Creep Deformation of Materials
Dr. Srikant Gollapudi
Department of Mathematics
Indian Institute of Technology, Bhubaneswar
Basics of plastic deformation and characteristics of dislocations

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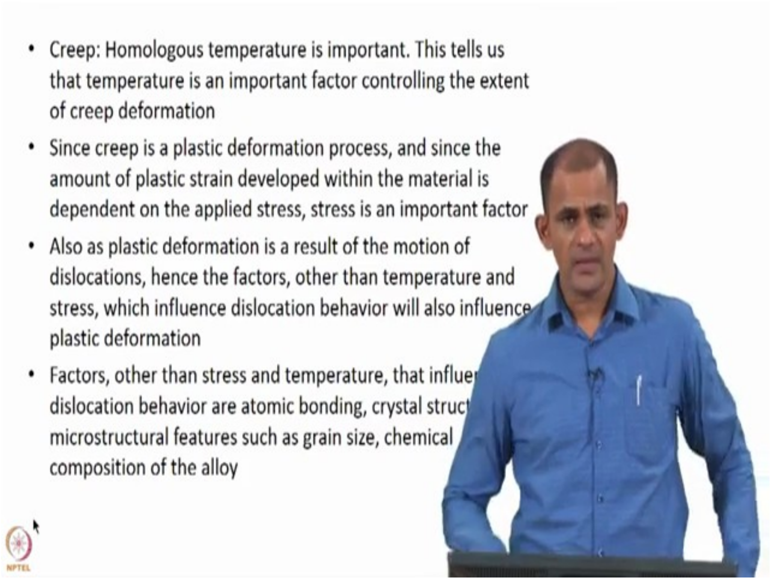

- Creep: Homologous temperature is important. This tells us that temperature is an important factor controlling the extent of creep deformation
- Since creep is a plastic deformation process, and since the amount of plastic strain developed within the material is dependent on the applied stress, stress is an important factor
- Also as plastic deformation is a result of the motion of dislocations, hence the factors, other than temperature and stress, which influence dislocation behavior will also influenc plastic deformation
- Factors, other than stress and temperature, that influe dislocation behavior are atomic bonding, crystal struct microstructural features such as grain size, chemical composition of the alloy

So we were talking about homologous temperature and its importance in determining whether a material would creep at a given temperature or not, for example solder as a material is known to creep at room temperature but steel would not that is because of the large difference in melting point between a solder and a steel material, so what it tells us is when we have to account for creep deformation, the first thing that we should do is evaluate the homologous temperature.

So while choosing a material for a particular application the important thing to remember is or understand is whether that material is would have a high homologous temperature or low homologous temperature during application, if it would have a high homologous temperature then probably material is going to creep significantly and hence creep deformation has to be accounted for during the product design.

Now creep is a plastic deformation process and since the amount of plastic strain develop within the material is dependent on the applied stress, stress is an important factor that needs to be accounted for, similarly plastic deformation is a result of motion of dislocations and hence the factors other than temperature and stress which influence dislocation behavior will also influence plastic deformation.

So at this point of time I am trying to establish the different factors that will influence creep deformation, so we said temperature is an important factor that must be understood while evaluating the performance of a material and to check whether it is going to undergo creep deformation or not, similarly we have to account for the amount of stress applied or the magnitude of stress applied that is because creep deformation is a plastic deformation process and we know very well that stress or the amount of stress will determine the amount of plastic strain that the material will develop.

And other than stress and temperature we will also have to account for some other factors which influence plastic deformation by way of their effect on dislocation behavior, now it is well known that plastic deformation happens via dislocation motion and hence the various factors that will influence dislocation motion will also influence plastic deformation for example atomic bonding, crystal structure and different microstructural features such as grain size, chemical composition of the alloy, etc. are known to influence dislocation behavior and hence will play a role in plastic deformation.

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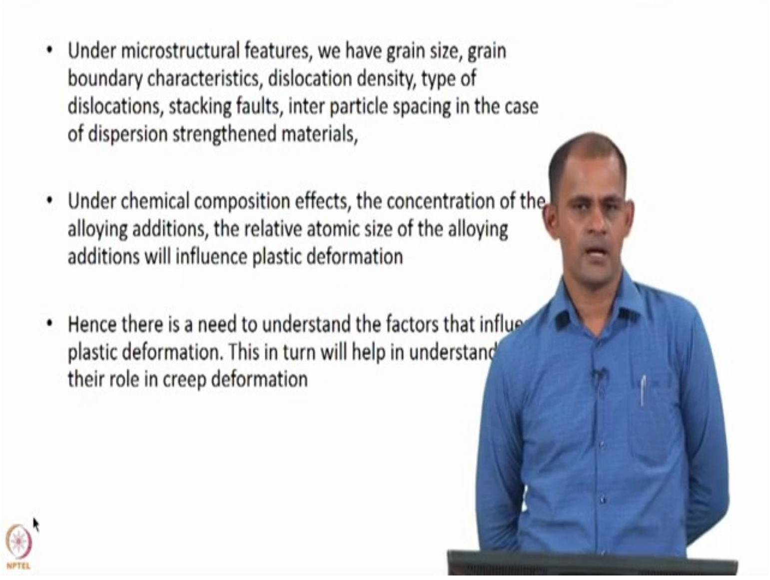

- Under microstructural features, we have grain size, grain boundary characteristics, dislocation density, type of dislocations, stacking faults, inter particle spacing in the case of dispersion strengthened materials,
- Under chemical composition effects, the concentration of the alloying additions, the relative atomic size of the alloying additions will influence plastic deformation
- Hence there is a need to understand the factors that influe plastic deformation. This in turn will help in understand their role in creep deformation

Now under microstructural features we can have grain size, grain boundary characteristics, the dislocation density, the type of dislocations, stacking faults, etc. etc. which will influence plastic deformation and under chemical composition effects the alloying additions, so the various elements that are added to the material and their concentration will determine the role of chemical composition on this plastic deformation.

Similarly the atomic size, relative atomic size of the alloying elements will also influence plastic deformation, so when we are trying to understand creep we have to understand that creep is a plastic deformation process and naturally all the different factors that influence plastic deformation will influence creep as well.

So before we go into creep as a topic I am going to take you through a few slides on plastic deformation and in the process explain some of these different factors and the role they play during plastic deformation, so now we are going to talk about some basics of plastic deformation.

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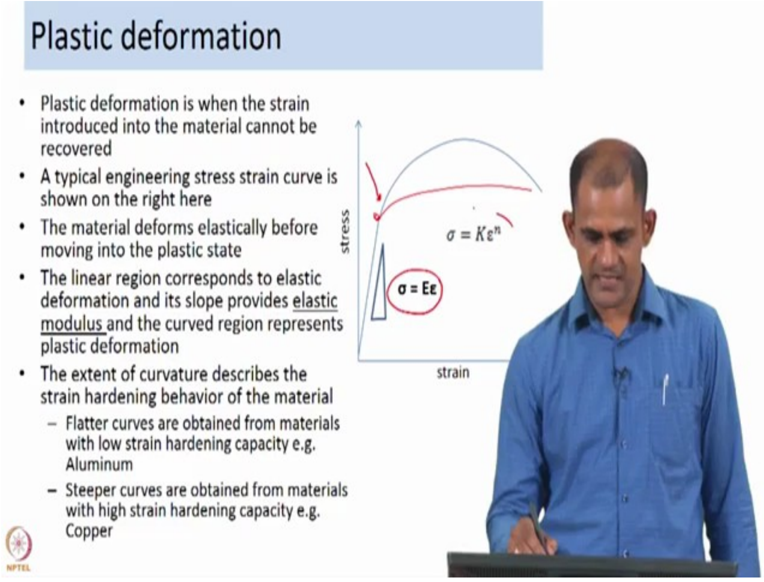
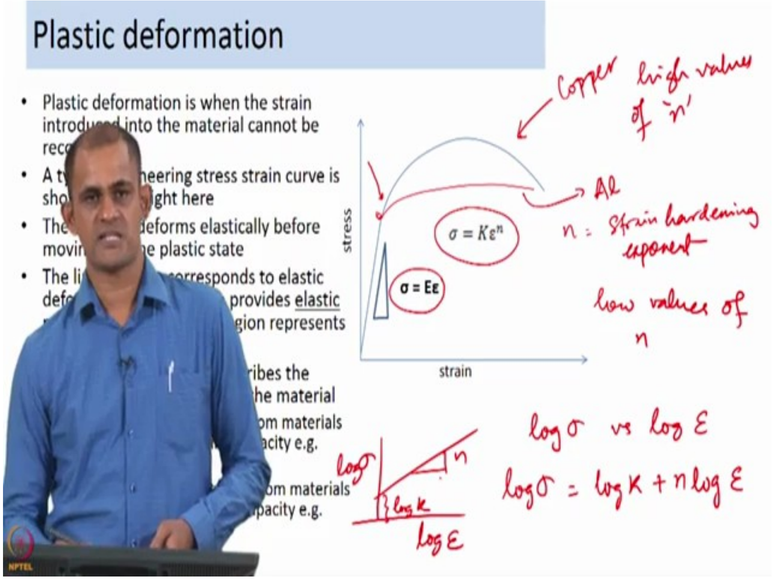


Plastic deformation

- Plastic deformation is when the strain introduced into the material cannot be recovered
- A typical engineering stress strain curve is shown on the right here
- The material deforms elastically before moving into the plastic state
- The linear region corresponds to elastic deformation and its slope provides elastic modulus and the curved region represents plastic deformation
- The extent of curvature describes the strain hardening behavior of the material
  - Flatter curves are obtained from materials with low strain hardening capacity e.g. Aluminum
  - Steeper curves are obtained from materials with high strain hardening capacity e.g. Copper



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$\log \sigma$ vs $\log \varepsilon$

$\log \sigma = \log K + n \log \varepsilon$

So a material is set to undergo plastic deformation when the strain introduced in the material cannot be recovered on the removal of stress so whenever we apply stress a material is known to deform, the deformation could be elastic in nature or it could be plastic in nature, so if you look at a typical stress strain curve as shown in the figure here, there are two stages that a material experiences.

The first stage is the elastic stage, so it is in this stage the material experiences elastic deformation so here the linear region of the stress strain curve signifies elastic deformation and the stress to strain relation is given by the following equation, where E is the elastic modulus, in the elastic region we all know that strain is recoverable that is if you remove the stress the material is going to go back to its original shape or state.

Whereas when the applied stress is higher than a certain limit then the material starts moving into the plastic region so once the stress exceeds this point then the material moves into the plastic region so the curved region here represents plastic deformation behavior of the material, this curved region is generally described by this equation sigma is equal to K epsilon to the power n where n is the strain hardening exponent.

And there is a some amount of information that can be gathered from the curvature so from the curvature of the plastic deformation region one would know if the material is a low strain hardening material or a high strain hardening material, so flatter curves are typically obtained from materials with low strain hardening capacity such as aluminum, so aluminum as a material is known to provide low values of n and in such a case you will see curves, very flat curves, so that is for aluminum.

Whereas steeper curves are obtained from material with high strain hardening capacity such as in copper so steep curve like that is generally observed in a material is generally observed in copper and copper provides you high values of strain hardening exponent, of course n can be determined by making a plot of log sigma verses log epsilon that is because when you take logs of both sides you get log k plus n log epsilon.

So if you make a plot of log sigma verses log epsilon the intercept will be log K and the slope will give you n. So we are saying that the material moves into the plastic region when they are applied stress is higher than a certain value, so that value is known as the yield strength of the material.

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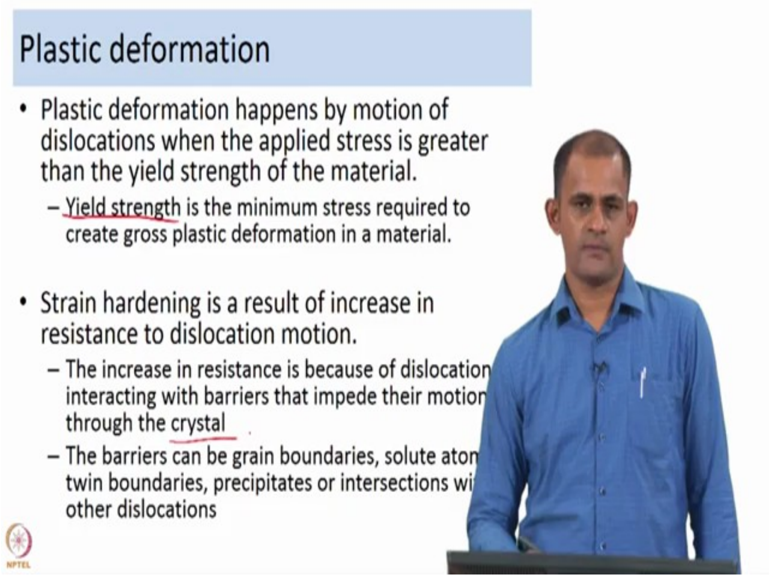

Plastic deformation

- Plastic deformation happens by motion of dislocations when the applied stress is greater than the yield strength of the material.
  - Yield strength is the minimum stress required to create gross plastic deformation in a material.
- Strain hardening is a result of increase in resistance to dislocation motion.
  - The increase in resistance is because of dislocation interacting with barriers that impede their motion through the crystal
  - The barriers can be grain boundaries, solute aton twin boundaries, precipitates or intersections wi other dislocations

So yield strength is the minimum stress required to create gross plastic deformation in a material and when the applied stress exceeds the yield strength, what happens is there is a large number of dislocation motion that happens within the material and we said in the plastic region there is some amount of strain hardening and the strain hardening is what determines the curvature of the plastic deformation region.

So now strain hardening is basically a result of increase in resistance to dislocation motion, so as the plastic strain in the material increases, the amount of stress that you need to apply also increases accordingly, so the flow stress increases with plastic strain and that increases because of strain hardening and strain hardening is because the dislocation start experiencing barriers to their motion.

So these barriers impede the motion of the dislocations through the crystal, so there are different type of barriers that impede dislocation motion, the barriers can be grain boundaries or they could be solute atoms, twin boundaries or precipitates or even other dislocations which intersect with each other.

