Dynamic Behaviour of Materials
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Lecture-35
Plastic Deformation at High Strain Rates 2

Hello everyone, so we are in the chapter or plastic deformation at high strain rates. So we have discussed about the constitutive relations involving high strain rate problems. And then we also talked about little bit of dislocation dynamics, so we will continue these discussions today.

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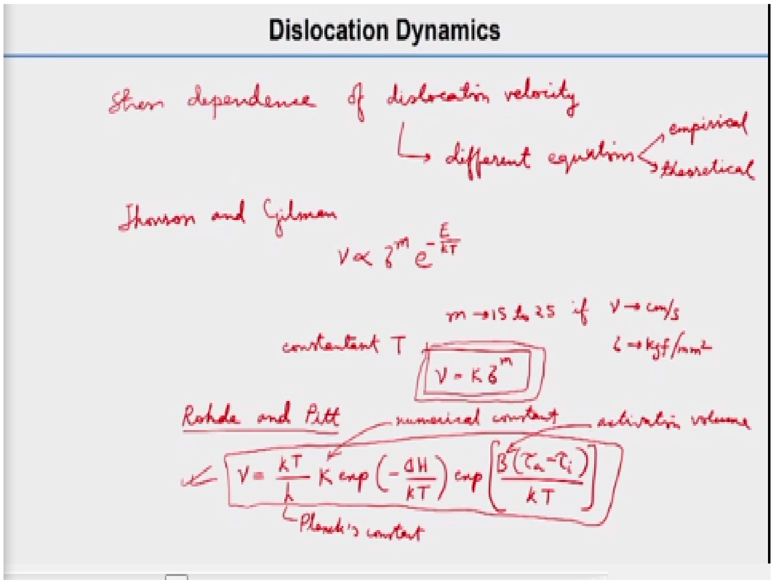

Dislocation Dynamics

Stress dependence of dislocation velocity

$\hookrightarrow$ different equation $<$ empirical, theoretical

Jhonson and Gilman

$$V \propto \tau^m e^{-\frac{E}{kT}}$$

$m \rightarrow 15$ to 25 if $V \rightarrow$ cm/s

$\tau \rightarrow$ kgf/mm^2

constant T

$$\boxed{\boxed{V = K\tau^m}}$$

Rohde and Pitt

numerical constant

activation volume

$$\boxed{V = \frac{kT}{h} K \exp\left(-\frac{\Delta H}{kT}\right) \exp\left[\frac{B(\tau_a - \tau_i)}{kT}\right]}$$

Planck's constant

So that the stress dependence of dislocation velocities has been fitted into different types of equations. So there are different equations both empirical and some are of theoretical basis. So for example Johnson and Gilman have shown that the velocity of dislocation is proportional to the applied stress to the power m and exponential - E K T. So in this case m is from 15 to 25, if V is measured in centimeter per second and sigma is measured in kg force per millimeter square.

So if it is constant temperature, constant T, so what we can get is V is proportional sorry V = k sigma to the power m. So similarly we will write another relation, so there are several relation can be found of the dependence of dislocation velocity on stress. So for example Rohde and Pitt relation is little longer and little complex looking so this is KT by H capital exponential - delta H small k the Boltzmann constant and then exponential B tau a tau i divided by kT.

So this relation here H is the Planck's constant, so this would be Planck's constant K is a numerical constant this K is a I will write here itself it is a numerical constant. And then a small k is the Boltzmann constant, and B is activation volume. And similarly delta H is enthalpy of activation, tau a is applied resolve shear stress and tau 1 the long range internal stress. So we do not write or probably discuss details about this equation, so because we do not need it.

So or if you are interested more, so you can study the Mark Meyer's book, the textbook. So just to show you that these are some kind of relation exists between this location velocity and applied stress. So just to show you the type of what type of relations they are.

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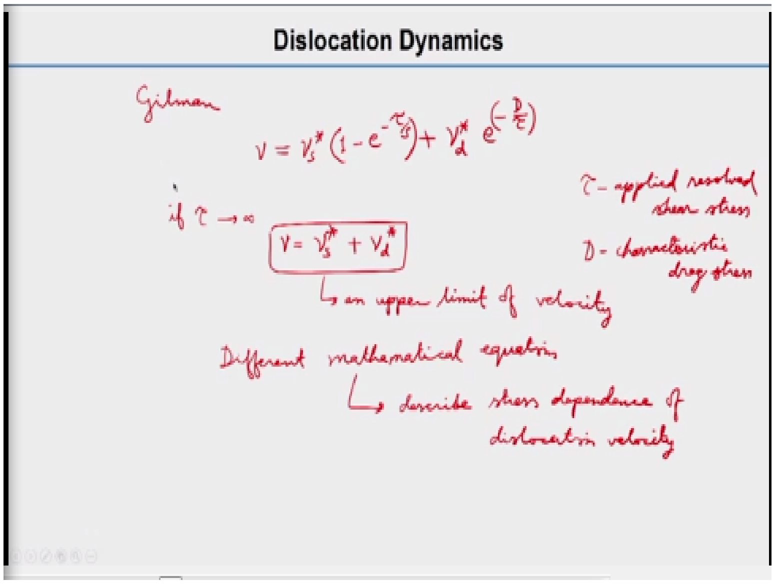

