Principles of Physical Metallurgy

Prof. R. N. Ghosh

Department of Metallurgical & Materials Engineering

Indian Institute of Technology, Kharagpur

Lecture No. # 14

Crystal Defects in Metals (Contd.)

Good morning. We continue our lecture on crystal defects in metals. And here basically we have considered, I mean that concept of crystal defect was introduced.

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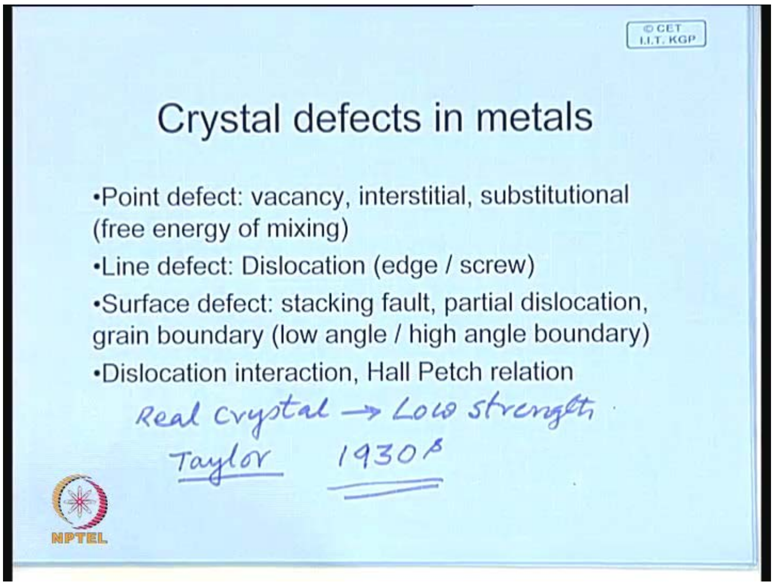

Crystal defects in metals

- Point defect: vacancy, interstitial, substitutional (free energy of mixing)
- Line defect: Dislocation (edge / screw)
- Surface defect: stacking fault, partial dislocation, grain boundary (low angle / high angle boundary)
- Dislocation interaction, Hall Petch relation

Real crystal → Low strength

Taylor 1930s

And what was mention last class is that although that initially that concept of dislocation was necessary, primarily to explain, why real crystals have low strength, real crystals have low strength, and also we have seen that to for homogenous nucleation of dislocation, either homogenous nucleation of dislocation in a crystal or to move or to plastically deform ideal crystal, you need a very high order of strength. And Taylor introduce this concept the way back in 1930, I think this concept of dislocation was introduced by Taylor. But it was not until subsequently later, I mean when there was a direct evidence of presents of crystal defects like dislocation.

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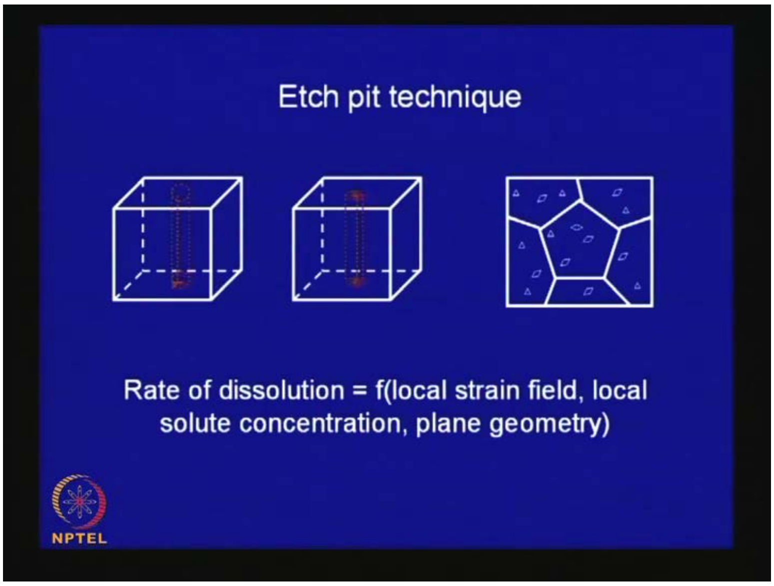

Etch pit technique

Rate of dissolution = f(local strain field, local solute concentration, plane geometry)

Now, one of the simplest way of looking at dislocation is a chemical that Etch pit technique. So, if you polish a metal and electro polish, and there are and there are special etching techniques and dislocations, we know that they cannot either they will be endless or if they have end on a free surface, so which is shown over here. Say suppose there is a dislocation in a solid, it cannot end, it can be an endless look within, but if it intersects, but it can intersect a surface this end point of dislocation. Now, depending on the nature of this dislocation, so there will be lattice disturbance here, so there will be one kind of lattice disturbance, in case of an edge dislocation; another kind in case of a screw dislocation.

And when you a polish surface, when it is chemically etched, this is where the atoms are in excited state you can say the higher energy state. So here the dissolution rate will be more. So it is possible to I mean, this portions will be attract more than the rest and this develops a pit has certain geometry and depending on. Similarly, this pit along screw dislocation will have another geometry and in fact when you look at that microstructure look under magnify under a microscope, you may see that these are the grains and within the grains this type of pits have developed and they can have different shapes depending on what is this plane, what is the crystal telegraphic orientation of this plane and how is the dislocation oriented with respect to this plane. Now rate of this resolution is actually a function of a local strain field local salute concentration and plane geometry. So, this has been one of the earliest proofs but, still it was not very direct evidence.

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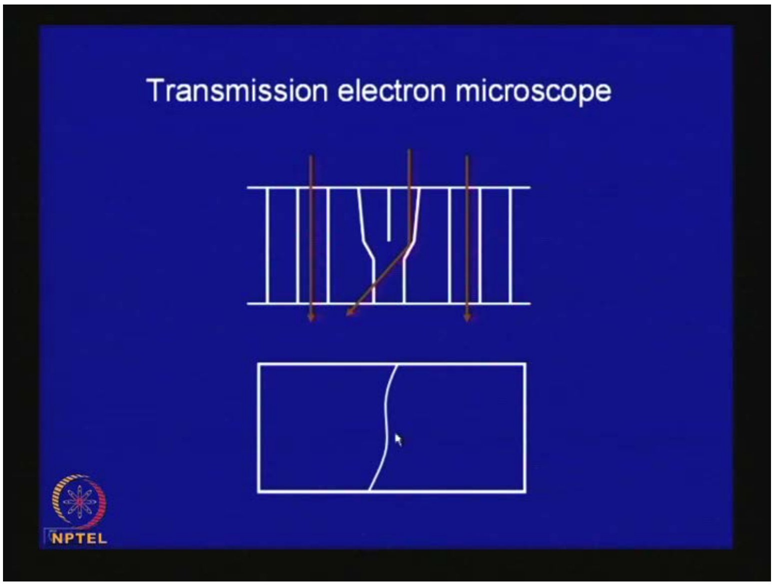

Later on when electron transmission electron microscopic techniques were perfect, they can develop and sometime when fifties and early sixties they have been lot of works can be done, which should conclusively direct evidence presents of crystals defects like dislocations in crystals and seen in transmission electron microscope, you examine a thin foil, suppose this is a thin foil and here visualize, let us visualize these are the regular this atom planes, which are arranged and this an edge dislocation this emulates a pictorial representation of and edge dislocation.

Now, when this beam passes through the region, which does not contain the dislocation, it will pass through and through. And when it strikes that image plane, it is focused on that image plane, it will appear this area will have a bright contrast. Whereas, look at what happens when this being passes through the region, where there is local lattice disturbance something like this it falls on this plane and get this diffracted. So it does not strike the image plane. Therefore, here locally there will be the intensity, there will be intensity contrast, there will be diffraction contrast and this line will appear dark and here also there is no defect so it just passes through it is not getting reflected the diffracted, so basically, from region containing the defect.

So, what you will find that dislocation will appear like a line and transmission electron microscope has several other advantages. Also this electron beam, it has a wave character. So you can also get diffraction pattern. So in that case see what is done here if you block this transmitted beam and you can remove that projective projected projection lens then on the image plane is diffracted beams will fall and this diffraction beams will give will give a pictorial I mean description of the orientations of the foil plane.

Now and etch and here also when you look we are looking at microstructure, there is a provision to tilt this sample and if you tilt this sample here you can also get orientations, where this line will disappear. That means this line beam will pass through and through. By these techniques these two techniques that mean local that selected area diffraction to find out orientations of the foil plane and by rotating the crystal and finding out, when this dislocations appears. It is not only possible to see the low crystal defect but, also to find out burger vector of the dislocations. I do not think, we can cover this, this, this is in further details I thing, which is not within the scope of this particular course.