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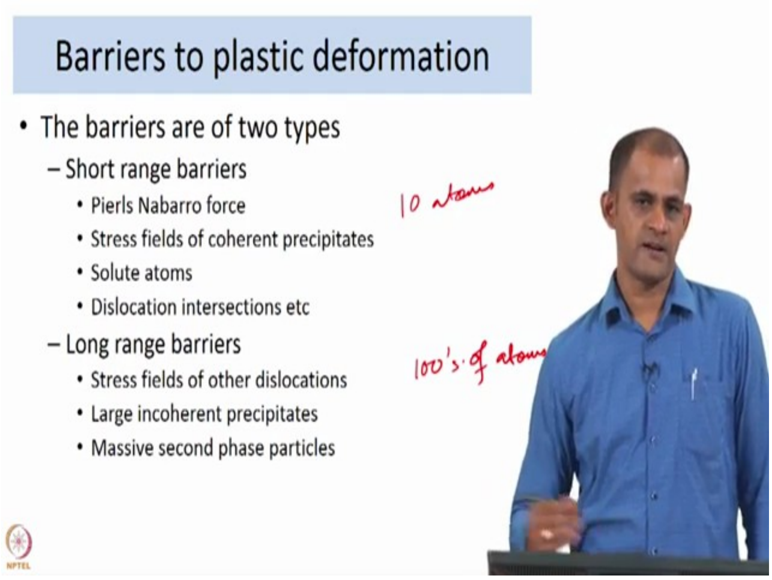

Barriers to plastic deformation

- The barriers are of two types
  - Short range barriers
    - Pierls Nabarro force
    - Stress fields of coherent precipitates
    - Solute atoms
    - Dislocation intersections etc
  - Long range barriers
    - Stress fields of other dislocations
    - Large incoherent precipitates
    - Massive second phase particles

10 atoms

100's of atoms

So the different barriers that we describe can be broadly categorized into two, the first category of barriers is short range barriers and the second category of barriers is long range barriers, examples of short range barriers are Pierls Nabarro force and stress fields of coherent precipitates, solute atoms, dislocation intersections, etc. whereas the long range barriers examples are stress fields of other dislocations, large incoherent precipitates and massive second phase particles.

So short range barriers typically involve atomic distances of around 10 atoms or so whereas long range barriers can run into hundreds of atoms, so basically the field over which the barrier or the distances over which the barrier is experienced by the dislocation can range from 10 atoms in short range case to hundreds of atoms in long range case.

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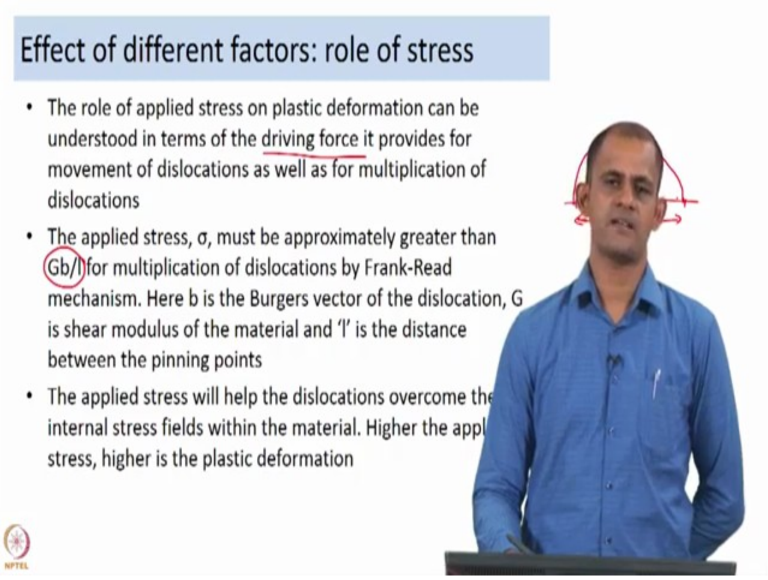
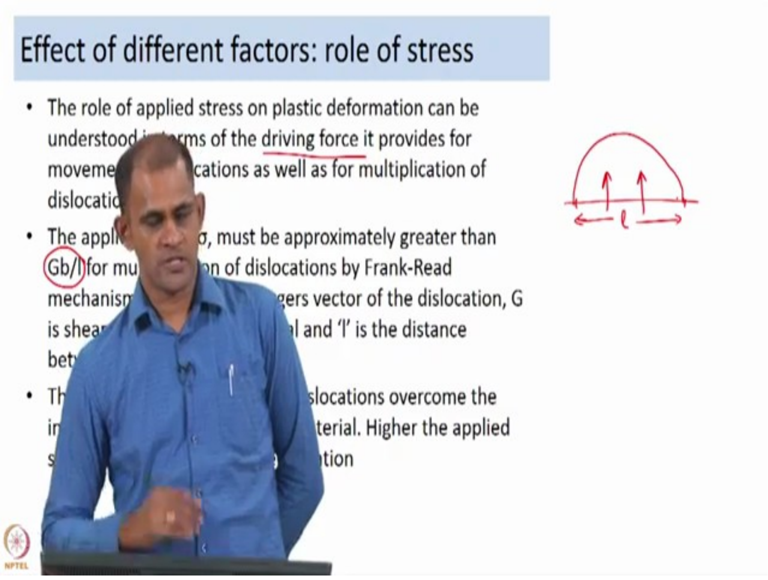


Effect of different factors: role of stress

- The role of applied stress on plastic deformation can be understood in terms of the driving force it provides for movement of dislocations as well as for multiplication of dislocations
- The applied stress, σ, must be approximately greater than Gb/l for multiplication of dislocations by Frank-Read mechanism. Here b is the Burgers vector of the dislocation, G is shear modulus of the material and 'l' is the distance between the pinning points
- The applied stress will help the dislocations overcome th internal stress fields within the material. Higher the appl stress, higher is the plastic deformation



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Now for plastic deformation to happen, the dislocations will have to overcome the barriers, so in this section I am going to talk about how stress and temperature can help dislocations to overcome their barriers to their motion. Let us first talk about the role of stress, so we said stress helps the dislocations to move so stress basically provides the driving force for movement of dislocations as well as for multiplication of dislocations.

So plastic deformation not only requires motion of dislocations but also as you produce more and more plastic deformation to support that you will need also multiplication of dislocations, multiplication of dislocations is known to happen by the Frank-Read mechanism and for the Frank-Read mechanism to operate the applied stress has to be approximately greater than Gb by l, here b is the Burgers vector of the dislocation, G is the shear modulus of the material and l is the distance between the pinning points.

So I am not going into the details of the Frank-Read mechanism at this point of time but generally if you have a dislocation which is pinned at 2 points and the distance between the 2 pinning points is ‘l’ then the stress that you apply has to be such that the dislocation can bow around these 2 pinning points and that a critical value of stress it emits a dislocation loop or escapes these pinning points.

Now Burgers vector is basically a descriptor of a dislocation and dislocation is what causes plastic deformation which is also known as slip, so the Burgers vector is basically along the closed packed direction in the crystal along which atoms find it easy to move and the plane along which the atoms move is usually planes of high atomic density and these are also typically planes which are widely separated for the spacing between the planes is high, inter planer spacing is high.

So applied stress helps in dislocation multiplication by Frank-Read mechanism, the applied stress also helps the dislocations overcome the internal stress fields within the material so we were talking about long range barriers and we said stress field of a dislocation is one type of long range barrier, now just like electrical charges, now we all know electrical charges have a electric field around them and the nature and magnitude of electric field will decide whether a particular charge is going to repel or attract another charge and at what distance away from this charge, will there be interaction, interactive forces between the two charges.

So similarly around a dislocation you have a stress field and because of this stress field other dislocations might find it difficult to move around, there could be repulsive forces or there could be attractive forces depending on the nature of the dislocation and what stress does is it helps the dislocations overcome the internal stress fields within the material, so higher the applied stress, higher is the plastic deformation.

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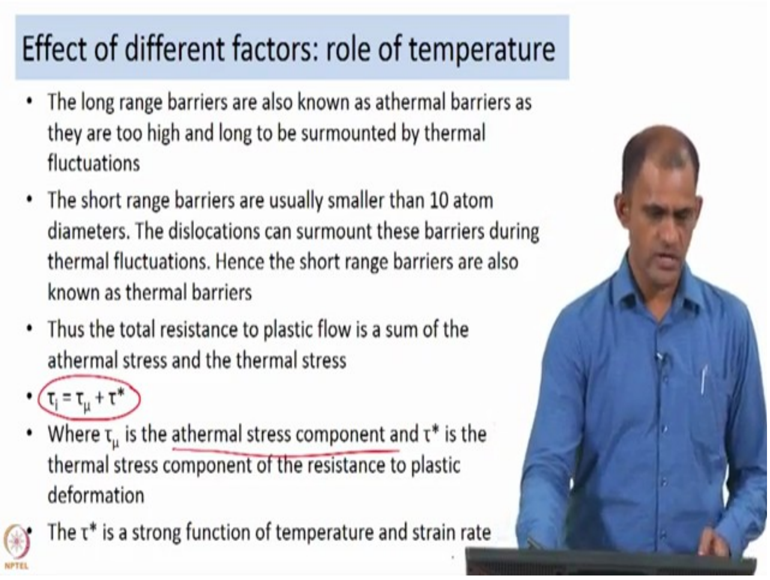

Effect of different factors: role of temperature

- The long range barriers are also known as athermal barriers as they are too high and long to be surmounted by thermal fluctuations
- The short range barriers are usually smaller than 10 atom diameters. The dislocations can surmount these barriers during thermal fluctuations. Hence the short range barriers are also known as thermal barriers
- Thus the total resistance to plastic flow is a sum of the athermal stress and the thermal stress
- $\tau_i = \tau_\mu + \tau^*$
- Where τ_μ is the athermal stress component and τ^* is the thermal stress component of the resistance to plastic deformation
- The τ^* is a strong function of temperature and strain rate

Now let us look at the role of temperature, so we understood the role of stress, the stress helps in plastic deformation, it helps in overcoming the internal stress fields present within the material, it also helps in the multiplication of dislocations and thus contributes towards plastic deformation, now what is the role of temperature? We talked about long range barriers and short range barriers now one key difference between the two other than the fact that the atomic distances over which they operate are different is that long range barriers are known as a thermal barriers.

These are known as the thermal barriers because they are too high and long to be surmounted by thermal fluctuations, whereas the short range barriers because they are smaller in size like I said 10 atom diameters or so, so the dislocations can surmount these barriers during thermal fluctuations, so if there is temperature and the energy provided by temperature is sufficient for dislocations to surmount the short range barriers, hence short range barriers are also known as thermal barriers.

Since you have two barriers to dislocation motion so we can also say that the resistance to plastic flow comes from resistance provided by the athermal barrier and the resistance provided by the thermal barrier, so we can also describe it as a sum of the athermal stress and the thermal stress, so the total internal stress that resists plastic deformation can be described as a sum of the athermal component and the sum of the thermal component.

So tau mu is the athermal stress component and tau star is the thermal stress component of resistance to plastic deformation, now between the two, tau mu is independent of temperature but tau star is a strong function of temperature as well as strain rate.

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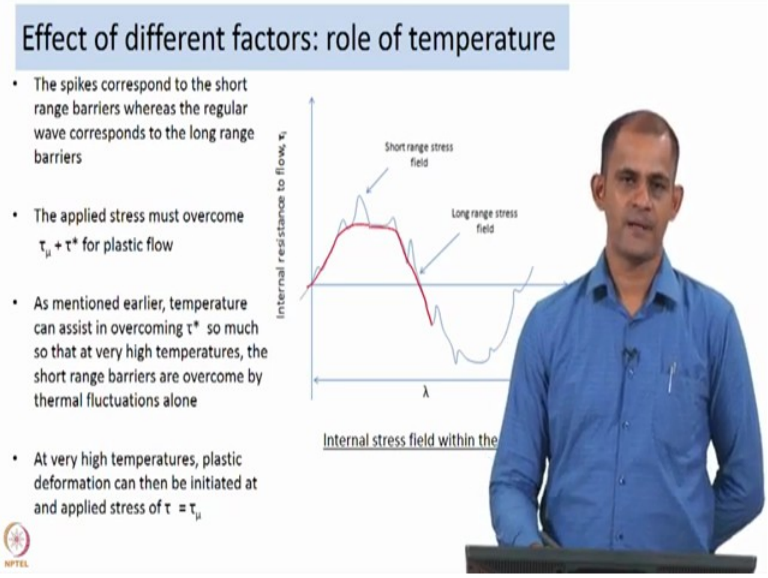
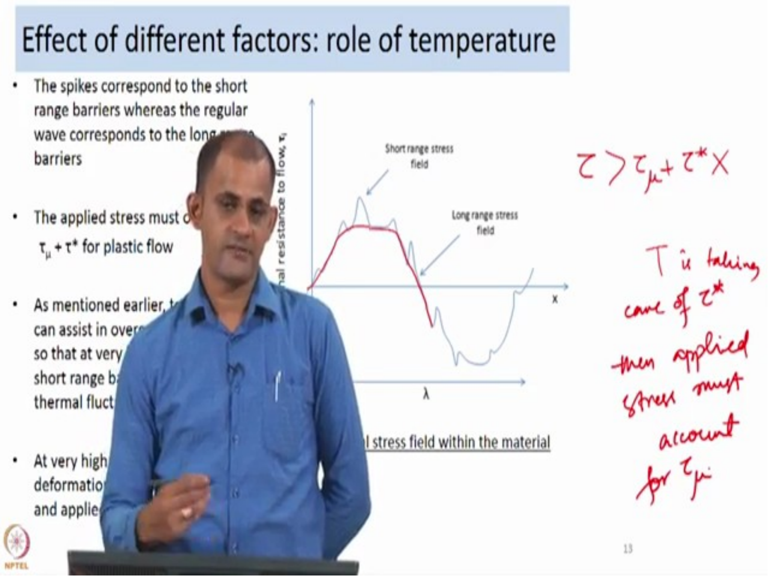


Effect of different factors: role of temperature

- The spikes correspond to the short range barriers whereas the regular wave corresponds to the long range barriers
- The applied stress must overcome $\tau_\mu + \tau^*$ for plastic flow
- As mentioned earlier, temperature can assist in overcoming τ^* so much so that at very high temperatures, the short range barriers are overcome by thermal fluctuations alone
- At very high temperatures, plastic deformation can then be initiated at and applied stress of $\tau = \tau_\mu$



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$\tau > \tau_\mu + \tau^* \times$

T is taking care of τ^* then applied stress must account for τ_μ

Now let us take a look at how the stress, internal stress fields exists within a given material, so here is a graph of how the internal stress field could vary inside a crystal. So the magnitude of the stress field is dependent on the direction within the lattice at which we are looking, so in this particular graph, the sine wave is basically the long range stress field, it signifies the variation of the long range stress field whereas the peaks are the short range stress field.

