yield stress of crystals. This is another important aspect very useful in you know strengthening mechanisms or real time material development and retreatment and so, on.

The dispersion and precipitation hardening has got a close connection with the dislocation and its energy and finally, why dislocations and fcc crystals break up into two I mean into partial dislocations? And why etch pits indicate the presence of dislocations? So, we will see in the future slides and dislocation can get dissociation into two dislocations. So, why it happens that also will be addressed in terms of energy, energy conservation. So, you see several questions can be nicely addressed by the dislocation and its energy.

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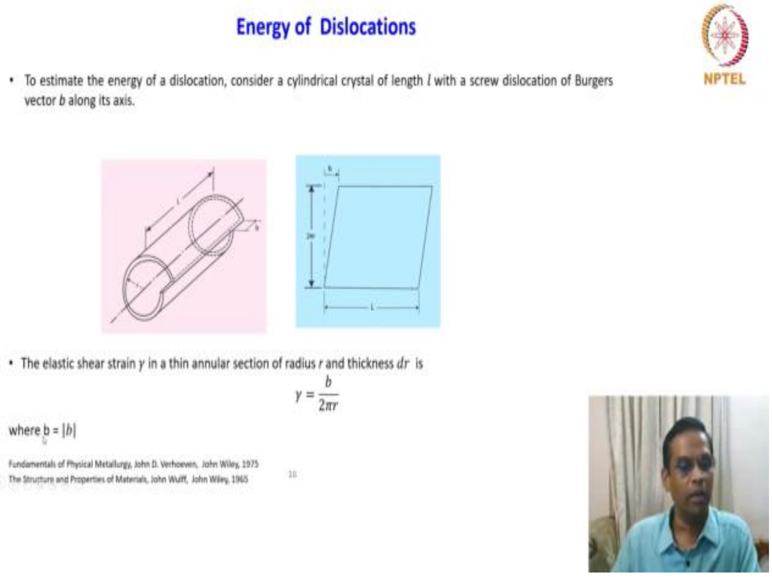


So, we will slowly get into this, I just want to tell you since I am just flipping the slides I am going it may I may go very fast in normal circumstances, when we do with I mean a blackboard and chalk the information and you know, what it transmits to you and what how much you absorb will be much slower. Since it is a PPT mode, it may look all you know going very fast and if you would not be conscious of this factor, you will also get you know, all this concepts will get evaporated from your mind so, fast.

So, do pay attention to this aspect, it is PPT presentation is not really a good way of teaching and at least you know this situation online teaching mode it is a one constraint. So, stop everywhere and then do not go very fast go slow and then think about it and slowly prepare your personal notes and then try to learn and you can always interact with us if you have any doubts.

So, now, we are going to look at the estimation of energy of a dislocation. So, what do we do to estimate the energy of a dislocation, we can consider a cylindrical crystal of length l with the screw dislocation of Burgers vectors b along its axis. So, we are going to consider this kind of a geometry. So, this is a cylinder cylindrical crystal and this is the screw dislocation as I just demonstrated in the previous slide, the Burgers vector is b here, the radius of the cylinder is r radius, I mean the length is L.

And what is shown here is just if you open the cylinder, it will be like this, it will be a sheet like this and this particular geometry is very familiar to you. What is this? We described in the video I mean some of our previous chapters, it is the shear displacement. So, what is that we are going to see b and $2\pi r$ that is because of the cylindrical geometry and this is L so, the elastic shear strain $\gamma$ in a thin annular section of radius r and the thickness dr is

$$\gamma = \frac{b}{2\pi r}$$

So, now, you have enough background to understand this simple calculation of the shear strain $\gamma$ and how it comes. So, we do not have to spend more time on this now, and where b is the Burgers vector here, but we are interested in the magnitude.

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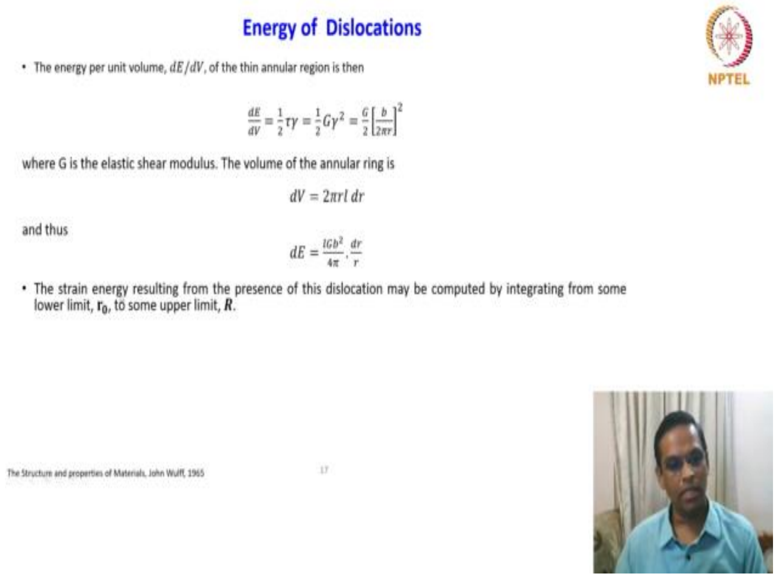