But you can refer to any standard text on transmission electron microscope and electron diffraction, which will give you methods of observing direct observation of dislocation in crystal line solids and determination of the orientation of the foil plane and dislocation direction in which the dislocation is line on its burger vector. So you can clearly establish whether you see a dislocation, weather it is an edge dislocations, screw dislocations or mixed dislocation.

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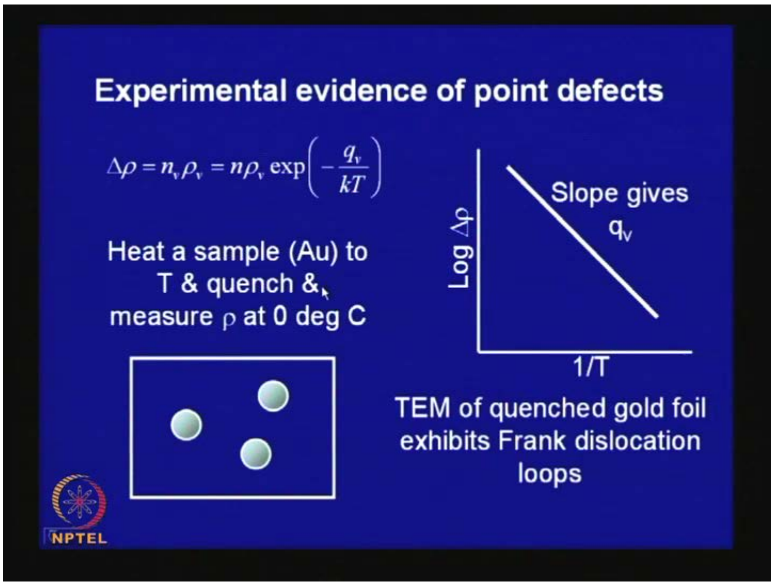

Experimental evidence of point defects

$$\Delta\rho = n_v\rho_v = n\rho_v \exp\left(-\frac{q_v}{kT}\right)$$

Heat a sample (Au) to
T & quench &,
measure ρ at 0 deg C

TEM of quenched gold foil
exhibits Frank dislocation
loops

There are having been many other methods, which gives in direct evidence of defects in materials. One of the simplest things is to measure certain physical properties; say like one of the physical property is that you can measure resistivity. Now, resistivity we know that if you increase the vacancy concentration, you can visualize set like this if you increase the vacancy concentration in a way, you can say that defective area decreases. Therefore, if you can increase vacancy concentration this actually that basically, this will that electron movement I mean electron, which is the carrier of electricity. It will encounter some additional resistance and this change in resistivity of material will be directly propositional to the concentration of the vacancy.

So, n v is the number vacancy and rho v is the change in this represents the change in resistivity, when you introduce one vacancy in the lattice. Therefore, if you have n v number of vacancy in the lattice, this will be the change in the resistivity and we have found out and expression for number vacancies that can exists in a material at a particular temperature and this is given as n is the total number of lattice sites, n exponential minus q v over k T, where k is Boltzmann constant and q is the energy, which is equal to create a vacancy in the lattice. So, this the very simple expression and you can find out resistivity easily of materials and in fact one of the earliest work that was done.

If you heat take a sample say a small piece of say sample, so earliest works done on gold it was heated to a high temperature, when you heated to high temperature a lot of vacancies that concentration of vacancy will be much higher than a get you room temperature. Now if you cool it very fast, in that case what you are doing you are retaining exist vacancy at room temperature or you can quench also sub zero temperature to ensure that vacancy does not diffuse out. You can quench it in a low temperature bath and then what you do you measure the vacancy a measure resistivity of the material at zero degree centigrade. So, you can now have a set of data if by heating gold to different temperature quenching sub zero temperature and measuring resistivity at constant temperature, say zero degree centigrade.

Now, you have a set of resistivity data as a function of the temperature at to which the sample was heated and we can make if you shown that since we are quenching at very fast and this temperature is very low, the diffuse this defects cannot diffuse out and they are held within the crystal and what you find actually the resistivity increases with as you increase the temperature and if you make a plot, if you look at this, if you plot log of change in resistance against 1 over t.

You get a linear plot something like this and this slope of this plot can give you an estimate of the energy of that you need to create a vacancy and indeed with the availability of TEM such samples then look or examine under electron microscope and when you look at electron microscope, what you see is actually something like this. There are rings here, which are actually really stacking fault and we may recall that this is the type of dislocation that you get here.

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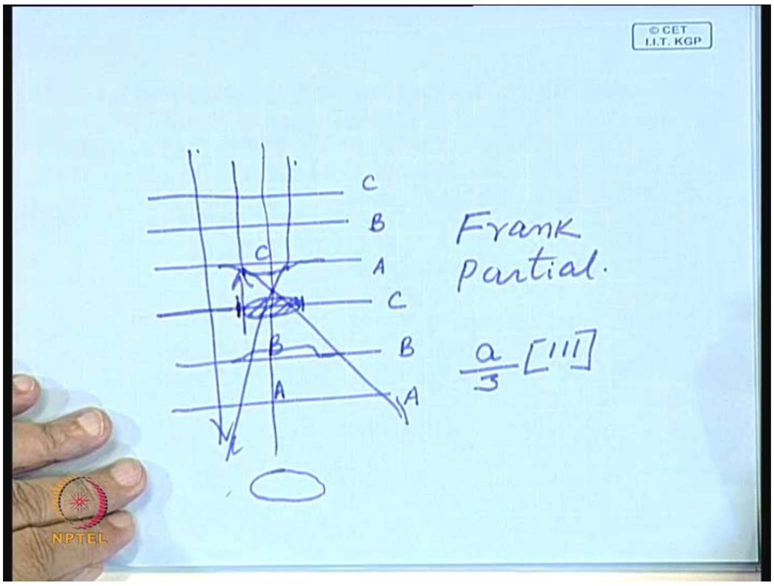

Within the plane, say we know that layers in face centred cubic crystals this 1 1 1 plane. They are arranged in the sequence A B C A B C. Now, what is happening here this vacancy, they are concentrating over here. So, this area these vacancies have come here and this goes out. So what you have here a sequence with in this you have a sequence A B, then you have C and here the lattice this plane will get slightly distorted. This plane get slightly distorted and there is a stacking fault in this stacking and this fault we have been told you have been told this type fault is known frank form due to formation of frank partial dislocation and this dislocation here is the extra plane of atom.

This is the slip plane and this is the burger vector of this and this burger vector will be a by 3 1 1 1 type and here when you are pass in this TEM that is electron beam. So from here and here you can see there will be the thick maze that means out of few layers. Because when you see the file the files are extremely thin they contain only very few I mean they may be an order of may be around say hundred to thousand armstrong that kind of thick maze. These files will very thin and here you can clearly see that when this is passes through this line here. So this planes are distorted like this gets refracted out, this gets refracted out. So the beam, which will pass through this region you will find that it will be refraction contrast and a ring like this and by measuring the dimension of the ring, it will have calculated this stacking fault energy, also can be calculated.

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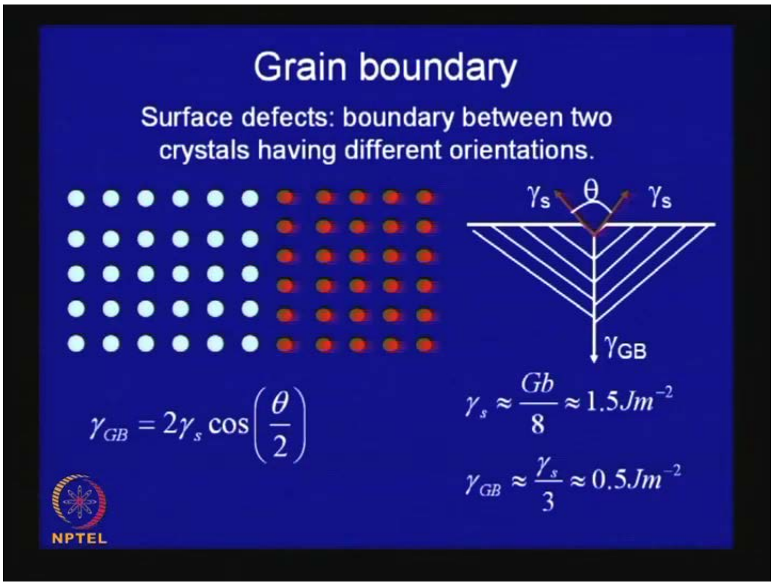

Grain boundary

Surface defects: boundary between two crystals having different orientations.

$$\gamma_{GB} = 2\gamma_s \cos\left(\frac{\theta}{2}\right)$$

$$\gamma_s \approx \frac{Gb}{8} \approx 1.5 Jm^{-2}$$

$$\gamma_{GB} \approx \frac{\gamma_s}{3} \approx 0.5 Jm^{-2}$$

Now, we are taking about surface defect and first surface defect, in terms of the dislocation concept that was introduce was the stacking fault and stacking fault also can be seen easily under the microscope and one example just been sighted. Now one of the simplest surface defect that we now of and you can see this defect under optical microscope these are grain boundaries. We know that metals are made of we look at the microstructure of a metal actually, what you see is several grains, they are orientated randomly.