So the peaks have been superimposed on the long range stress field. So that together the long range as well as the short range together describes the internal resistance to plastic flow within the material and lambda is the wavelength of this field, now like I said plastic flow will happen when the applied stress is greater than, if we apply a stress tau then tau has to be greater than tau mu plus tau star for plastic deformation to happen.

So temperature can assists in overcoming tau star is something that I mentioned earlier, so since temperature can assists in improve overcoming tau star if the temperature applied or experienced by the material is very high, a case can arise where the tau star is entirely overcome by temperature itself, so the applied stress need not account for tau star so if temperature is taking care, if T is taking care of tau star then applied stress must account for tau mu only.

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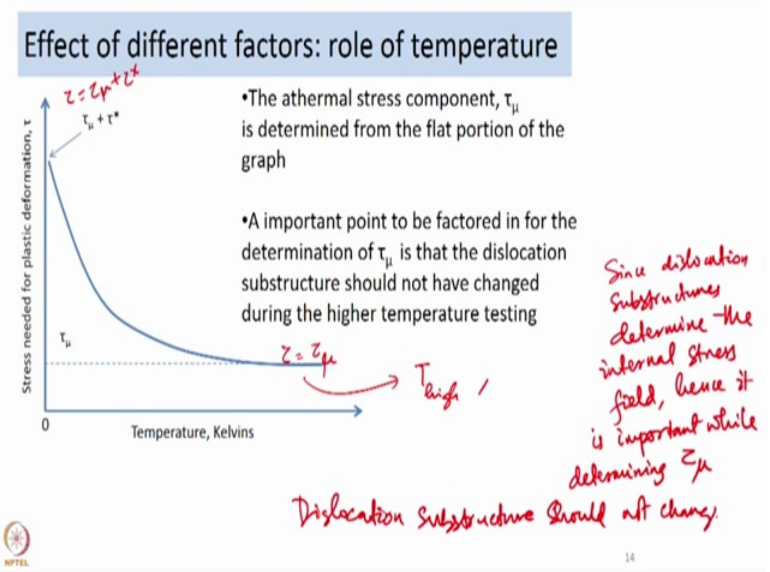

Effect of different factors: role of temperature

- The athermal stress component, τ_μ is determined from the flat portion of the graph
- A important point to be factored in for the determination of τ_μ is that the dislocation substructure should not have changed during the higher temperature testing

Since dislocation substructures determine the internal stress field, hence it is important while determining τ_μ

Dislocation substructure should not change.

Thus at very high temperatures plastic deformation can be initiated at the applied stress of tau equal to tau mu whereas if we look at the other side of the spectrum so we spoke about very high temperatures, now let us look at very low temperatures, let us say 0 Kelvin temperature, 0 Kelvin degree, now at that condition you do not have temperature to assists in the overcoming of your short range barrier.

So the stress on its own has to initiate plastic deformation as well as sustain plastic deformation so at very low temperatures the minimum stress required will be tau mu plus tau star so here we are showing how the internal stress or the stress required for plastic deformation, the minimum stress required for plastic deformation varies as a function of temperature so the minimum stress can be tau is equal to tau mu at very high temperatures and it is equal to tau mu plus tau star at very low temperature.

One of the important things to be factored in for the determination of tau mu so a curve like this will help you in determining the athermal stress component, however while determining the athermal stress component an important point to be factored in is that the dislocation sub structure should not have changed during the higher temperature testing.

So when you are testing your material at very high temperatures, T high you are saying T high is taking care of tau star, so tau is equal to tau mu but sometimes when you apply very high temperatures, the dislocation sub structures tend to change. Since dislocations sub structures determine the internal stress field hence it is important while determining tau mu that dislocations sub structure should not change.

Of course the dislocation arrangements, configurations or sub structures could change because of a process called recovery so temperature helps in recovery of the sub structures so recovery as a concept will be covered when we move into creep but the important point here or the bottom line here is while determining tau mu please make sure that the material has not undergone any recovery process.

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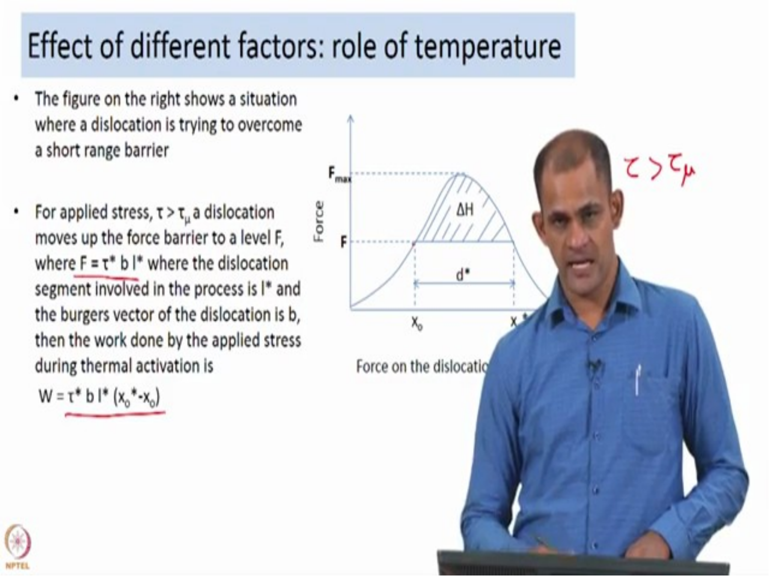
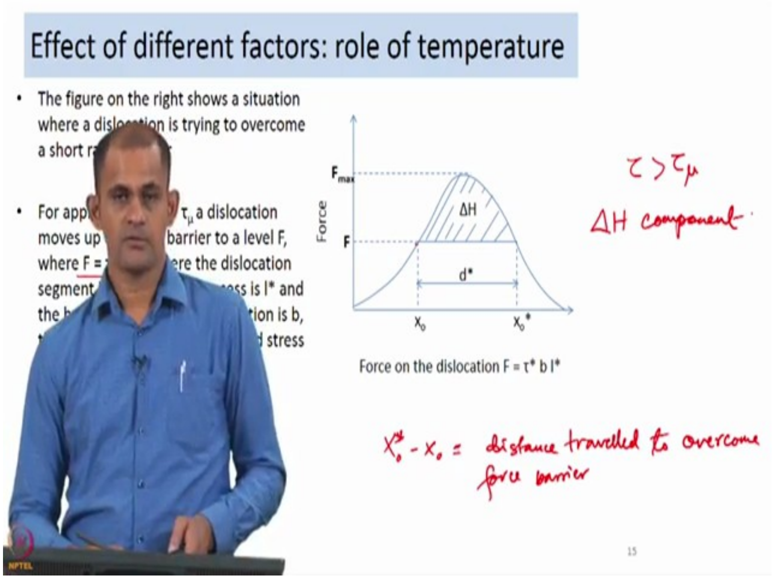


Effect of different factors: role of temperature

- The figure on the right shows a situation where a dislocation is trying to overcome a short range barrier
- For applied stress, $\tau > \tau_\mu$ a dislocation moves up the force barrier to a level F, where $F = \tau^* b l^*$ where the dislocation segment involved in the process is l^* and the burgers vector of the dislocation is b, then the work done by the applied stress during thermal activation is $W = \tau^* b l^* (x_0^* - x_0)$

$\tau > \tau_\mu$



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$\tau > \tau_\mu$

ΔH component

Force on the dislocation $F = \tau^* b l^*$

$x_0^* - x_0$ = distance travelled to overcome force barrier

Now continuing in the same vein of thought basically on the role of temperature we said temperature helps dislocations overcome short range barriers, here I am trying to illustrate how stress and temperature together help in the overcoming of a short range barrier, so the dislocation is trying to overcome the short range barrier which has a force verses distance described by this plot and for applied stress tau greater than tau mu because we are only talking about short range barriers, so the inherent assumption is that the applied stress is greater than tau mu which means the dislocation is able to overcome the long range barriers to its motion.

So tau greater than tau mu, the dislocation moves up the force barrier to a level f, so say the dislocation is at that point in the plot of force verses distance so F can be described as tau star into b into l star where tau star is the stress or the thermal stress component and the dislocation segment involved in the process is l star and the Burgers vector of the dislocation is b, so the work done by the applied stress during thermal activation will then be tau star into b into l star into x_0^* minus x_0, $x_0^* - x_0$ is the distance the dislocation has travelled to overcome the force barrier.

So the work done for overcoming the force barrier is given by that so here we have a delta H component so delta H corresponds to the energy involved or the energy provided by temperature for overcoming the short range barrier.

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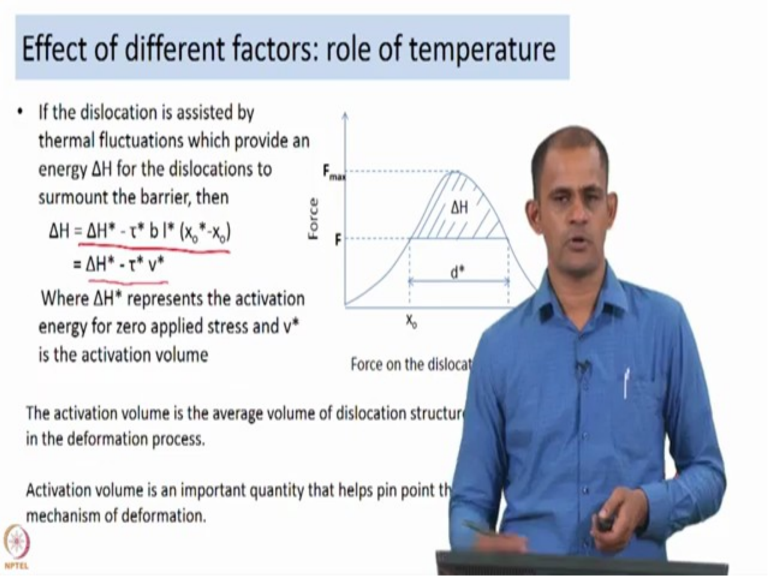


Effect of different factors: role of temperature

- If the dislocation is assisted by thermal fluctuations which provide an energy ΔH for the dislocations to surmount the barrier, then

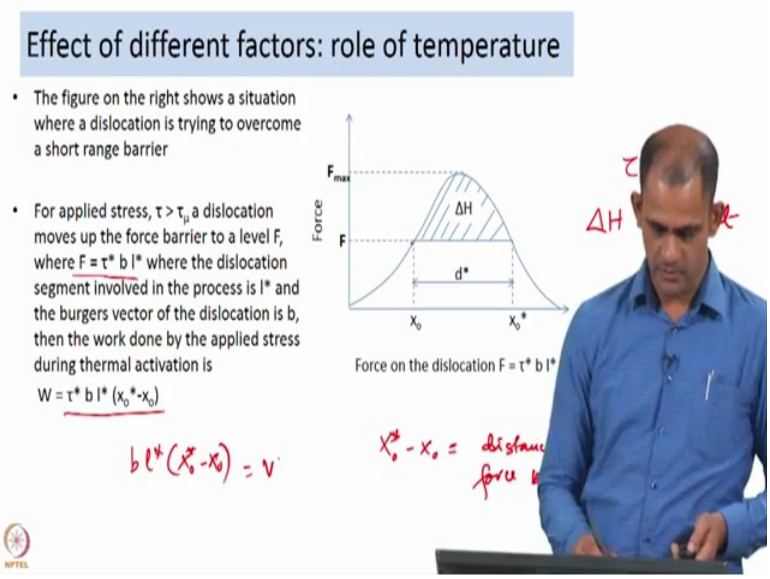
  $\Delta H = \Delta H^* - \tau^* b l^* (x_0^* - x_0)$

  $= \Delta H^* - \tau^* v^*$

  Where ΔH^* represents the activation energy for zero applied stress and v^* is the activation volume

The activation volume is the average volume of dislocation structur in the deformation process.

Activation volume is an important quantity that helps pin point th mechanism of deformation.



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  $W = \tau^* b l^* (x_0^* - x_0)$

$b l^* (x_0^* - x_0) = v$

$x_0^* - x_0 =$ distanc forc

The thermal fluctuations assists the dislocation by providing an energy delta H to surmount the barrier so delta H can then be described as delta H is equal to delta H star minus tau star into b into l star into x_0^*minus x_0 so which can also be written as delta H star minus tau star into v star, so delta H star is basically the area under the force distance curve, so if you do not have any stress applied, if you do not have any stress greater than tau mu applied then the amount of work required to surmount the barrier will be delta H star and that represents the activation energy for zero applied stress.

And v star is the activation volume, the activation volume is the average volume of dislocation structure involved in the deformation process so we are talking about the dislocation, we are talking about the Burgers vector and then we are saying that this dislocation is going to move over a distance x_0^* minus x_0 and the work done there is given by tau star into b into l star into etc. etc. as described in the previous equation. So all these term b l star into x_0^* minus x_0, this is all activation volume, so that is all activation volume v star.

So activation volume as a concept or as a parameter is an important parameter because it helps in pinpointing the mechanism of deformation, if dislocations are getting assisted by stress and temperature both then perhaps if their motion is going to happen over several hundreds b^3 then the mechanism of deformation is based on dislocation motion whereas if activation volume is on the order of b^3 then it is diffusion processes.

So diffusion based processes are dominant in overcoming these short range barrier if the activation volume is in the range of b^3 whereas if it is in the order of hundred or thousand b^3 then dislocation based mechanisms are dominant, so this is something again that we will talk in a little more detail, how do you determine the activation volume things like that we will talk in a little more detail in the subsequent lectures.

That was about the role of temperature and stress in overcoming barriers to dislocation motion, we also talked about the different barriers, now we are going to go into the details of dislocation, so I am going to introduce you to some characteristics of dislocations because we are also going to talk about barriers to dislocation motion so in order to understand this barriers better, it is important to know a few characteristics of the dislocations.