So, what we are interested in? We are interested in the energy per unit volume that is dE/dV of the thin annular region is then given by

$$\frac{dE}{dV} = \frac{1}{2}\tau\gamma = \frac{1}{2}G\gamma^2 = \frac{G}{2}\left[\frac{b}{2\pi r}\right]^2$$

this expression also quite familiar to you, we may not have used exactly dE/dV but then to see that you know 1/2 ($\tau\gamma$) should go back to initial plasticity theory we have seen all this. So, $\gamma$ you substitute that the whatever we have seen earlier then you get this expression dE/dV where G is the elastic shear model is the volume of the annular ring is $dV = 2\pi rl\, dr$.

And you can write

$$dE = \frac{lGb^2}{4\pi}.\frac{dr}{r}$$

the strain energy resulting from the presence of this dislocation may be computed by integrating from some lower limit $r_0$ to some upper limit R. you see, we are looking at the cylindrical annular system so, but we have not fixed the R. So, to calculate the strain energy resulting from this kind of a dislocation the r can be varied from $r_0$ to capital R so, that is idea.

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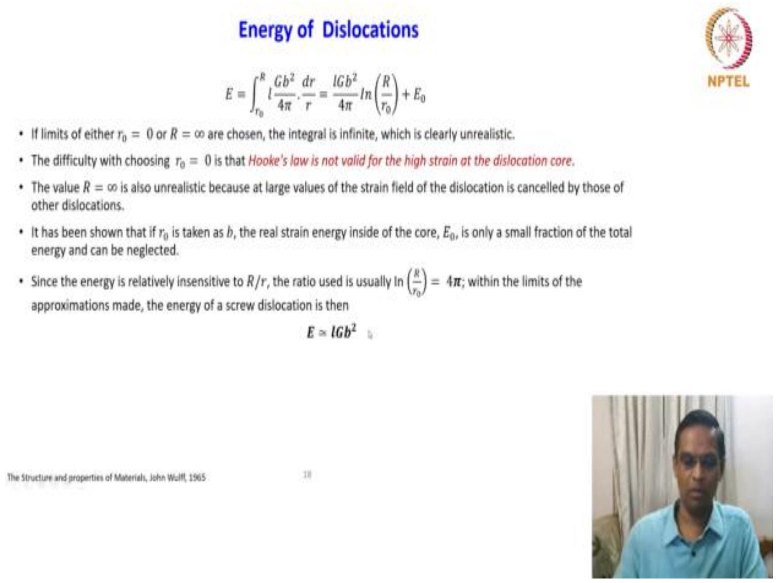


So, for that, we are going to integrate this expression that is

$$E = \int_{r_0}^{R} l \frac{Gb^2}{4\pi} . \frac{dr}{r} = \frac{lGb^2}{4\pi} \ln\left(\frac{R}{r_0}\right) + E_0$$

this is simple integration. If the limits of either $r_0 = 0$ or $R = \infty$ I have chosen the integral is infinite which is clearly unrealistic. So, either you cannot I mean either you choose $r_0$ or R as a 0 then the integral becomes unrealistic.

The difficulty with choosing $r_0 = 0$ is that Hooke's law is not valid for the highest strain or the dislocation core very important point we have reached the very recent I have just to move to this topic of dislocation before going to anything else is the energy system and the stress field around the dislocation everything is dealt with elasticity theory. Since, we have just looked at all the concepts are brushed up all the elasticity theory I thought it would be very easy to just to describe the dislocation before you forget everything in total.

So, the whole stress field around a dislocation are explained by elasticity theory only. So, the if you take $r_0 = 0$ then the Hooke's law is not going to be valid because of the very high strain core because we are talking about elastic behaviour, the core of the dislocation may not be a need not follow the elasticity theory concepts that is idea the value capital R is equal to infinity is also unrealistic because at large values of strain field of the dislocation is cancelled by those other distributions.

We are going to qualify all these statements one by one. So, it has been shown that if $r_0$ is taken as b the real strain energy inside the core, $E_0$ is only a small fraction of total energy and can be neglected. Since the energy is relatively insensitive to R/r the ratio use is usually

$$\ln\left(\frac{R}{r_0}\right) = 4\pi$$

within the limits of the approximations made then the energy of the screw dislocation is given as $E = lGb^2$.