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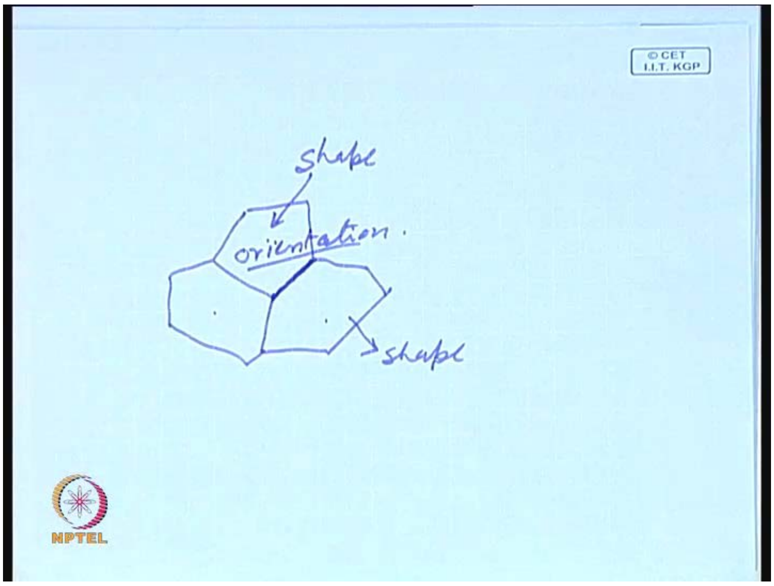

Say something like this you see this grain another grain this is how the microstructure may look like so these grain each may have different orientation, this will be the appearance of the that microstructure. Now point is this is the boundaries. Now these boundaries two things, this boundary it is on the micro microscope what sees is the line but, into reality it is a surface. Now this surface may be bending like this, all is bending like this and that will depend on the shape of these grains, shape of it will depend on the shape of the neighbouring grain. It will also depend on the orientation of the grain, shape and orientation of the grain and we can easily visualize if this orientation this crystal random orientated, this atomic structure that we the atom are arranged on the grain boundaries. This will be very difficult to visualize.

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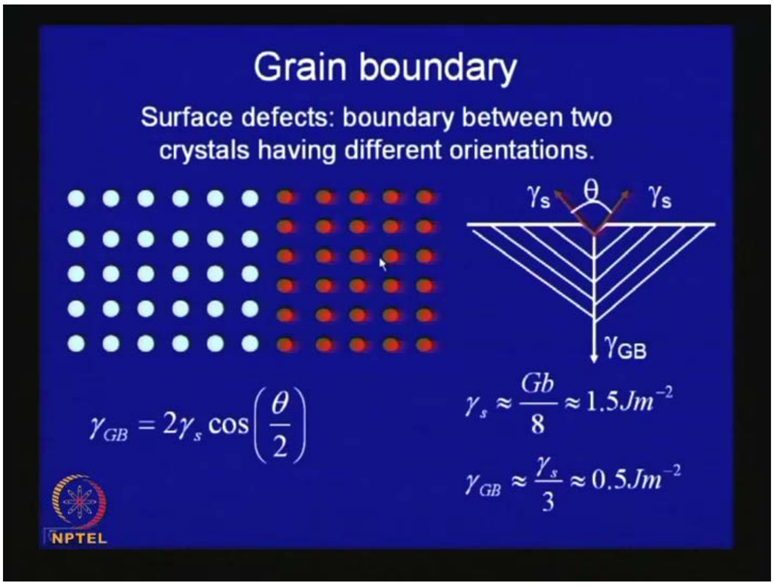

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Of course, in a view what we can see that this boundary although we see this easily. But, its structure is extremely difficult to visualize, what will be the nature. Now let us take up a case this is pictorially what I am representing. So this is one grain, this is another grain and we very often will find thus is means you know this atoms. You know there may not be any match they will be randomly oriented like here, there is an atom here there is an atom here. So, there is no miss no exact crystallography match over here and in this case you know what happens you can see this boundary easily, because along the boundary, there is a some amount of disorder within the grain there is some crystal order crystalline order is there atoms are arranged in a periodic fashion.

Here also atoms are arranged in periodic fashion but, this arrangement there is a no definite arrangement near the grain boundary. So, definitely this surface is a distinct surface and there will be some amount of energy associated with it what is one of the easiest ways of the measuring having an idea about the grain boundary energy is to heat it. Say suppose a polish sample as say as you heat this grain boundary area, you know it will form a groove by heat age and if you can take a section through the grain boundary it is possible to measure the angle.

Now, this is the free surface of that grain this is the free surface of the grain, they have been some attempted to measure the this is the known this gamma may be from we can get a rough estimate of gamma s from strength of the material and so this is say suppose this is known. Now, what happens if you resolve this stress here? So, if you resolve so one component which is horizontal component this will be gamma s sin theta over two and this also will be of similar magnitude in opposite direction. So, this horizontal component will cancel each other but, the vertical component they will add up together.

So, that is why and there will be an equilibrium between this forces and so that grain boundary energy will be something given by this and it has been found that usually this free surface energy, which is rather high this is the order of 1.5 joule per meter square. For certain for many materials this may be of this order and in that case this grain boundary energy that angle depends on the angle and roughly we will take it this will be one-third of this, so around 0.5 joule per meter square. Now compare to this coherent boundary like coherent boundary, one coherent boundary will looked at is stacking fault energy. So at along across the stacking fault at atoms and there is some regularity may be the stacking sequence disturbed.

But, still there is regularity in the lattice and so that energy you know on the either side there is a perfect crystal lattice matching is there. So, this boundary is a coherent boundary. Similarly, twin boundary the twin plane around that also they are perfectly coherent. Now this coherent boundary will have much lower energy as again is that coherent boundaries the grain boundaries normally we considered there incoherent in the sense it is impossible to find any regularity in the atomic arrangement across grain boundary. That is why we call it incoherent and incoherent boundary will always have higher energy than coherent boundary.

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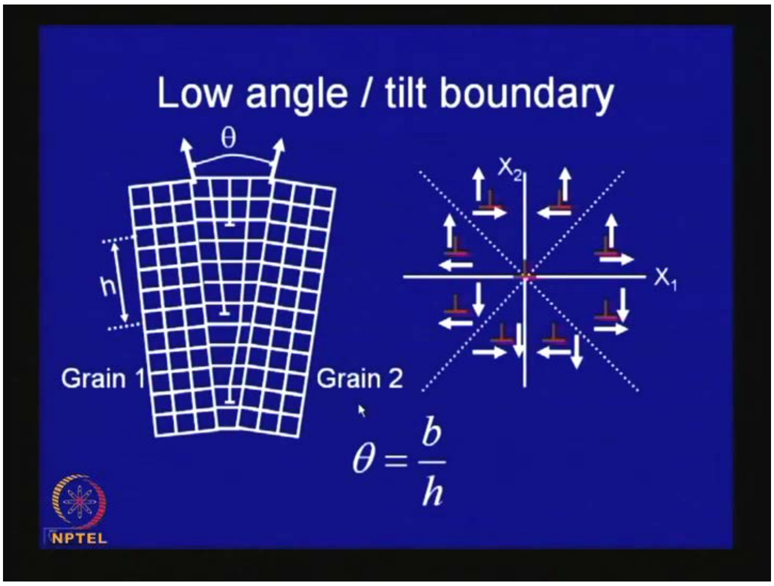
Low angle / tilt boundary

$\theta = \frac{b}{h}$

Now, let us look at the how this boundary can form are what are different types of boundary. One extreme case that will look at is the stacking fault energy that stacking fault is one boundary, which is perfectly coherent. Now, are there any other coherent boundaries? Now we get look at this stress field natural stress field edge dislocations and how this stress, how this stress field of one dislocation interacts with another and we have found at if you have dislocation over here. Another dislocation somewhere here, in that case this dislocation we experience a force and the direction and magnitude of force will depend on the distance between the two and also the location.