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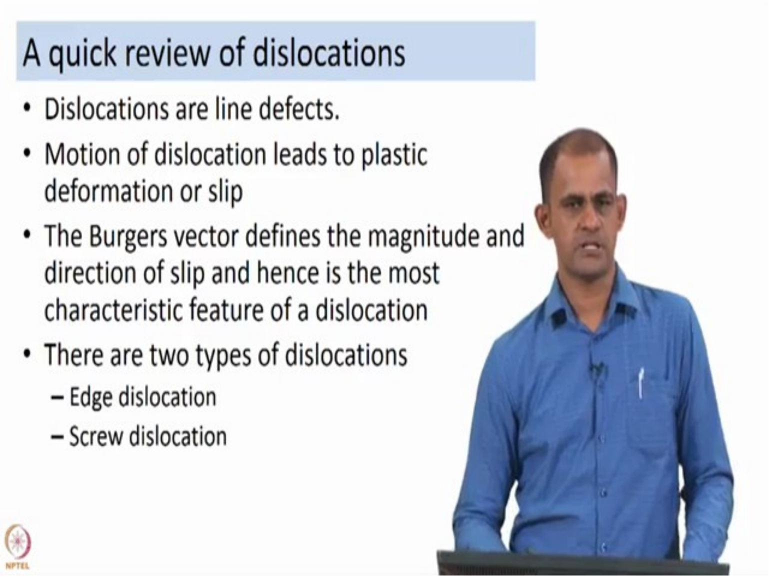

A quick review of dislocations

- Dislocations are line defects.
- Motion of dislocation leads to plastic deformation or slip
- The Burgers vector defines the magnitude and direction of slip and hence is the most characteristic feature of a dislocation
- There are two types of dislocations
  - Edge dislocation
  - Screw dislocation

So dislocations are defects within a material and these defects are actually important because if you do not have any defects then the amount of stress required for deforming a material will be significantly high, in fact it will be on the order of a few Giga pascals so because dislocations are present, because defects are present in material that is why we are able to plastically deform materials at very low stresses that is stresses of the order of a few hundred Mega pascals instead of a few Giga pascals.

So that is the advantage of having dislocations within a material. So the motion of dislocations leads to plastic deformation or slip, the Burgers vector defines the magnitude and direction of slip and hence is the most characteristic feature of dislocation and there are generally two types of dislocations, edge dislocations and screw dislocations.

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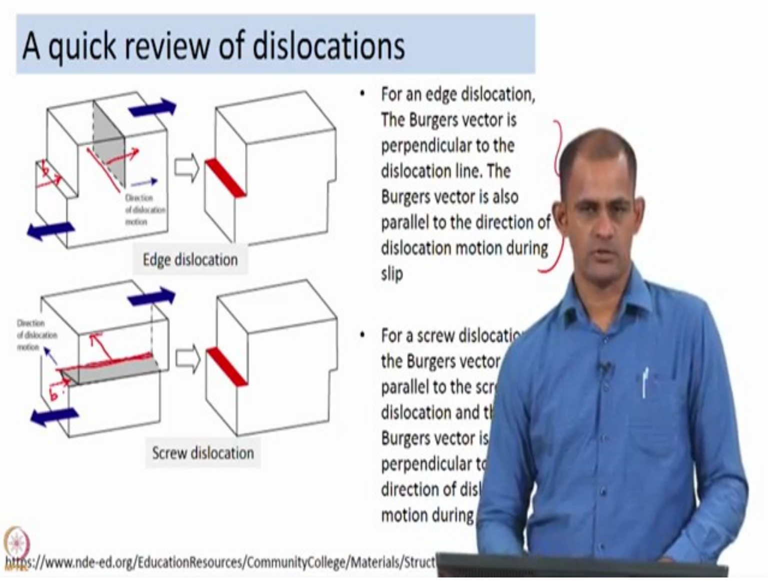

A quick review of dislocations

- For an edge dislocation, The Burgers vector is perpendicular to the dislocation line. The Burgers vector is also parallel to the direction of dislocation motion during slip
- For a screw dislocatio the Burgers vector parallel to the scr dislocation and t Burgers vector is perpendicular t direction of dis motion during

https://www.nde-ed.org/EducationResources/CommunityCollege/Materials/Struct

So what are edge dislocations and what are screw dislocations is what I am covering in this slide, so an edge dislocation is characterized by its Burgers vector being perpendicular to the dislocation line, so the dislocation line is basically an interface between the slipped and unslipped region of a crystal, so that is the line over there which is a dislocation line separating the slipped and unslipped region and the Burgers vector given by that direction b is clearly perpendicular to the dislocation line.

So the Burgers vector is perpendicular to the dislocation line for an edge dislocation, so when slip happens the dislocation moves in this direction so that is the direction of slip and that is the direction in which the dislocation is moving, so in an edge dislocation the Burgers vector is parallel to the direction of dislocation motion during slip, so these are the two key characteristics of edge dislocation, A, Burgers vector is perpendicular to the dislocation line and B, the Burgers vector is parallel to the direction of dislocation motion during slip.

Let us look at the second type of dislocation that is screw dislocation, so in a screw dislocation you have a twist kind of action working on the crystal, so what happens here is this is going to be the Burgers vector b and that is again the dislocation line separating the slipped and unslipped region of the crystal, so here the Burgers vector is parallel to the screw dislocation so b is parallel to the screw dislocation and during this process of slip the dislocation is going to move in that direction and what we are seeing here is here the Burgers vector is perpendicular to the direction of dislocation motion during slip.

So clearly the difference between a screw dislocation and an edge dislocation is that the Burgers vector for a screw dislocation is parallel to the dislocation and the Burgers vector for the screw dislocation is perpendicular to the direction of its motion during slip.

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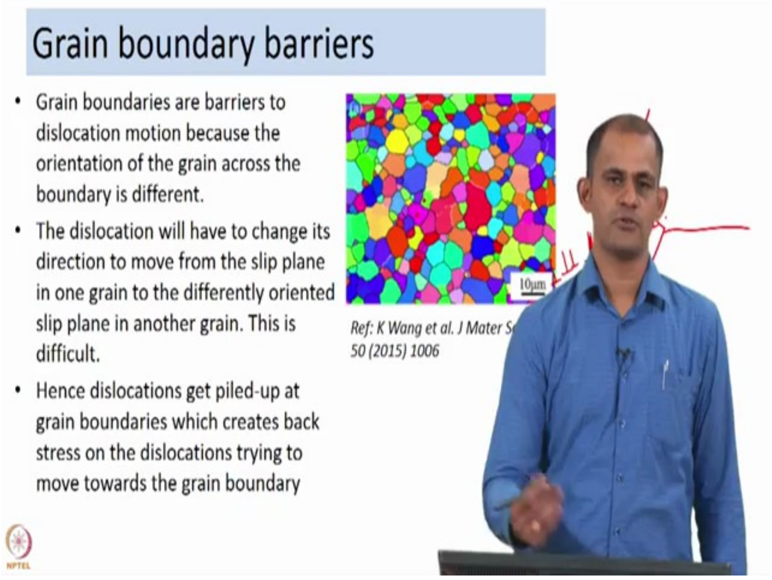

Grain boundary barriers

- Grain boundaries are barriers to dislocation motion because the orientation of the grain across the boundary is different.
- The dislocation will have to change its direction to move from the slip plane in one grain to the differently oriented slip plane in another grain. This is difficult.
- Hence dislocations get piled-up at grain boundaries which creates back stress on the dislocations trying to move towards the grain boundary

Ref: K Wang et al. J Mater S
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So that is the whole objective of introducing you to the barriers of plastic deformation, so one of the well-known barriers to plastic deformation is grain boundaries, so grain boundaries are barriers to dislocation motion because as you move from one grain to another typically the orientation of the grain changes, so here is a EBSD map, electron backscatter diffraction map where you are seeing many different colored grains as you move from one grain to another you are seeing there is a change in color.

So this change in color is because of the change in orientation and the grain boundary is basically a result of the difference in orientation, if both the grains have similar orientation there would not be any grain boundary, so when a dislocation is moving, so edge dislocation is generally represented by that, so when edge dislocation is moving inside a grain and it encounters a grain boundary what happens is it is stopped in its motion.

The reason it is stopped in its motion when it encounters a grain boundary is because it is travelling on a certain slip plane and once you move from a grain of one orientation to another orientation the slip plane direction or the orientation of the slip plane is also going to change, so what the dislocation now has to do is that it has to change its direction of motion in order to be able to go into the next grain.

Since that is very difficult that is why the grain boundary which is separating the two grains of different orientation prevents the dislocation from moving, so what happens is as plastic deformation happens you are multiplying the dislocations and now all these dislocations they get piled up at the grain boundary and this creates a back stress on the dislocation trying to move towards a grain boundary and thus control the amount of plastic strain that you are generating.

In fact this concept is what Hall Page equation is based upon, the fact that grain boundaries are barriers to plastic deformation that is why when you refine the grain size, when you reduce the grain size, you are creating a harder and harder material.

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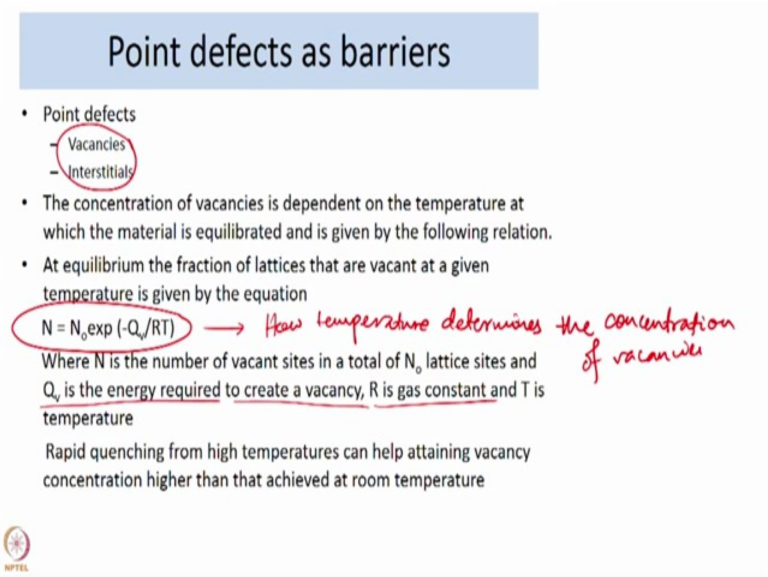

Point defects as barriers

- Point defects
  - Vacancies
  - Interstitials
- The concentration of vacancies is dependent on the temperature at which the material is equilibrated and is given by the following relation.
- At equilibrium the fraction of lattices that are vacant at a given temperature is given by the equation

$N = N_0 \exp(-Q_v/RT)$ → How temperature determines the concentration of vacancies

Where N is the number of vacant sites in a total of N_0 lattice sites and Q_v is the energy required to create a vacancy, R is gas constant and T is temperature

Rapid quenching from high temperatures can help attaining vacancy concentration higher than that achieved at room temperature

The second type of barrier that I would like to talk about is point defects, so dislocation is a line defect whereas vacancies and interstitials are examples of point defects, let us talk about vacancies, vacancies basically the absence of an atom, so in a crystal or in a lattice you have periodic ordering of atoms wherever an atom is missing is where vacancy is present, now the concentration of vacancies, basically how many vacancies do you have in a certain crystal.

So the concentration of vacancies is dependent on the temperature at which the material is tested or the temperature that the material is experiencing, so the concentration of vacancies is basically at equilibrium with the temperature at which the material is and this equation here describes the number of vacancies that you will have at a given temperature, so N is the number of vacant sites in a total of N_0 lattice sites and T is the temperature. Qv is the energy required to create a vacancy and R is the gas constant.

So the concentration of vacancies is clearly dependent on the temperature at which you are holding the material, higher the temperature, higher will be the concentration of vacancies or the number of vacancies generated within the material, so this equation tells you how temperature determines the concentration of vacancies, however if you have high temperature you are going to have high concentration vacancies, at low temperature you will have low concentration of vacancies.

However there is a way by which you can increase the number of vacancies present within the material even at low temperature, that is if you equilibrate, if you go to very high temperature, hold your material at that temperature, introduce or generate a large number of vacancies within the material and suddenly quench it, so you take that material and drop it say in a bucket of water, so you have quenched it now the vacancies do not get sufficient time to escape from the material at low temperature and so are going to get trapped within the material thus increasing the number of vacancies within the material even at room temperature.

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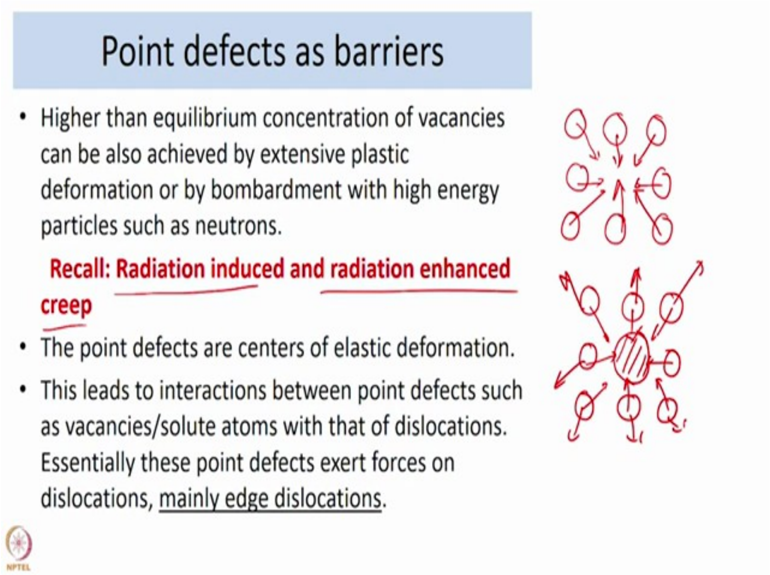

Point defects as barriers

- Higher than equilibrium concentration of vacancies can be also achieved by extensive plastic deformation or by bombardment with high energy particles such as neutrons.

Recall: Radiation induced and radiation enhanced creep

- The point defects are centers of elastic deformation.
- This leads to interactions between point defects such as vacancies/solute atoms with that of dislocations. Essentially these point defects exert forces on dislocations, mainly edge dislocations.

Other approach of achieving high concentration of vacancies is also by extensive plastic deformation so people have observed that when you introduce a large number of dislocations within the material there is a lot of interaction between the dislocations and in the process that also leads to creation of high number of vacancies within the material. Another approach of introducing large number of vacancies is also by bombardment with high energy particles such as neutrons.