So, finally, we be with all this assumptions, we got one expression of energy of screw dislocation E is going to $lGb^2$. So, G is a constant l is geometry anyway. So, what is the message the energy is proportional to square of the Burgers vector this year to remember that is what we have shown the beginning but this is what we have finally arrived at also.

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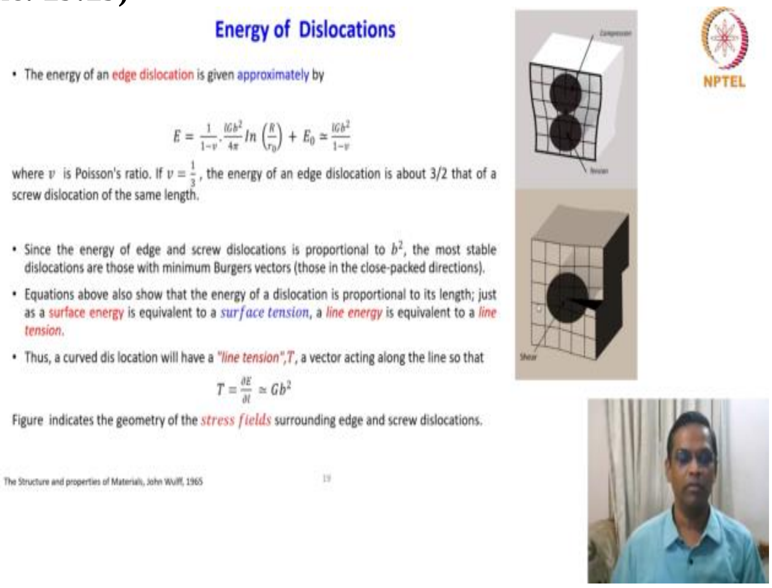


So, what I am now showing here is two schematic one is edge dislocation and a screw dislocation. And what is shown there is a shadow behind there behind this three dimensional schematic. There is a shadow, the kind of light to show the stress speed around this dislocation. The energy of a dislocation edge dislocation is given by approximately

$$E = \frac{1}{1-\vartheta}\frac{lGb^2}{4\pi}\ln\left(\frac{R}{r_0}\right) + E_0 \approx \frac{lGb^2}{1-\vartheta}$$

See all of you now must get alerted the moment you change from screw dislocation to edge dislocation the modulus part is changing to not just G it is $G/(1 - \upsilon)$. So, you just recall we have derived this where do you get $1 - \upsilon$ term in elasticity theory we have derived a lot of small, small derivations, especially in the elastic stress strain relations, if you go back and see we have just derived this 1 – υ term where does it come you look at what is the modulus given for plane stress problem and a plane strain problem, very important.

So, the moment you go to the plane strain problem, then this kind of 1 – υ terms comes in a elasticity theory something like that, we are not getting into the details, but I am just giving you a tip. So, when you move from screw dislocation to edge dislocation expressions, you will always see that this 1/(1 – υ) terms come in the edge dislocation. So, you can just imagine that you know how it would have got inserted that is because you are now considering the state of stress is a plane problem.

That is the plane strain problem, then the 1 – υ term comes. So, if you understand all these subtle differences, then you do not have to worry about all this mathematical terms. It is very easy to look at it where the υ is the poisons ratio. If υ is 1/3 the energy of edge dislocation is about 3/2 that of the screw dislocation of the same length. Since the energy of the edge and screw dislocation is proportional to $b^2$ the most stable dislocations are those with the minimum Bugers vector which is those in that close packed direction.

So, this is very important information again. It is talking about stability, most stable dislocation are those with a minimum Burgers vector. The equation above also show that the energy of a dislocation is proportional to its length, $E = lGb^2$ that is what we have seen. So, just as a surface energy is equivalent to surface tension, your line energy is equivalent to line tension, this is kind of analogy.

Thus a curved dislocation will have a line tension T a vector acting along the line. So, we can write it like this T is equal to rate of change of energy or change of energy per unit length is

$$T = \frac{\partial E}{\partial l} \approx Gb^2$$

line tension, we will use this term when we talk about dislocation interactions and dislocation interact with obstacle these concepts will go a long way when you discuss about centering mechanisms and so on. So, it is good that we get familiar with all these terms right at the beginning the line tension.

So, this is a stress field behind this two dislocations, again, when you talk about stress, now, so far we have just seen the energy of dislocations now we are going to move on to stress fields, which is again very interesting and it will be very, you know you will be very happy to see that most of the expression you will you are already familiar with, because they are all treated by elasticity theory. So I think we will stop here and we will move on to the next topic in the next class. Thank you.