Like here, if it is located over here you will find that there will be a climb force, force acting on this which can help it to climb that this location to climb and there will also be a repulsive force which will try to push to this dislocation further apart. But, if you have a dislocation over here in that case true it will have a climb force acting plus another force of attraction which will try to bring it somewhere here and this is a please which is position of equilibrium. So if you disturbed it from this position move the dislocation likely this way there will be a restoring force which will try to bring it back.

So this is a very stable configuration. In fact, such a configuration is actually found in a many crystals and particularly in a nil crystals, you do find in a this kind of dislocation arrange say which has been a piece of metal, which has been deformed and given some amount of thermal activation, you do find this kind of arrangement and this is so pictorially you can visualize this. You have this dislocation here, another dislocation above with, another above it and when you arrange this dislocation like these several of these. Then obviously you are going to form a tilt boundary.

Thus two part of the crystal will get tilted they will get tilted and there will be the rotation and the energy of this boundary is very easy to calculate. How will you calculate this boundary energy? Say suppose you can think about the dislocation it has a unit length and we know that the each dislocation has an amount of elastic energy. So, we can know say suppose within this volume there is only one dislocation and then so this particular area what we can say with this area this length and perpendicular to the plane of this drawing. Say this is the boundary which is perpendicular to the plane of the drawing. So it is possible to calculate this stored energy per unit area of the boundary.

Now for that first step that you need to do, what is the distance between the two dislocations? Now this distance between two dislocations it is very easy to find out. Say the two dislocations if is basically if you have one dislocation there will be a displacement, displacement in this direction. So, if you have one dislocation the displacement is b and b over h is the angle. So basically so roughly what you can say if there are two dislocations as if there are these two part these two dislocations there will be pushed apart by a slip vector b and therefore, obviously you can calculate this displace that angular rotation this will be this b over h.

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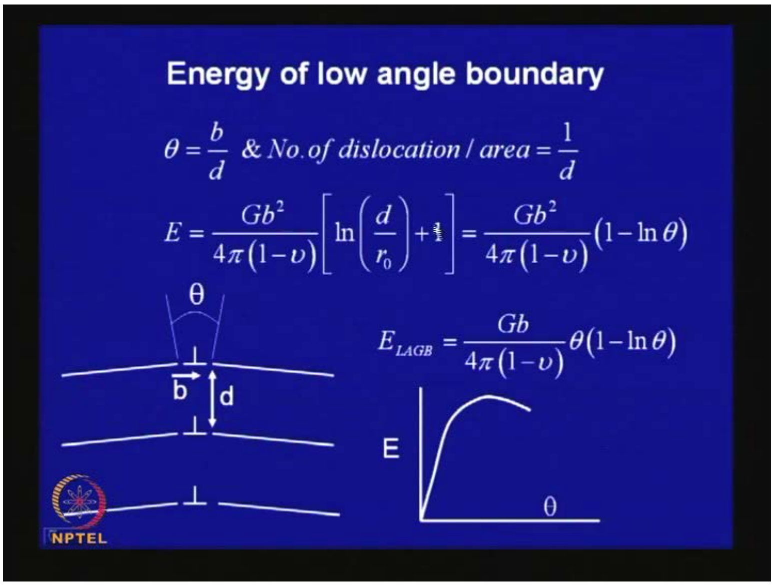

Energy of low angle boundary

$$\theta = \frac{b}{d} \ \& \ No.of\ dislocation\,/\,area = \frac{1}{d}$$

$$E = \frac{Gb^2}{4\pi(1-\upsilon)}\left[\ln\left(\frac{d}{r_0}\right)+1\right] = \frac{Gb^2}{4\pi(1-\upsilon)}(1-\ln\theta)$$

$$E_{LAGB} = \frac{Gb}{4\pi(1-\upsilon)}\theta(1-\ln\theta)$$

Now, it is very easy to calculate this elastic energy of this dislocation, which is shown here.

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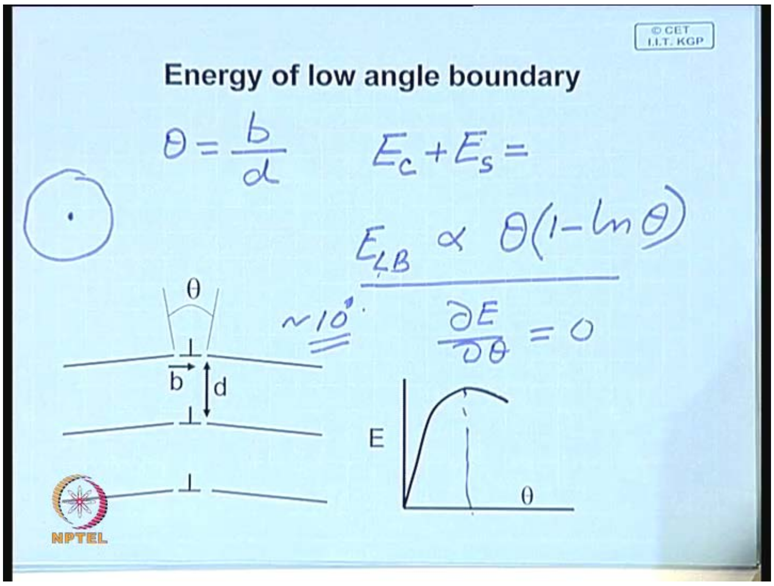

Energy of low angle boundary

$\theta = \frac{b}{d}$

$E_c + E_s =$

$E_{LB} \propto \theta(1 - \ln \theta)$

$\sim 10^{\circ}$

$\frac{\partial E}{\partial \theta} = 0$

What you do is you try and find out that we have just seen the theta is equal to b over d. Now, we know that elastic energy of this dislocation is actually a made up of two components, it is a core energy plus that elastic energy surrounding the dislocation. If you have a dislocation here surrounding this zone, you have that because of that elastic stress field that energy. Now this expression has already been derived and which is shown over here and here if you assume that this core is of the order of the dimension of the core is of the order of the burger vector. In that case core energy will be this is the part, which is giving the core energy.

This time thus is the energy of the dislocation core and this is the elastic stored energy for this dislocation and what will be the size, the dimension will be the distance between the two dislocations, this distance between the two dislocations d over here. Now this d you take d by 2 here, d by 2 here, so this is the 1 and imagine the perpendicular imagine that perpendicular to the plane is the boundary. In that case the energy is given by this and here you can substitute the value of d. So, d is b over theta. So if you substitute b over theta. So you get 1 over theta and r 0 is equal to b if you assume that you get this expression.

Therefore, here you can so this is the energy per unit length of the dislocation. Now you have to multiply by you have to multiply this by this distance. So if you multiply this then you get this energy per unit area of this boundary will be equal to theta. So, in that case this will be boundary energy. Now one important thing is this boundary energy is equal to this low angle boundary energy it is proportional to therefore, that mismatch orientation mismatch that one minus l n theta. So this is the function of theta as you can clearly see if the theta is 0, then energy of the boundary I mean, it will be it will be0.

But, as theta increases then you can say that energy boundary energy will increase and always we think about low angle boundary. That mismatch is very low may be maximum of the order of five or ten degree around that. But if you extend if you assume that extends beyond that. Of course, there are lot of approximations when in this derivation it is possible to show that this energy it increases with theta. But there will be a particular value beyond which it starts decreasing if this is the relationship, which you can show that in this case if you differentiate this with theta and equate this to 0. You will find at a certain position this will be maximum. Of course, this will over estimate that value quite because there is some built in assumptions in this derivation.