So in the first portion of this lecture we were talking about the nuclear industry and if you recall I mentioned radiation induced as well as radiation enhanced creep, creep is enhanced in the presence of radiation because the high energy neutrons knock off atoms from their regular sites and in the process create a large number of vacancies as well as interstitials. Now as you would learn in the subsequent classes vacancies play an important role not only in terms of interaction with the dislocation but also in the sense they also help in enhancing diffusions within the material.

So vacancies enhance diffusion and thus vacancies play a key role in enhancing creep so that is why you have radiation induced as well as radiation enhanced creep, now why are vacancies important, so I gave you, I introduced you to vacancies, the role temperature plays in introducing vacancies, generating vacancies within the material, the role plastic deformation plays or the role neutron bombardment plays.

So the whole objective of talking about this is point defects such as vacancies are going to interact with dislocations and why are they going to interact with dislocations, well the reason is point defects are known as centers of elastic deformation, point defects such as solutes create a field of elastic, elastic field around it and these point defects apply or exert forces on dislocations and that too mainly edge dislocations.

So interaction between dislocations as well as point defects such as vacancies or solute atoms happen because of these strain field generated around a vacancy or a solute item, just a simple illustration of how there is going to be an elastic deformation field around a vacancy or solute item, so let us say this is a periodic arrangement of atoms, so this is your matrix or this is your parent material and now what you do is you remove one atom from there, so what happens when you remove an atom?

There is space created so the other atoms try to accommodate the space created within the material, so probably they are going to converge towards the center and because they are strained or stretched from their original location towards the space that has been created that leads to creation of a elastic deformation field around the defect.

Now let us look at the other case, the case of an interstitial, again you have regular arrangements of atoms and now you remove one of these atoms and introduce a smaller atom, so this atom in the middle is now a smaller atom, so the atoms where originally the atoms within the parent crystal were habituated to be configured in a certain way so they were touching each other, let us say the atoms were touching each other so for example in the FCC crystal structure you know the atoms on the faces touch each other with the atoms at the corner.

Now if we were going to remove one of the atoms at the face and replace it with a smaller atom again there is going to be some amount of accommodation or convergence of atoms towards the center to accommodate this smaller atom, a similar situation, an opposite situation would be if you introduce a atom which is larger than the matrix atoms in that case they atoms will have to be pushed apart.

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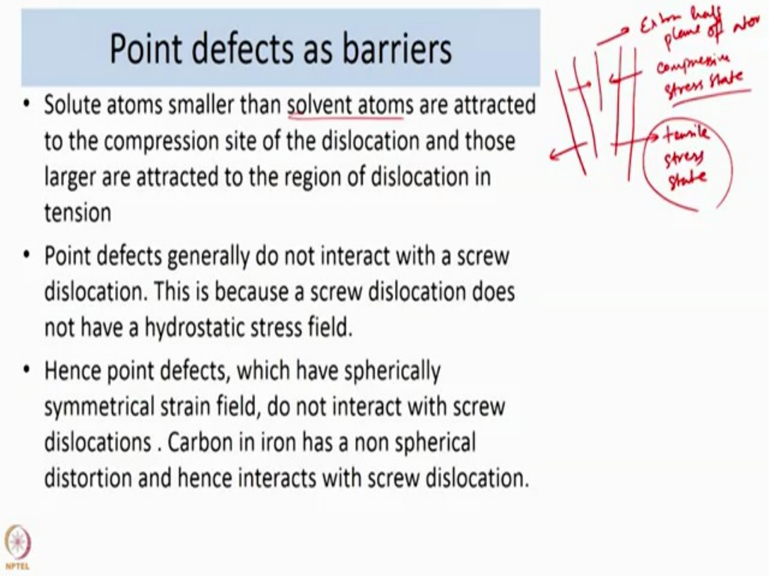

Point defects as barriers

- Solute atoms smaller than solvent atoms are attracted to the compression site of the dislocation and those larger are attracted to the region of dislocation in tension
- Point defects generally do not interact with a screw dislocation. This is because a screw dislocation does not have a hydrostatic stress field.
- Hence point defects, which have spherically symmetrical strain field, do not interact with screw dislocations . Carbon in iron has a non spherical distortion and hence interacts with screw dislocation.

In each of the case, three cases whether you have a vacancy, interstitials or smaller atom or a larger atom, you are going to create a elastic field and these elastic fields are known to interact with dislocations and I said interact mainly with edge dislocation, so what is the reason that they interact with edge dislocation, in an edge dislocation which we generally describe as an extra plane of atoms, so an edge dislocation.

So in the edge dislocation which we generally describe as a extra half plane of atoms, so you have two types of stress fields here, so below the dislocation you have a tensile stress state and just above the dislocation you have a compressive stress state where this is the extra half plane of extra half plane of atoms for the edge dislocation, so you have an extra half plane of atoms and just below the dislocation you have a tensile state of stress and above just a few atomic distances above the dislocation you have a compressive state of stress.

And depending on whether there is a tensile state of stress or the compression state of stress different types of solute atoms get attracted like listed here, solute atoms which are smaller than the solvent atoms are attracted to the compression site of the dislocation that is this and those which are larger than the solvent atoms are attracted to the region of dislocation in tension.

So the screw dislocation is generally known to be pure shear and because it does not have a hydrostatic stress field that is why the point defects do not interact with screw dislocations, so the key point here is that the strain field generated around the point defect has to be spherically symmetrical, however certain cases such as carbon in iron, the strain field is not spherically symmetrical so it is non-spherical distortion.

And in cases like this you can have the screw dislocation also interacting with the point defect which in this case carbon in iron, the point defect is in interstitial atom. So in cases like this you can have the screw dislocation interacting with the point defects.

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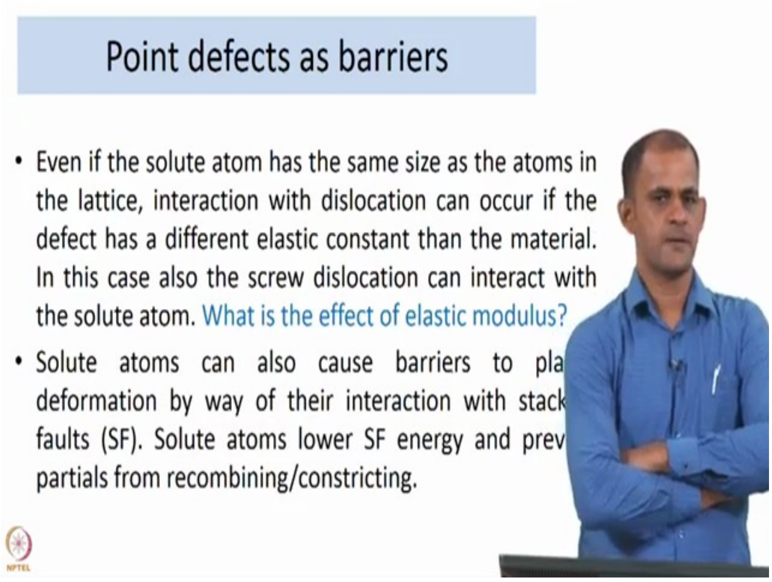

Point defects as barriers

- Even if the solute atom has the same size as the atoms in the lattice, interaction with dislocation can occur if the defect has a different elastic constant than the material. In this case also the screw dislocation can interact with the solute atom. What is the effect of elastic modulus?
- Solute atoms can also cause barriers to pla deformation by way of their interaction with stack faults (SF). Solute atoms lower SF energy and prev partials from recombining/constricting.

The screw dislocation can also interact with point defect if the solute atom has a different elastic modulus than the parent material so this is a case, so I talked in the previous slide I was talking about how the difference in size can lead to interaction between the dislocation, edge dislocation and the solute atoms, so I was talking between the interaction between the dislocations and the solute atoms when the solute atom was smaller or larger than the matrix atoms or the parent atoms.

However solute atoms could also interact with the parent atoms despite having same size, so if the solute atom even if the solute atom has a same size as the atoms in the lattice, interactions with dislocations can occur if the defect, the point defect has a different elastic constant than the material, in such a case the screw dislocation can also interact with the solute atom, so we are talking about the importance of the elastic constant or modulus of the solute atom and it playing a role in the interaction between the dislocation and the solute atom.

So what is the effect of the elastic modulus of the solute atom, that is something that I will talk about in the coming lecture, by way of interaction with dislocations screw dislocations or edge dislocations, solute atoms cause barriers to motion, similarly vacancies on account of the symmetrical strain field that elastic strain field that they create around themselves they also create barriers to dislocation motion.

Solute atoms can also cause barriers to plastic deformation by way of their interaction with stacking faults so stacking faults are created whenever a regular dislocation divides or dissociates into partial dislocations and these partial dislocations are separated by a stacking fault, so it has been observed that solute atoms can sometimes go and sit at these stacking faults or occupy sites within the stacking fault and when they do that they basically lower the stacking fault energy and what happens is when the stacking fault energy is lowered this prevents the partials from recombining or coming back together.

And whenever the partial dislocations are not able to recombine it becomes difficult for the dislocation to move through the matrix, so a dissociated dislocation finds it more difficult to move than a regular dislocation so that is why solute atoms can also create barriers to dislocation motion because of their interaction with staking faults.

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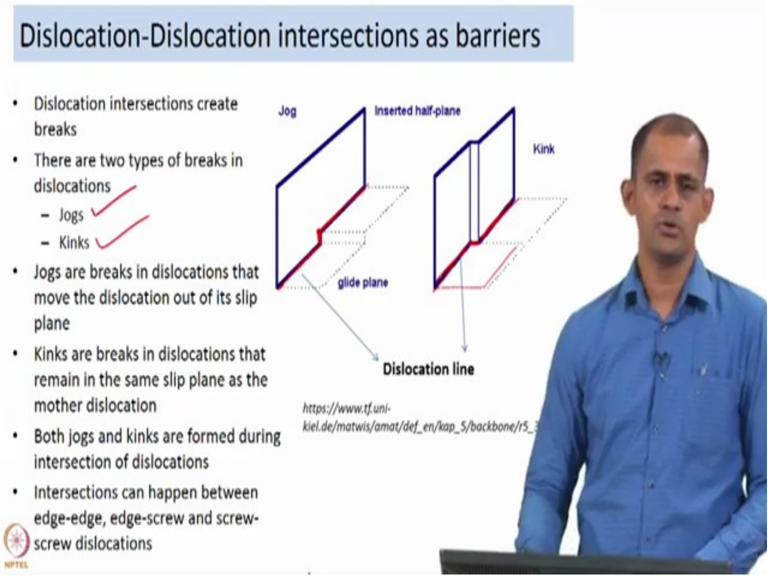

Dislocation-Dislocation intersections as barriers

- Dislocation intersections create breaks
- There are two types of breaks in dislocations
  - Jogs ✓
  - Kinks ✓
- Jogs are breaks in dislocations that move the dislocation out of its slip plane
- Kinks are breaks in dislocations that remain in the same slip plane as the mother dislocation
- Both jogs and kinks are formed during intersection of dislocations
- Intersections can happen between edge-edge, edge-screw and screw-screw dislocations

https://www.tf.uni-kiel.de/matwis/amat/def_en/kap_5/backbone/r5_

So another category of barrier is created when dislocations interact or intersect with each other. So in this particular slide I am talking about intersections between dislocations, so far I have talked about grain boundaries as barriers to dislocation motion, I have talked about point defects as barriers to dislocation motion, now I am talking about dislocation-dislocation intersections as barriers to dislocation motion. So what happens when dislocations intersect with each other?

So when two dislocations intersect with each other they create breaks so there is a break in the dislocation that is created when a dislocation intersects with another, there are two types of breaks that can be created within a dislocation, first type is called jogs and the second type is called kinks, so jogs are breaks in dislocations that move the dislocation out of its slip plane.

So let us look at this dislocation, so this is a dislocation where a portion of the dislocation has moved out of the slip plane or the glide plane so the dotted line implies the glide plane and the portion of the dislocation has moved out of the glide plane and the portion that has moved out is what is a jog, let us look at the second case, case of a kink, again a dislocation on the glide plane but again the dislocation has a break but this break continues to be within the glide plane.

So a kink is a break in the dislocation that lies within the glide plane whereas a jog is a break in a dislocation that moves the dislocation out of the glide plane, now both jogs and kinks are formed during intersection of dislocations and they can happen between different types of dislocations, they can happen when edge-edge dislocations meet each other or intersect with each other or edge and a screw dislocation intersect with each other or screw and screw dislocations intersect with each other.

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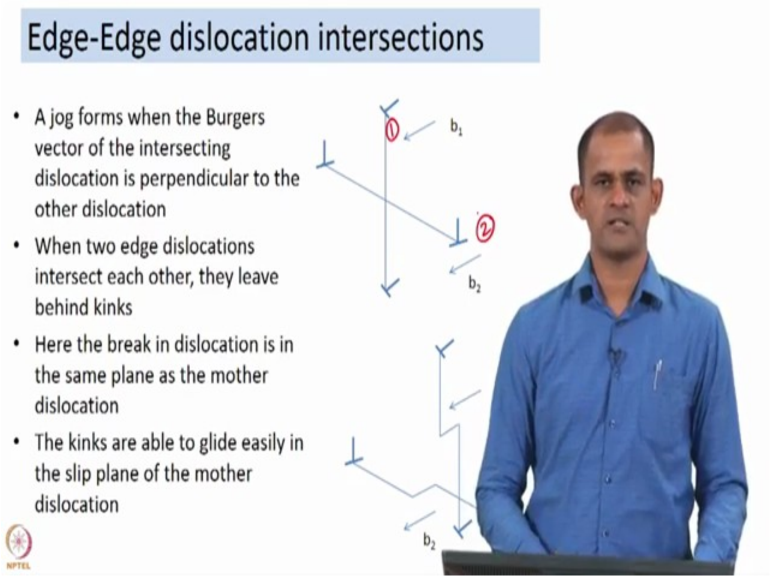
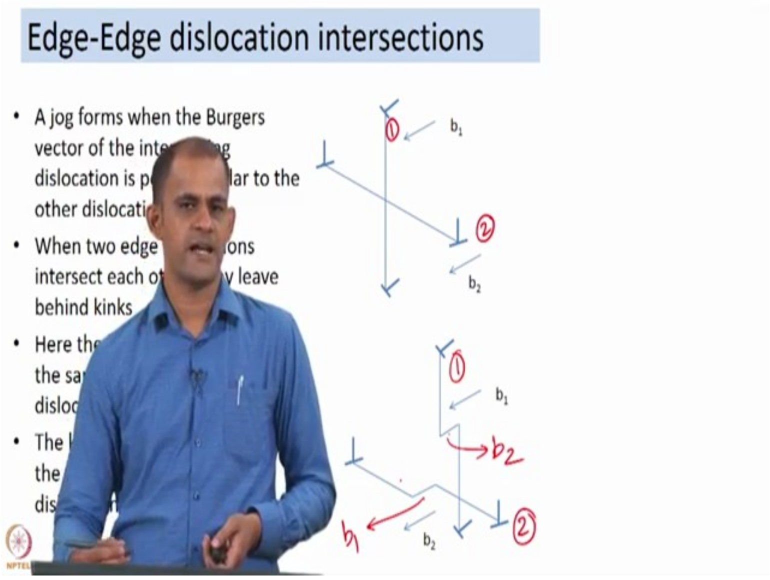


Edge-Edge dislocation intersections

- A jog forms when the Burgers vector of the intersecting dislocation is perpendicular to the other dislocation
- When two edge dislocations intersect each other, they leave behind kinks
- Here the break in dislocation is in the same plane as the mother dislocation
- The kinks are able to glide easily in the slip plane of the mother dislocation



Edge-Edge dislocation intersections

- A jog forms when the Burgers vector of the int g dislocation is p lar to the other dislocati
- When two edge ons intersect each o y leave behind kinks
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So here we are talking about formation of jogs and kinks and how they can act as barriers to plastic deformation so I introduced you to jogs, their breaks and dislocations, moving the dislocation out of the glide plane and we talked about kinks as breaks in the dislocation but which continues to lie within the glide plane now in some cases, in some books you might come across kink as being described as a subset of jog, so jog is what is described broadly as a break in a dislocation and kink is what is taken as a subset of jog especially when the break in the dislocation is within the glide plane.

Now one key factor to be understood for the formation of a break in the dislocation is the Burgers vector of the intersecting dislocation should be perpendicular to the other dislocation, so let us look at this case where we have two dislocations, dislocation 1 and dislocation 2 and the Burgers vector of dislocation 1 is perpendicular to the dislocation line 2 and Burgers vector of dislocation line 2 is also perpendicular to dislocation line 1.

So what happens in this case if we go by the rule that when the Burgers vector of the intersecting dislocation is perpendicular to the other dislocation then it creates a break so that is exactly what is happening here because b1 is perpendicular to dislocation line 2 so there is a break created within dislocation line 2, similarly because b2 is perpendicular to dislocation line 1 so there is a break created within dislocation line 1 as well and what is very interesting is the magnitude of the break for b1 is equal to b2 and the magnitude of the break for dislocation line 2 is equal to b1 okay.

And what we observe is that the break in the dislocation is in the same plane as the mother dislocation that is why both these breaks in dislocation 1 as well as in dislocation 2 are kinks and the kinks are able to glide easily in the slip plane of the mother dislocation and it is generally known that these kinks are gradually annihilated and that is why they do not create a lot of resistance to dislocation motion.

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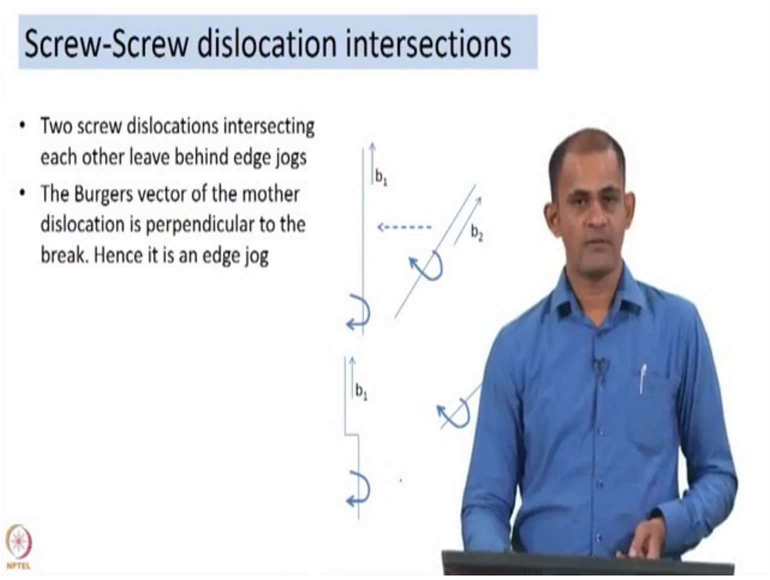
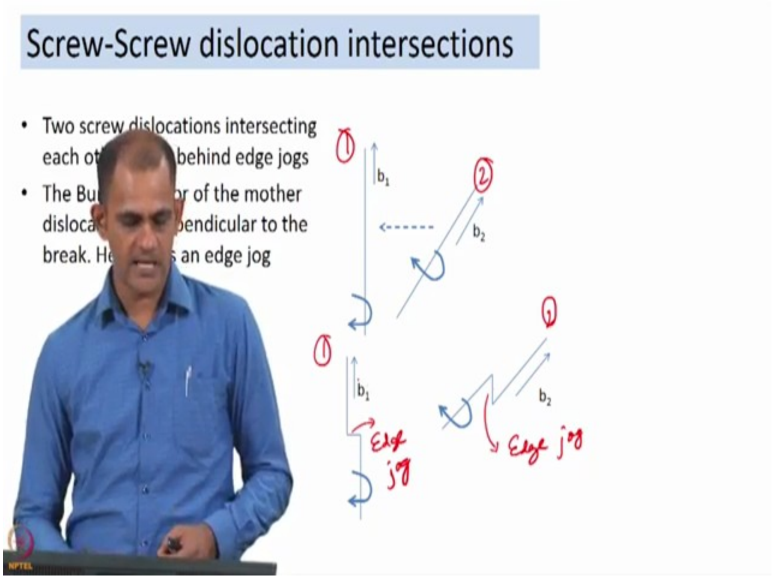


Screw-Screw dislocation intersections

- Two screw dislocations intersecting each other leave behind edge jogs
- The Burgers vector of the mother dislocation is perpendicular to the break. Hence it is an edge jog



Screw-Screw dislocation intersections

- Two screw dislocations intersecting each other leave behind edge jogs
- The Burgers vector of the mother dislocation is perpendicular to the break. Hence it is an edge jog

However one type of break in dislocation which is known to create significant resistance to dislocation motion is that which is developed when screw-screw dislocations intersect with each other, so let us look at this case here so we have two screw dislocations, dislocation 1 and dislocation 2, they are screw dislocations because the Burgers vector is parallel to their respective dislocations.

So the dotted arrow here indicates the direction in which dislocation 2 is moving so it is basically perpendicular to dislocation line 1, so what is observed in this case is after the dislocation intersect and pass away from each other they leave behind edge jogs, so jogs are created so if you look at dislocation line 1, an edge jog is created because the jog is created first of all because the break is outside of the slip plane it is an edge jog because it is an originally dislocation line 1 is a screw dislocation and its Burgers vector b1 is perpendicular to the break or the jog here that is why these jog is a edge jog.

Similarly if you look at dislocation line 2, the break that has been created there is again perpendicular to the Burgers vector and that is why it is also a edge jog, so here this is perpendicular to Burgers vector b2, here this is perpendicular to Burgers vector b1 so both this breaks are edge jogs.

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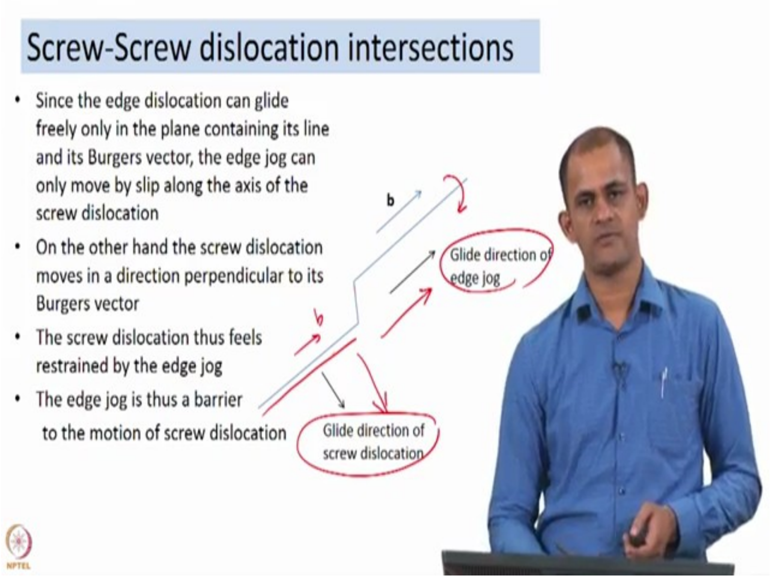

Screw-Screw dislocation intersections

- Since the edge dislocation can glide freely only in the plane containing its line and its Burgers vector, the edge jog can only move by slip along the axis of the screw dislocation
- On the other hand the screw dislocation moves in a direction perpendicular to its Burgers vector
- The screw dislocation thus feels restrained by the edge jog
- The edge jog is thus a barrier to the motion of screw dislocation

Now what is interesting is why this jogs are barriers to dislocation motion is because when you talk of a screw dislocation so this is a screw dislocation and you have the Burgers vector parallel to the dislocation line and what we know about screw dislocation is the direction of motion of the screw dislocation is generally perpendicular to its Burger vector so which means this will be the glide direction for the screw dislocation so this is the screw dislocation and because its Burgers vector is parallel and the glide direction of the screw dislocation is going to be perpendicular to the Burgers vector.

However the jog that is present is a edge jog, so it is an edge dislocation as I mentioned earlier the Burgers vector is perpendicular to this dislocation so it is an edge dislocation and now what we know is in an edge dislocation the Burgers Vector is pointed in the direction of glide, so for the edge jog the glide direction is in this direction, so now because it is by and large screw dislocation with a small edge component.

So when the screw dislocation wants to move in this direction the edge dislocation is going to prevent its motion that is because the edge dislocation wants to move in that direction, so that is why the edge jog is a barrier to the motion of a screw dislocation and hence creates barrier to plastic deformation and is one of the causes of strain hardening.

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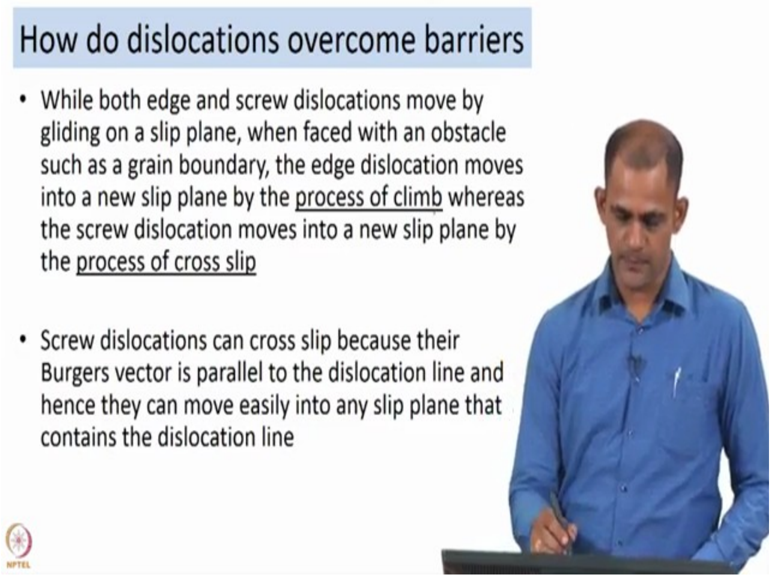
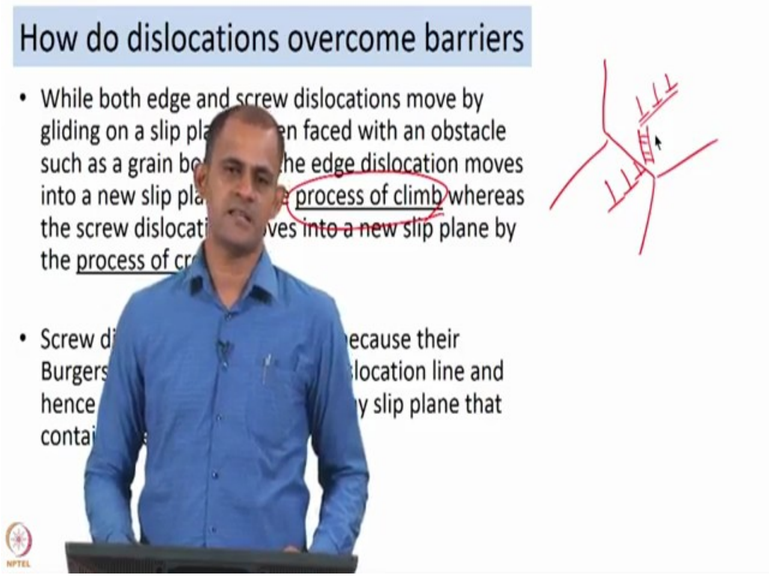


How do dislocations overcome barriers

- While both edge and screw dislocations move by gliding on a slip plane, when faced with an obstacle such as a grain boundary, the edge dislocation moves into a new slip plane by the process of climb whereas the screw dislocation moves into a new slip plane by the process of cross slip
- Screw dislocations can cross slip because their Burgers vector is parallel to the dislocation line and hence they can move easily into any slip plane that contains the dislocation line



How do dislocations overcome barriers

- While both edge and screw dislocations move by gliding on a slip pl… …n faced with an obstacle such as a grain bo… …he edge dislocation moves into a new slip pl… …process of climb whereas the screw dislocati… …ves into a new slip plane by the process of cr…
- Screw d… …ecause their Burgers… …location line and hence… …y slip plane that contai…

We talked about grain boundaries as barriers to dislocation motion, we talked about point defects as barriers to dislocation motion, we talked about dislocation, dislocation intersections, creating barriers to dislocation motion, so for plastic deformation to continue you need the dislocations to overcome these barriers, so how do the dislocations overcome these barriers?