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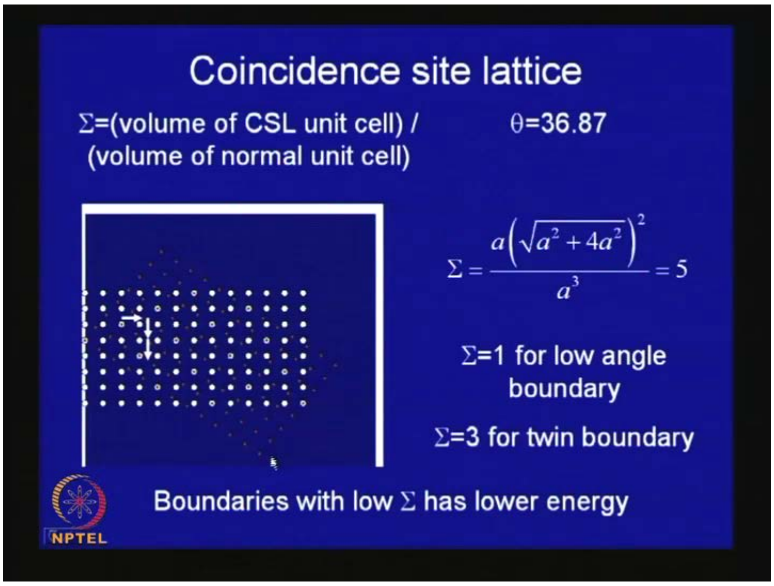

Coincidence site lattice

Σ=(volume of CSL unit cell) / (volume of normal unit cell)

θ=36.87

$$\Sigma = \frac{a\left(\sqrt{a^2+4a^2}\right)^2}{a^3} = 5$$

Σ=1 for low angle boundary

Σ=3 for twin boundary

Boundaries with low Σ has lower energy

Nevertheless, this type of concept that low angle boundary, thus give you an idea how to estimate the boundary of energy of a grain boundary. Now, how can you visualize is there is a way we can visualize or classify the grain boundary, according to the orientation of the grains and the surface on which they meet they have been several attempt and one very simple attempt is what they try to do the visualize the two crystals.

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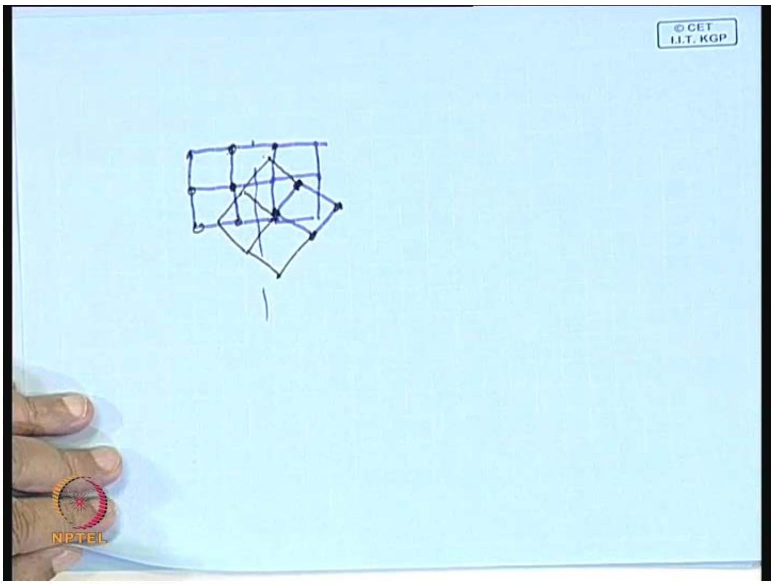

Say if visualize one crystal here and this is another crystal which is side by side, which forms a boundary. Now point is if you extend say suppose this is the boundary. Now this is the atomic arrangement here is like this. Now if you extend this structure even beyond the boundary. So that means this is the hypothetical construction even beyond the boundary, you make this type of construction beyond the boundary, which is basically is totally hypothetical construction. In the same way you can also extend this boundary as well.

This also you can extend beyond this and this construction, it is very easy to do it even in a computer using what you have to do you assign 2D quite easy. You assign some coordinates here and assign these coordinates and one of these keep this fix and suppose you rotate it give a rotation and this rotation matrix you have to visualize and multiplying that when you rotate the matrix rotate this array. It is possible when you give a rotation it is quite easy to calculate the coordinate of these points when you get the rotation. Now so with that if you just superimpose you may find there will be some points, which are which will be lying one over the other and this is what is shown over here.

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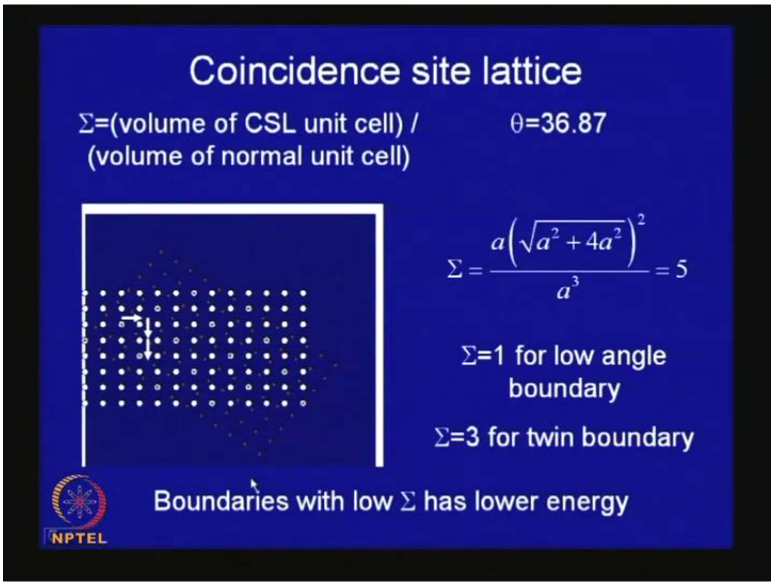

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Boundaries with low Σ has lower energy

This concept is called coincidence site lattice concept. Coincidence site lattice is actually non existence. What you are saying is you are trying to visualize, what will be the energy of the atom and for that what has been done here this white array white one is the one grain and this red points this is the another grain, which is not so clear. But I do not know this is clear. Here you can see there are arrays here. Here this is one grain and this is the other one, this is the other one. Now some of the place is you will find the two points they are coincidence like here. Now if you join this coincident point in that case you generate the coincidence lattice, which is actually something like this.

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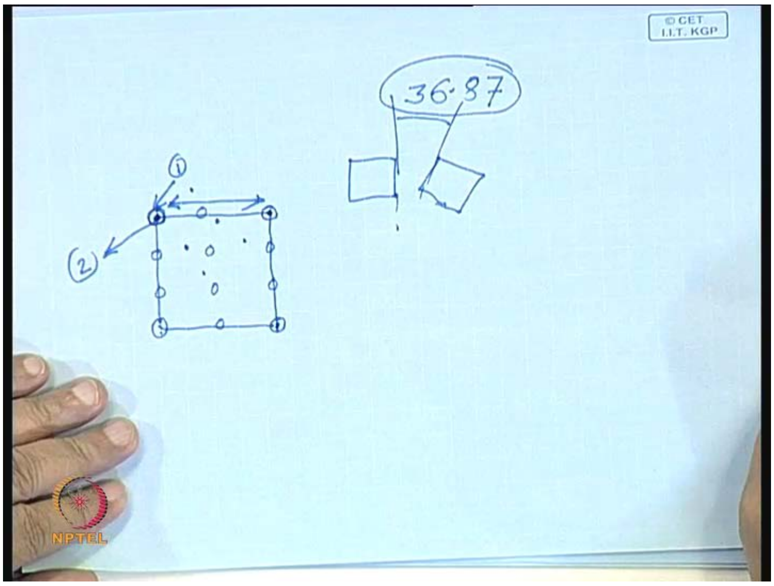

So, if you have certain case where these points both are but, you will find that this dimension is much larger than this lattice, where this is one grain boundary. One grain first grain this is the lattice point of the second grain. But this second grain there is other points also for the second grain, which are orientated like this. Similarly, the other one are also orientated like this. Say may be there are other points oriented like this and in that case what you can find out you can find out dimension of this coincidence lattice.

So this is the planer dimension and in this particular example what have taken here this they have been the two simple cubic lattices. So both are simple cubic structure and they are rotated by a particular angle and this angle is 36.87. So when you rotate by this angle then you generate a certain points, which are coincident and you can measure this. In this particular case the dimension of this shown over.