So we have edge dislocations and screw dislocations and each dislocation has its own way of overcoming barriers, so the edge dislocation when it is moving in a glide plane and if it happens to face a barrier or an obstacle such as a grain boundary, the edge dislocation overcomes the grain boundary by moving into a new slip plain by the process of climb, so earlier I had illustrated how edge dislocation when they interact with the grain boundary they start piling up but they can overcome these grain boundary by climbing up to a new slip plane.

So if say on a lighter note assume there is some form of a ladder and the dislocation, edge dislocation is climbing up the ladder into a new slip plane but the screw dislocation does not need any ladder to climb into new slip plane, what the screw dislocation does is it employs a process called cross slip, so the screw dislocation moves into a new slip plain by the process of cross slip.

Unlike the edge dislocation which is described as a extra half plane of atoms, the screw dislocation can cross slip into a new slip plane because of its characteristic, a particular characteristic that with dislocation, the screw dislocations Burgers vector is parallel to the dislocation line and hence the screw dislocation can move easily to into any slip plane that contains the dislocation line.

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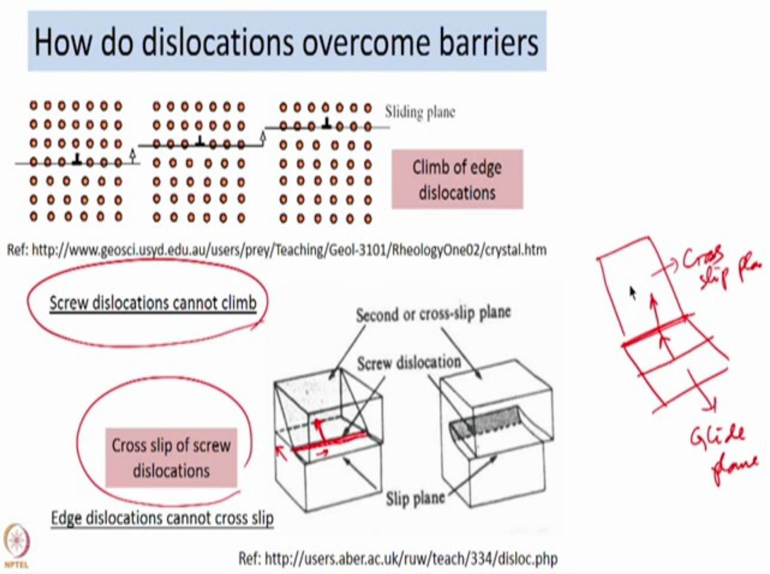

How do dislocations overcome barriers

Climb of edge dislocations

Ref: http://www.geosci.usyd.edu.au/users/prey/Teaching/Geol-3101/RheologyOne02/crystal.htm

Screw dislocations cannot climb

Cross slip of screw dislocations

Edge dislocations cannot cross slip

Ref: http://users.aber.ac.uk/ruw/teach/334/disloc.php

So here is an illustration of the process of climb as well as cross slip, so you have an edge dislocation here which is climbing up into a new slip plane whenever it faces a barrier, important point is screw dislocations cannot climb but they move around barriers by employing a process of cross slip, so like I said earlier, so this is the screw dislocation, Burgers vector is in this direction and the dislocation while its moving it comes across a barrier so what it does is instead of climbing it just moves by slipping into the new slip plain.

The main point is it can move into a slip plane, any slip plane that contains the dislocation line, so if you have say this is the cross slip plane and this is the original glide plane and say you have a dislocation which is parallel to the direction common to both these planes, so the dislocation can move into this new plane because it is parallel to this direction which is common to both the planes. So that is what a screw dislocation does but edge dislocations do not have the same luxury, edge dislocations cannot cross slip but they need to climb.

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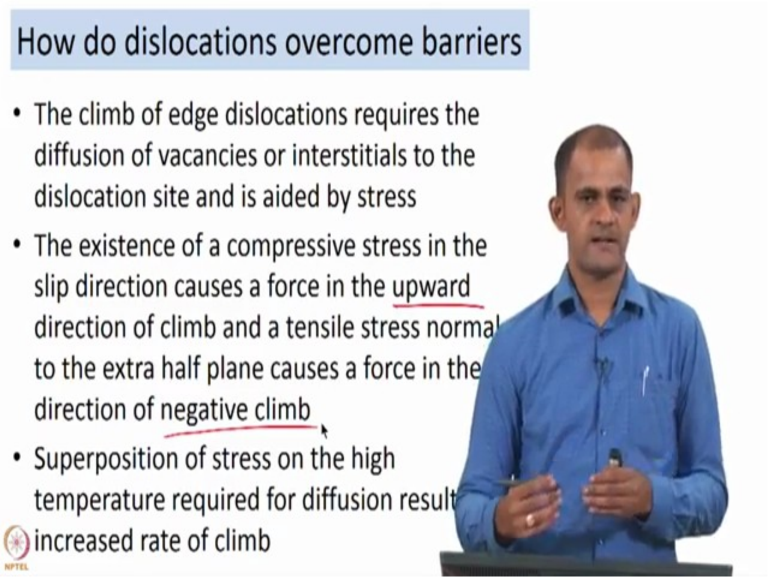

How do dislocations overcome barriers

- The climb of edge dislocations requires the diffusion of vacancies or interstitials to the dislocation site and is aided by stress
- The existence of a compressive stress in the slip direction causes a force in the upward direction of climb and a tensile stress norma to the extra half plane causes a force in the direction of negative climb
- Superposition of stress on the high temperature required for diffusion result increased rate of climb

Continuing in the same vein of thought of how dislocations overcome barriers, so when we talk of climb of edge dislocations the climb happens with some assistance given by temperature, how does temperature assists in the climb of dislocation, well temperature helps in the diffusion of vacancies or interstitials to the dislocation site and that is how it climbs, of course stress also assists in the climb of dislocations, the nature of the stress that is whether it is compressive in nature or tensile in nature we will also determine the direction in which the dislocation climbs.

And so for example if it is a compressive stress then acting on the dislocation, then the dislocation climbs upward and whereas if it is a tensile stress normal to the extra half plane then that forces the dislocation to climb down which is negative climb so when you have both stress and temperature together superimposed then that results in higher rate of climb.

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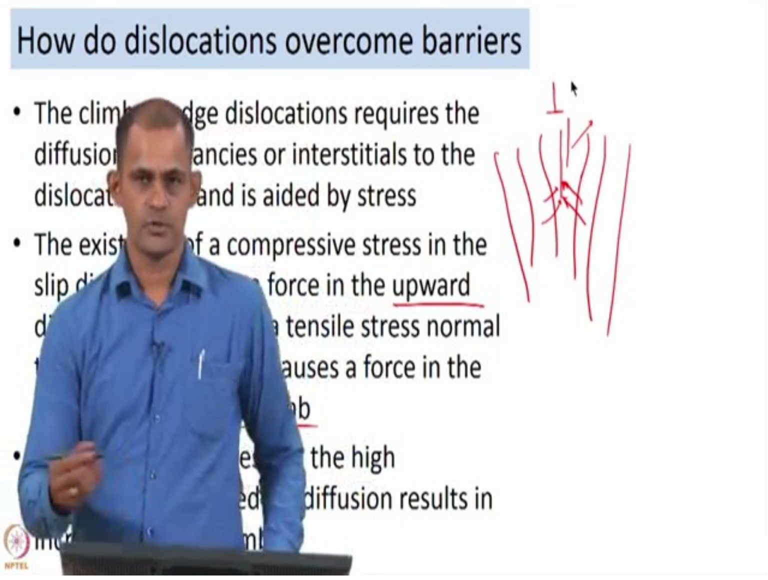

How do dislocations overcome barriers

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Just to illustrate my point so say this is the dislocation, edge dislocation also known as in extra half plane of atoms so say this is the extra half plane of atoms, this is edge dislocation so if the dislocation wants to climb up which means so when you are talking of climbing up say this was its original location and say this is its new location, so when the dislocation is climbing up what has basically happened is you have this original set of atoms which were present here, they have moved up and that moving up could happen if you have vacancies coming here.

So if you assume that there are some vacancies coming here and sitting under the dislocation so vacancies basically mean vacant space then that means the line has basically moved up so you need vacancy diffusion to happen to the dislocation. Let us look at the other situation, so the dislocation has climbed up because the vacancies have diffused to the core of dislocation.

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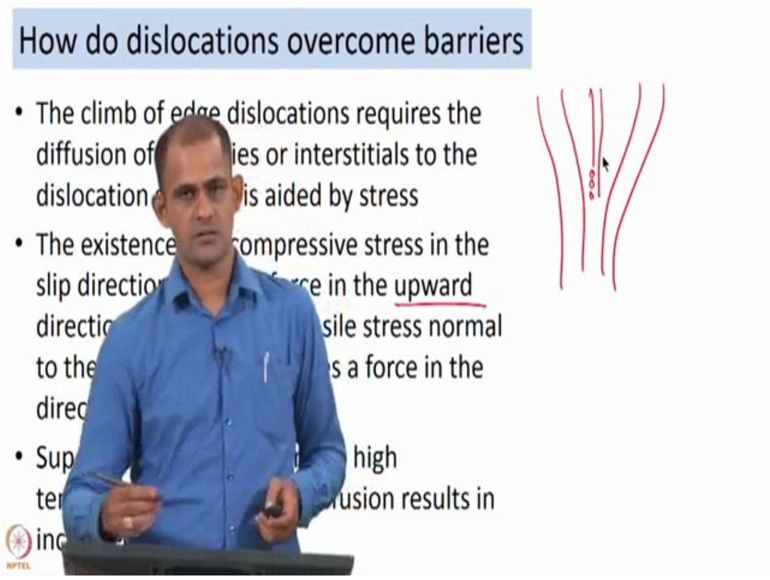

How do dislocations overcome barriers

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Now let us look at the other case, dislocation climbing down that is negative climb so when the dislocation is climbing down that means this is what is happening so you have the dislocation moving down the extra half plane of atoms is moving down so that would happen if you have atoms more atoms coming and sitting at the dislocation, so if that happens then that means the dislocation is moving down.

So both this vacancies diffusing to the extra half plane of atoms or atoms, interstitials diffusing to the extra half plane of atoms is aided by temperature and stress and that is why them together can result in increased rate of climb so when there is increase rate of climb then you will have increased rate of plastic deformation that is because climb comes about whenever the dislocation faces a barrier or an obstacle and if the temperature and stress together help in the dislocation climbing up that barrier then they will support further plastic deformation.

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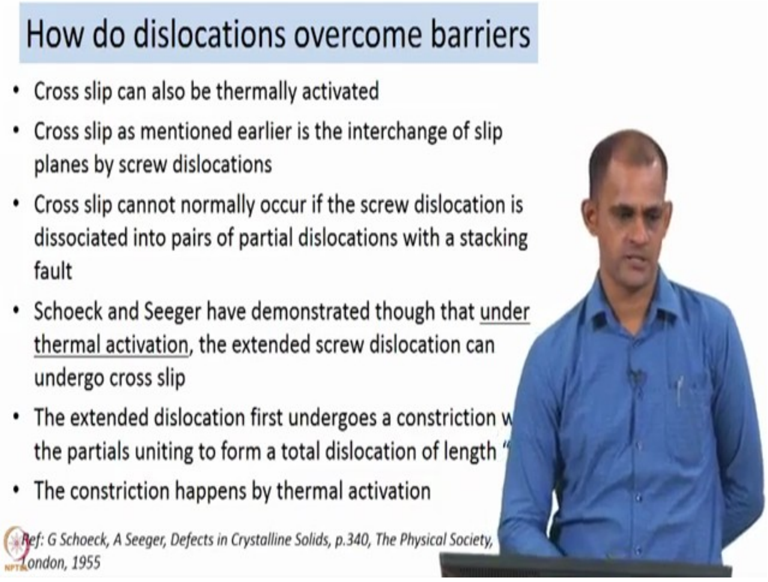
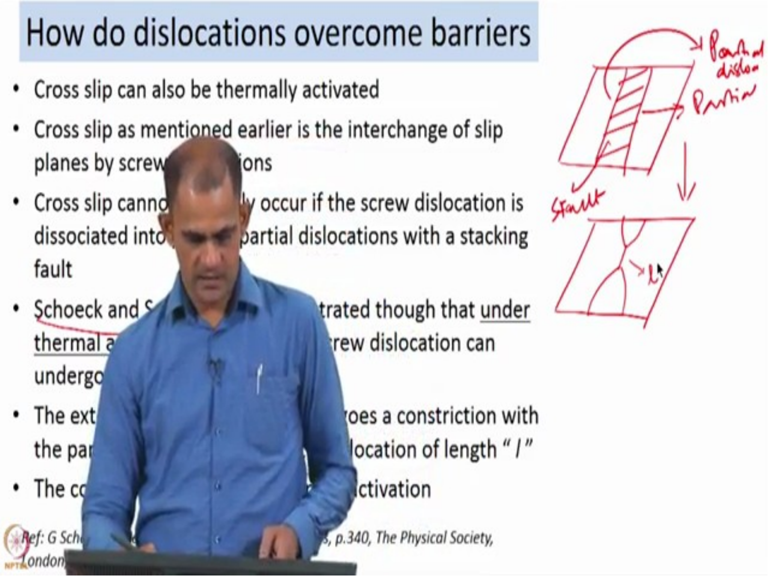


How do dislocations overcome barriers

- Cross slip can also be thermally activated
- Cross slip as mentioned earlier is the interchange of slip planes by screw dislocations
- Cross slip cannot normally occur if the screw dislocation is dissociated into pairs of partial dislocations with a stacking fault
- Schoeck and Seeger have demonstrated though that under thermal activation, the extended screw dislocation can undergo cross slip
- The extended dislocation first undergoes a constriction w
the partials uniting to form a total dislocation of length "
- The constriction happens by thermal activation

Ref: G Schoeck, A Seeger, Defects in Crystalline Solids, p.340, The Physical Society, London, 1955



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So that was about edge dislocations overcoming barriers, now let us look at screw dislocations, so how do screw dislocations overcome barriers? So I already said screw dislocations can overcome barriers by cross slip but there is also temperature effect, this cross slip can also be thermally activated, at room temperatures you can have screw dislocations moving by general cross slip but if you have high temperature then the rate of cross slip can also be supported by temperature so it can also be thus thermally activated.