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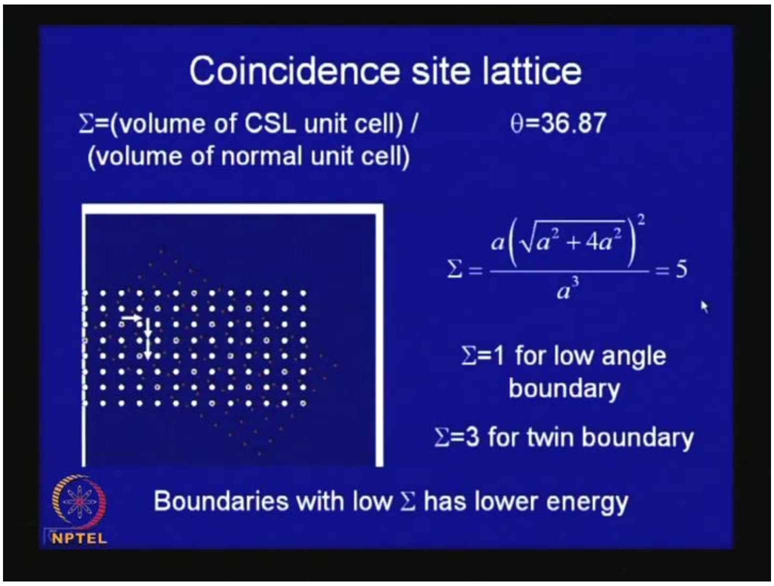

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Here, this arrow so here one direction you get one lattice, another direction you get two lattice points therefore, what you can say this lattice dimension is from here to here. So, this is the coincidence lattice. so this dimension is much larger than this dimension. So, this is one unit here two unit the site. So, you can therefore, calculate this diagonal and which is shown over here it is root over a square plus 2 a whole square, so four a square. So, basically and then you can calculate the volume of this coincidence site lattice then perpendicular direction that atomic distance is still because that is be we are not disturbing. It is only a 2D construction with boundary is 2D.

So, basically so with this is where we get we can calculate the volume of the coincidence site lattice and divide it by the volume of the normal lattice which is a cube you get 5. So this we define a term call sigma so sigma is a basically is a ratio of the volume of coincidence site lattice in itself over volume of normal unit cell. In this case this comes out to be 5. So, usually if sigma is low so basically if sigma is low means if sigma is one for low in that case it is a low angle boundary, there is a these boundaries are perfectly coherent and it has been shown easily for twin boundary that sigma is equal to 3 and all boundaries which have low sigma.

Low sigma they have lower grain boundary energy. So, this is one way of visualizing or characterising grain boundary and it is interesting I mean this process of rotating the one these two grain giving a relative rotation it is possible to generate different types of sigma boundaries and usually the lower one are some of these which has been mentioned. But, they can be many other which where the coincidence lattice sites they are much larger. So obviously they will have much higher energy. Now, we have talked about a stacking fault quite a lot and there is a lot of similarity between stacking fault and stacking fault and grain and stacking fault energy is quite easily determine.

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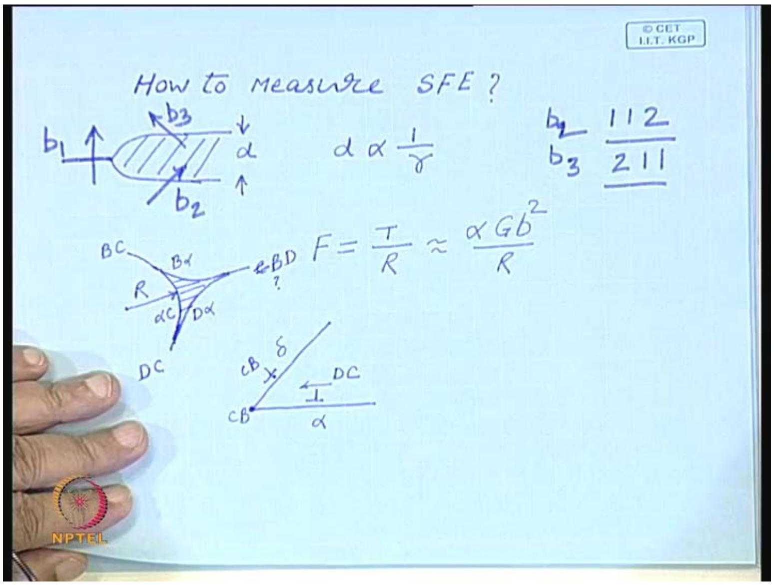

One way of estimating stacking fault energy is by measuring the distance of separation between the partial. So, we have seen that if you have a dislocation here. Say, basically this is a perfect dislocation this is b 1. Say, basically it breaks down into two partials b 2 b 3 and the two will have some angle. Now this is of the type we know that this b 1 and b 2 they are of the type 1 1 2 both of them. So, only thing is and they will subtend a particular angle b 2 is 1 1 2, b 3 is also another 1 1 2 with the different order. Say may 2 1 1 something like this. So, this in that case what will be the plane? So, plane you have to imagine whether I mean these two are can lie in a particular plane or not. So that you have to check it has been just written without conforming they may not be in the same plane.

But, in a particular plane we know that here there will be 3 1 1 two directions. Like these directions, this is a 1 1 2 direction, this is another 1 1 2 direction, this is another 1 1 2 direction. So, if you extend this and extend that and this angle will be 60 degree. Because these are each of this they are subtending equal angle in a plane. So, that angle is 120 degree this angle is 120 but, they are actually if you extend this angle is 120 but, you extend this angle is say 60 degree. Now the question comes up is it possible to measure this distance.

Now, this will depend totally on the magnitude of the stacking fault energy, if this stacking fault energy is low this d is large and in that case possibly it can be seen with may be within the resolving power of the microscope under TEM, you can see these two partial separated by a fault and faulted region, also gives stacking fault fringes. So, this is one way of a finding out the stacking fault energy but, this will be applicable only in case is where the stacking fault energy is very low. But, there are materials and we have talk about it there are materials the stacking fault energy is very high.

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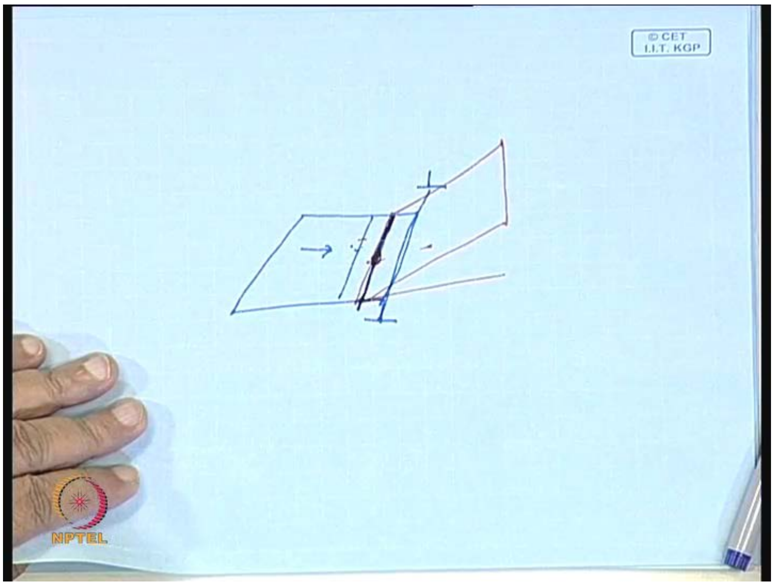

These materials they can cross slip here the dislocation can cross slip easily. Suppose a dislocation which is moving in a plane here. So, these are the partials so if it meets some obstacle over here, which is not allowing the dislocation to move these dislocations a part of it if you apply this, they can join together along this particular line it can come here. So, basically it can move it can come here and it form a constriction and this can say if this is the another plane, which is intersecting slip plane, it can move there.

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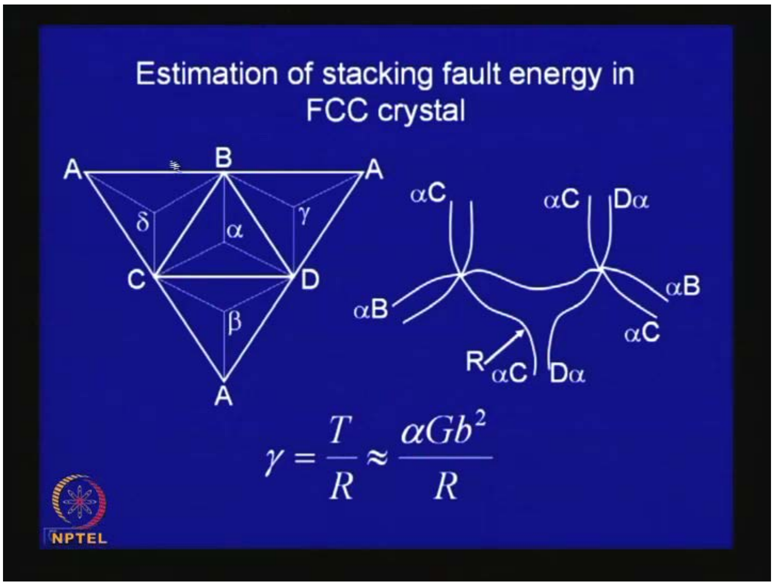

Estimation of stacking fault energy in FCC crystal

$$\gamma = \frac{T}{R} \approx \frac{\alpha G b^2}{R}$$

This is what shown in cases of material, where the stacking faults energy is high. In this case the dislocations moving say in one plane is a delta, another say in alpha. So, they can meet along the line B C and they can intersect this one dislocation moving here with burger vector say D C and this can intersect a dislocation moving here having burger vector B C and they can create a constriction and when such constrictions are formed and rest of the part this nodes are formed, rest of the part the split that means they split on these planes.

In that case you can generate this kind of dislocation networks where these dislocation these are nodes and these are partial dislocations and here this partial dislocations, basically they will try there will be some force repulsive force that will try to push them apart plus depending on the energy that it will try to minimize it. It will because the fault which is created it has a certain energy, so that will exert another opposing force will not allow into grow so you have some situation like this where you may have this dislocation lines which are curved and if you can measure this radius of curvature.

It is possible to calculate that stacking fault energy and which is shown over here. This is the line tension the stacking fault energy is equal to the line tension over R and here the line tension energy, which is given as alpha G b square. So, many cases looking at transmission electron microscope examination it has been possible estimate stacking fault energy.

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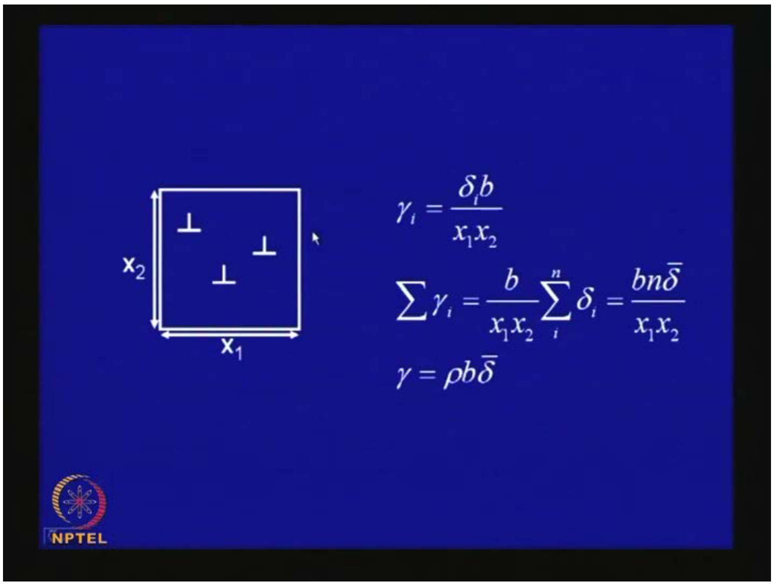

$$\gamma_i = \frac{\delta_i b}{x_1 x_2}$$

$$\sum \gamma_i = \frac{b}{x_1 x_2} \sum_i^n \delta_i = \frac{b n \bar{\delta}}{x_1 x_2}$$

$$\gamma = \rho b \bar{\delta}$$

Now, let us take up a case where in very often, we have seen that experimental measurement of dislocation. We can also measure the dislocation density. Now dislocation density means many times we define a term dislocation density and usually it has been mentioned this dislocations they will intersect at the plane the top plane. Let us say this is the perpendicular plane where these dislocations are intersecting and this is the number of the intersections that means number of dislocations, locations per unit area. This is the dislocation density.

Now in that case it is possible if you know dislocation density it is possible to relate it to the magnitude of shear strain and which is shown here. If one dislocation moves from this end to that that means if it moves a distance x 1 it creates a slip step of magnitude b. therefore, say this is b over so basically so this is b you create b but, all dislocation may not move the distance x 1. So, that means it does not move from one end of the crystal to the other, it is quite likely dislocation will move a fraction of this distance.

And suppose this distance the dislocation moves, we consider the dislocation i th dislocation there are several dislocation. Let us consider a specific dislocation i and that can move a distance delta i, then the strain that i mean it will generate will be delta i b over x 1 and this will be the magnitude of the step that will be created and if you divide by this distance x 2, then you will get the shear strain.

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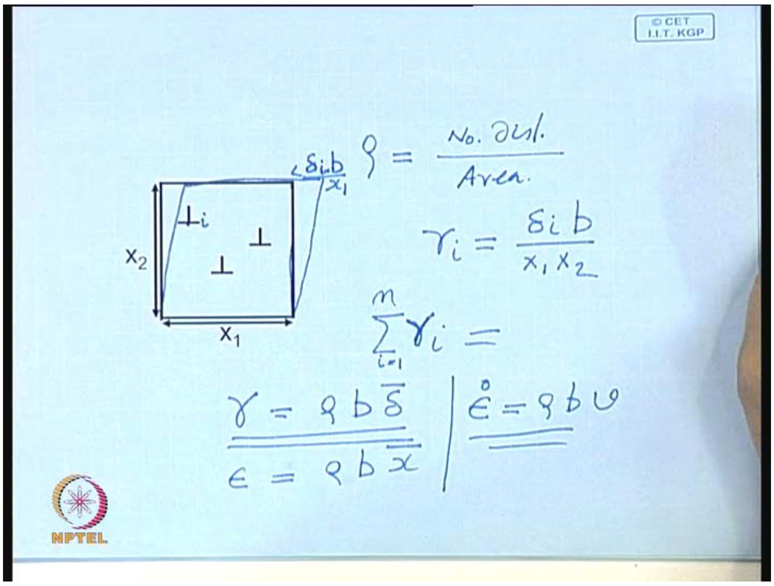

$$\rho = \frac{\text{No. disl.}}{\text{Area.}}$$

$$\gamma_i = \frac{\delta_i b}{x_1 x_2}$$

$$\sum_{i=1}^{n} \gamma_i =$$

$$\underline{\underline{\gamma = \rho b \bar{\delta}}}$$

$$\epsilon = \rho b \bar{x}$$

$$\underline{\underline{\overset{\circ}{\epsilon} = \rho b v}}$$

So, actually what is happening the shear happening means, how do you find out shear strain shear strain is this step. This is the step say if it is delta i times b average distance over x 1. So this is actually is the size of the step if you divide by say this is the dislocation i dislocation. Therefore, if you divide this x 2 so in that case gamma i is comes out to be delta i b over x 1 x 2. Now this is one dislocation to get total strain what you have to do you have to sum over all the dislocations. So i equal to one to n and when you sum up then you get this and if you can say that average distance dislocation can move is delta bar.

In that case this is and we can say this is the number of dislocations over the area. In that case we say that this is the density. So, this is therefore, we can say that total shear strain is equal to rho b the distance at dislocation that`s average distance dislocation moves. Very often i mean we are using the symbols it may vary from book to book. But, basically what we say the strain shear strain also will have direct relationship to longitudinal strain and we can approximate so that means that strain is proportional to or strain is equal to rho b and then average distance say dislocation moves and in that case and if you say that strain rate if you try and convert it into strain rate, in that case it will be strain rate will be rho b, then x dot. So that is the velocity of the dislocation. This is the strain rate.