So cross slip as mentioned is interchange of slip plane by screw dislocations, cross slip cannot normally occur if the screw dislocation is dissociated into pairs of partial dislocations with a stacking fault. So let us look at this, let us say this is its glide plane and you have a screw dislocation that has been dislocated into two so you have a stacking fault that separates the two partials and what people have noticed is if there are partials into which the screw dislocation has dissociated then it loses its ability to cross slip into a cross slip plane.

However under certain conditions of high temperature, there is a mechanism that has been proposed by Schoeck and Seeger who have demonstrated that under a certain thermal excitation the extended screw dislocation can undergo cross slip, well how does that happen? The first step of thermal activation helping in cross slipping of dislocation is that thermal activation helps the dislocation constrict so you had partials so this is one partial dislocation, this is the second partial dislocation and both this partials are separated by the stacking fault and then we are saying these partial dislocations could get constricted at high temperature.

So that is what temperature does, it helps in the constriction of the partial dislocation so locally a portion of the partial dislocations are going to come together, let us say the length of this constricted region is l and this constriction happens by thermal activation.

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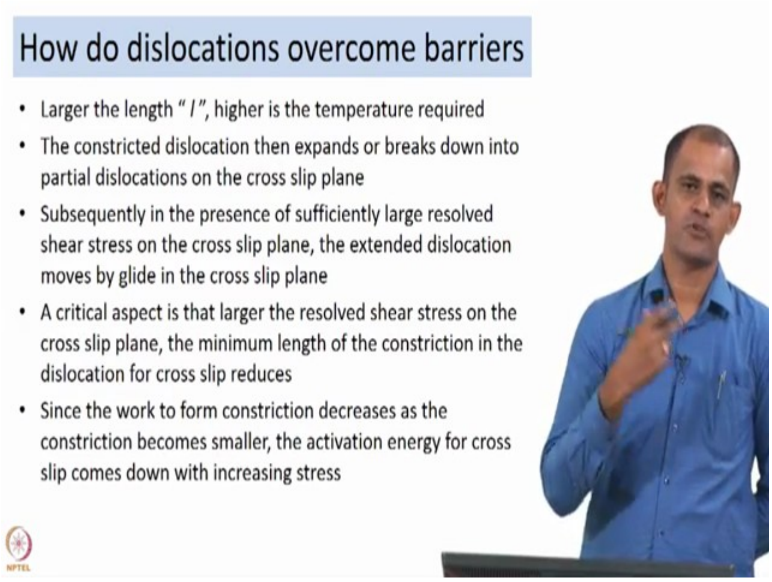
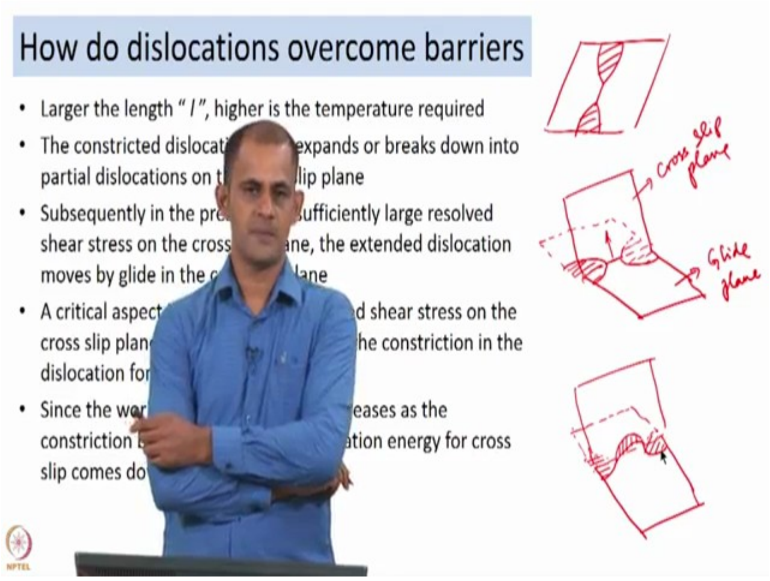


How do dislocations overcome barriers

- Larger the length "*l*", higher is the temperature required
- The constricted dislocation then expands or breaks down into partial dislocations on the cross slip plane
- Subsequently in the presence of sufficiently large resolved shear stress on the cross slip plane, the extended dislocation moves by glide in the cross slip plane
- A critical aspect is that larger the resolved shear stress on the cross slip plane, the minimum length of the constriction in the dislocation for cross slip reduces
- Since the work to form constriction decreases as the constriction becomes smaller, the activation energy for cross slip comes down with increasing stress



How do dislocations overcome barriers

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So what people have noticed is larger the length l, higher is the temperature required, so if you want a greater length of the dislocation to constrict then you will have to apply higher temperature, now once the dislocation has constricted in its slip plain what it is now capable of doing is it can move into a cross slip plane, so this is the region of constriction and that is the partial dislocation.

So now the constricted dislocation can move into a cross slip plain, so that is the cross slip plane and this is the original glide plane, of course the important point to be noted here is the cross slip plane should have a sufficiently large resolved shear stress so in the presence of a sufficiently large resolved shear stress on the cross slip plane the extended dislocation moves by glide in the cross slip plane.

So what happens is once the constricted dislocation moves into the cross slip plane, it is again going to separate out into partials, so you have the constricted dislocation moving into the cross slip plane and then the constricted dislocation again opens up into again forms an extended dislocation so this is again this tacking fault forming within the cross slip plane.

So for this extended dislocation to move again in the cross slip plane the cross slip plane should have a sufficiently large resolved shear stress, also larger the resolved shear stress on the cross slip plane the minimum length of the constriction in the dislocation for cross slip increases, critical aspect is that larger the resolved shear stress on the cross slip plane the minimum length of the constriction in the dislocation for cross slip reduces.

Since the work to from constriction decreases as the constriction becomes smaller, the activation energy for cross slip comes down with increasing stress so the constriction happens by thermal activation if you find that the cross slip plane has a large resolved shear stress then then even a smaller constriction can make it into the cross slip plane.

So basically if you have a large resolved shear stress then the constriction size reduces so if the constriction size reduces that means the temperature required for constricting the dislocation can also come down, so automatically the activation energy for cross slip is going to come down with increasing stress, so this is how thermally activated cross slip happens and this is how the role of, this is what the role of temperature and stress is, the stress helps in increasing the resolve shear stress present on the cross slip plane and the temperature helps in constricting the dislocation together the extended dislocation together so that it can move into the cross slip plane.

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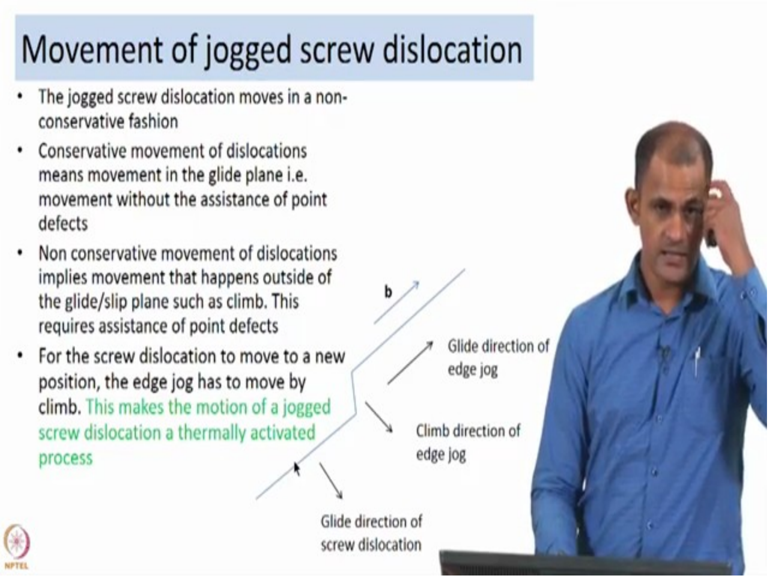


Movement of jogged screw dislocation

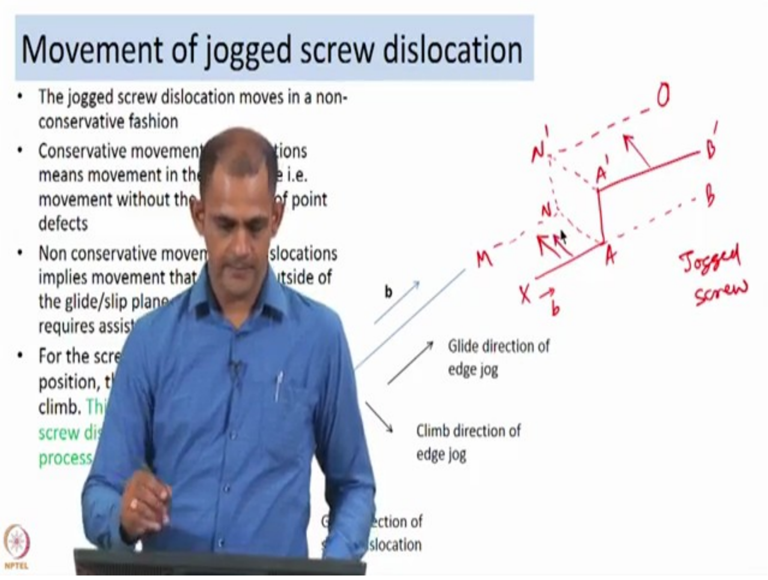
- The jogged screw dislocation moves in a non-conservative fashion
- Conservative movement of dislocations means movement in the glide plane i.e. movement without the assistance of point defects
- Non conservative movement of dislocations implies movement that happens outside of the glide/slip plane such as climb. This requires assistance of point defects
- For the screw dislocation to move to a new position, the edge jog has to move by climb. This makes the motion of a jogged screw dislocation a thermally activated process

b

Glide direction of edge jog

Climb direction of edge jog

Glide direction of screw dislocation



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b

Glide direction of edge jog

Climb direction of edge jog

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That was about how edge dislocations can overcome barriers by climb, how screw dislocations can overcome barriers by cross slip which is also thermally activated, now let us look at the another case, this is the case of the jogged screw dislocation, so previously I mentioned how when you have two screw dislocations intersecting with each other they lead to the formation of jogs and I said how the edge jog, the jog is edge in nature, it has an edge character and because it has an edge character it restrains the screw dislocation from moving along its glide direction or along its glide plane.

And so it creates a barrier to the motion of the screw dislocation, however the jogged screw dislocation can move in a non-conservative fashion, so what is conservative and non-conservative motion? So conservative motion of dislocation means movement of the dislocation in the glide plane that is movement which happens without the assistance of point defects, so when the dislocation is moving on its preferred plane that is the glide plane, it does not need any diffusion of vacancies or interstitials for its motion that is why the movement is known to happen without the assistance of point defects.

However when you have non-conservative motion, an example of non-conservative motion is dislocation climb, so non-conservative motion means the dislocation movement happens outside of its glide or slip plane such as dislocation climb and for this you need diffusion of vacancies as well as point defects, now when we talk of the jogged screw dislocation, for the screw dislocation to move to a new position it has to drag its edge jog along and the edge jog can move out of its preferred plane of glide only by climb that is why for the edge jog to climb it needs diffusion of vacancies or interstitials.

And diffusion is a high temperature process that is why the motion of the jogged screw dislocation is a thermally activated process, just to illustrate this point this is your jogged screw, this is its Burgers vector, this is its edge jog, now for this dislocation to move to a new location say this is A, A dash and so this is the original location of the screw dislocation jogged screw dislocation.

Now it wants to move to a new location so let us call this new location M, N, N dash, O, so the jogged screw can move from its original location at say X, A, A dash, B dash to M, N, N dash, O, this motion can only happen if the edge dislocation can climb from its location at A, A dash to its location at N, N dash whereas the rest of the screw dislocation can glide.

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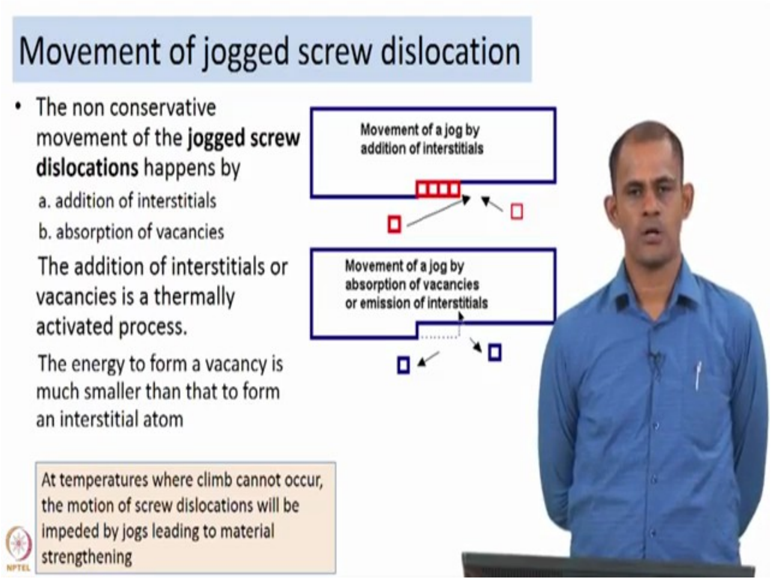

Movement of jogged screw dislocation

- The non conservative movement of the **jogged screw dislocations** happens by
  - a. addition of interstitials
  - b. absorption of vacancies

The addition of interstitials or vacancies is a thermally activated process.

The energy to form a vacancy is much smaller than that to form an interstitial atom

At temperatures where climb cannot occur, the motion of screw dislocations will be impeded by jogs leading to material strengthening

So the non-conservative movement of the jogged screw dislocation like dislocation climb happens, dislocation climb happens by addition of interstitials or diffusion of vacancies or absorption of vacancies so similarly the non-conservative movement of the jogged screw dislocation happens by addition of interstitials as well as absorption of vacancies, so this is a illustration of how interstitials atoms moving to the jog can help in its motion or absorption of vacancies at the jog can help in its motion.

Between vacancies and interstitials, the energy required to form a vacancy is lower than that required to form an interstitial atom so preferably the motion of a edge jog will happen by diffusion of vacancies, so what we have understood is temperature is required for the motion of a jogged screw dislocation because it helps in the diffusion of vacancies in interstitials, however if the temperature at which the material is present or being tested is not high enough then climb cannot occur in which case the motion of screw dislocations will be impeded by the jogs leading to material strengthening or strain hardening.