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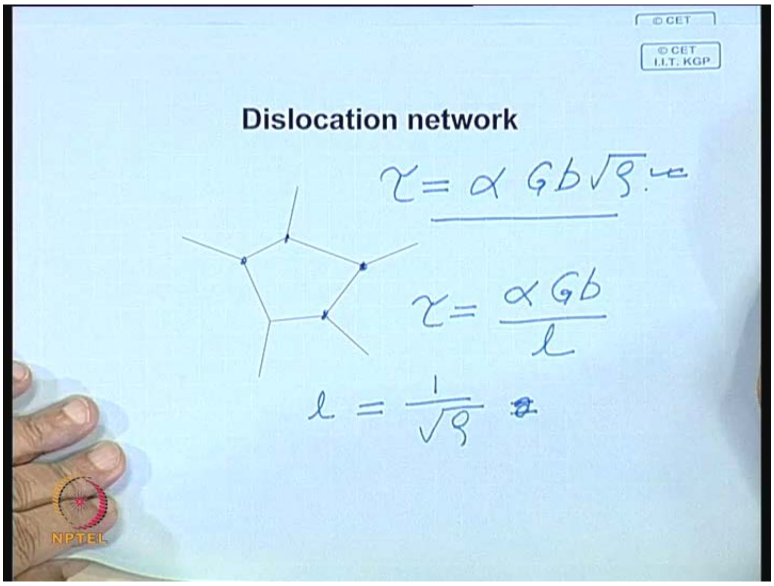

Dislocation network

$$\underline{\tau = \alpha G b \sqrt{\rho}}$$

$$\tau = \frac{\alpha G b}{l}$$

$$l = \frac{1}{\sqrt{\rho}}$$

Now dislocations are always present I mean in the material and they can form a network of dislocation and you get a very stable network. In cases is where you have high stacking fault energy and something like this and in this case it is quite easy to show that rho. We have seen this expression rho so you can visualize, so these are the pin dislocation they can act as Frank read source. So, yield stress or shear stress at which deformation takes place will be this and here l is the link length and it is quite easy to show that dislocation density, this l is actually equal to 1 over root over this dislocation density. Therefore, what we can say the tau that yield stress is equal to G b root over rho. So that means as the dislocation density increases, the shear strength of the material increases.

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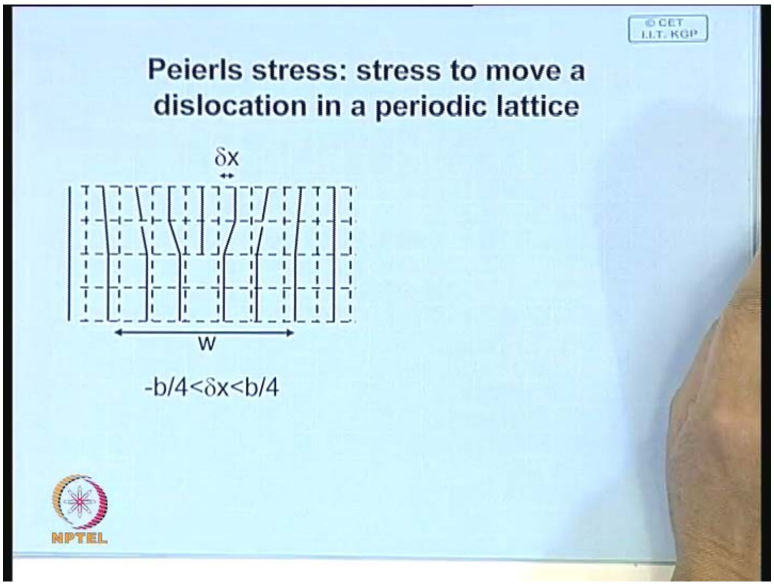

Peierls stress: stress to move a dislocation in a periodic lattice

$-b/4<\delta x<b/4$

Now, another important thing is to consider the movement of a dislocation in a periodic lattice and we had made an approximate estimate in this sense that if you look at the lattice and if you try and introduce a dislocation. You will find the top part is under compression bottom is under tension and therefore, we said approximately to move in such cases to move this top part, you are doing a positive work and bottom you are doing a negative work. Therefore, network is zero. So stress to move a dislocation in a lattice is nearly zero. But, in fact it is not sure actually you have you have to move the dislocation in a lattice where are atoms are arranged periodically, which is shown over here.

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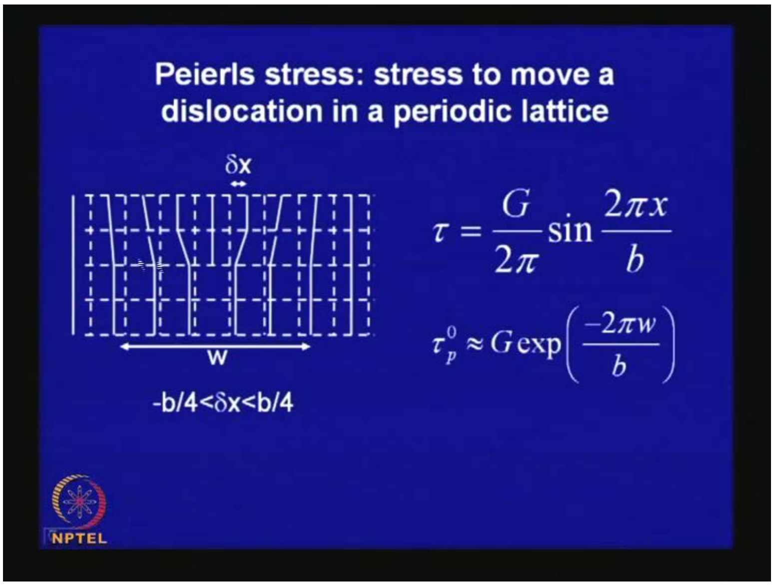

Peierls stress: stress to move a dislocation in a periodic lattice

$$\tau = \frac{G}{2\pi}\sin\frac{2\pi x}{b}$$

$$\tau_p^0 \approx G\exp\left(\frac{-2\pi w}{b}\right)$$

Therefore, you will need some additional friction force will be required to move the dislocations and this is particularly shown over here. This dotted diagram is a perfect lattice there no dislocation. Now if you try an extra plane you get this lattice line they get distorted and this distortion persist over a length and this length is called the width of the dislocation. Now it is possible to show that this force or stress required to move this dislocation will depend will depend on the width of the dislocation and this has been done by actually Peierls stress.

They estimate it with some approximation that means we use this particular approximation that see while to calculate strength of an ideal crystal. We have seen the tau equal to G over twice pi sin 2 pi x over b. So, if you look at the shear stress there are certain positions of equilibrium at b by 2. So when you displace it here displace it slightly you know it is tilted to come back. But, when it goes close to this half width then you can say it is a stable configuration. So, with this basically if you have to move the dislocation through this periodic lattice, they you will get or experience an additional, you have to overcome an additional force and they have found out that this tau is equal to this depends exponentially on w. So you can just substitute.

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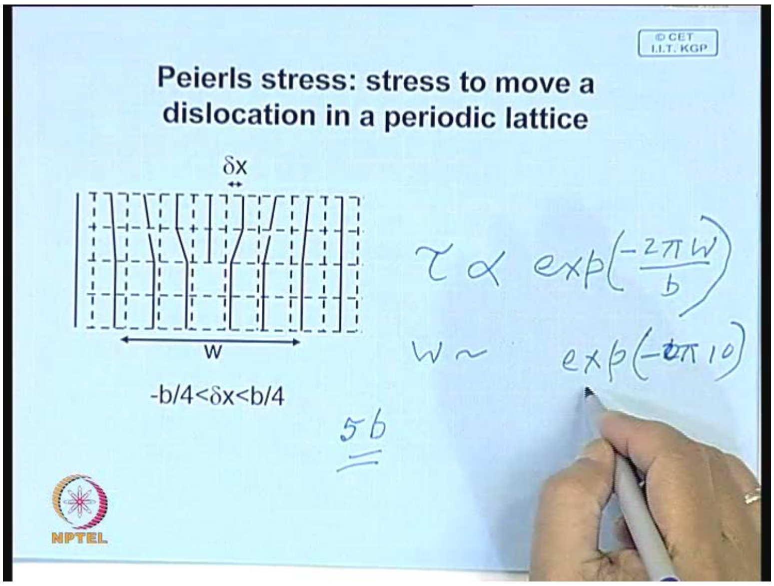

Peierls stress: stress to move a dislocation in a periodic lattice

$\tau \propto \exp\left(-\frac{2\pi W}{b}\right)$

$W \sim \quad \exp(-2\pi\, 10)$

$5b$

So, basically this Peierls stress is proportional to exponential, this is width of dislocation over burger vector. Now this width, if you say that this width in particularly metallic crystals, they extend over several atomic distance may be 10 as say it will be say dislocation core itself some time we take as 5 b. So, it may be little more may be 10 times that if you substitute that you will find extremely low; say suppose even if you substitute let us say 5 b is a dislocation width; in that case, if you say 5 b. So, e to the power minus 10 2 pi or pi times 10. So, 30 e to the power minus 30, so that means this stress is extremely low.

So with this, we finish of our discussions or the lectures on crystal defects, and how these defects affect material properties; and later on, we will see there are few other interactions, which we have been considered like how the dislocations interact with point defects, because this also will be associated with how the defects can moving crystal, and may be later stage, how this dislocation and the vacancy and interstitial or solid atom can interact with dislocation will take up later, when we consider strengthening mechanisms or methods or strength of alloys or actual materials. Thank you.