Dislocation Dynamics

Gilman

$$V = V_s^* \left(1 - e^{-\tau/\tau_s}\right) + V_d^* e^{\left(-\frac{D}{\tau}\right)}$$

τ - applied resolved shear stress

D - characteristic drag stress

if $\tau \rightarrow \infty$

$$\boxed{V = V_s^* + V_d^*}$$

$\hookrightarrow$ an upper limit of velocity

Different mathematical equation

$\hookrightarrow$ describe stress dependence of dislocation velocity

So please refer to the book if you are more interested in it, for several other relations are available in the literature and these relations are for different materials like Gilman et al discussed about copper. And similarly for zinc by Pope et al open co-workers and for aluminum garment in coworkers fit the curve of fit that some relationship with aluminum and lead data.

So however Gilman described the behavior there are almost any materials, so that is the velocity of the dislocation is equal to V s star, so they are the limiting velocity I will let you know though this is 1 - e - tau s + V star d, e to the power - D tau. So this is these exponential terms, so here tau is the as you know that resolved shear stress. So this tau so I would write better applied resolve shear stress.

And then these are the characteristic drag stress, so it is called characteristic drag stress and similarly s is also a constant. So what happens is that if the applied stress is very high, it tends to infinity, so V is equal to V s so V s star and V d star. So that means there is an upper limit of velocity, so these values will not go higher than this even if you are increases the stress more. So there are different category questions used to describe the dynamic behavior of the dislocations that can be little confusing.

So different mathematical equations to describe the applied stress dependence of dislocation velocity, so that may create some confusion in our mind.

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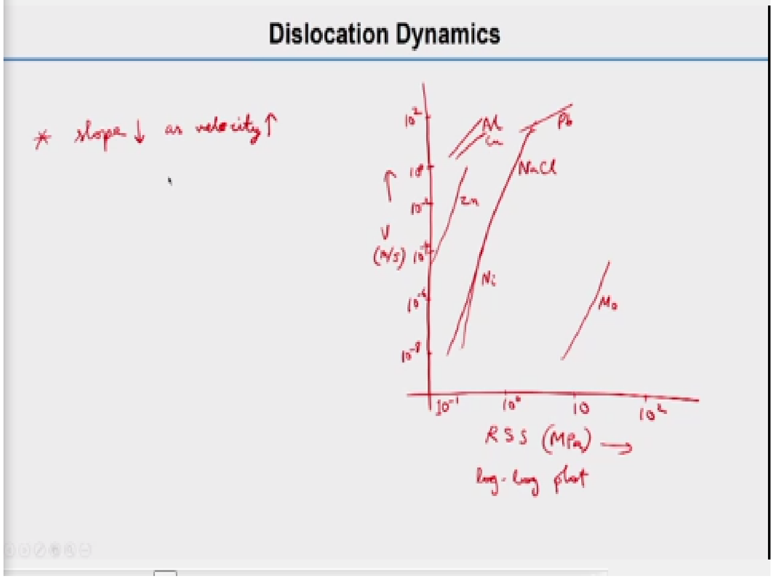

Dislocation Dynamics

* slope ↓ as velocity ↑

But we will see some of the behavior from which is from a plot which is compiled in this Mark Meyer’s book. So that plot is nothing but a log plot of resolved shear stress, I will write RSS for resolve shear stress which is in mega Pascal. And resolve shear stresses, I discuss this in our materials science basics class, so resolve shear stress that is resolved on the slip plane whether dislocations on which planes the dislocation move.

And then here we have dislocation velocity V in units of meter per second, so what happening is here if you see the scale, scale will look something like this 10 to the power - 1 10 square. So if you see this will be very approximate you for a proper plot you check the textbook, so I will just draw very you know very rough for plot here that may not be equal to the real one.

So sorry this will be kind of a straight line for nickel something like this and then let us say for molybdenum it looks something like this. It is a molybdenum it is very close to this is kind of a straight line and then zinc will be something like this, sodium chloride will be like this and little sodium chloride will look something like this NaCl. Then lead will be something like this Pb lead will be something like this.

And then aluminum comes here aluminum even copper is also somewhere close, so these are the you know plots that shows that dislocation velocity depends on the resolve shear stress. So from these curves we can come to a conclusion that the slope of these plots slope decreases as velocity increases. So this is actually not very clear in this plot probably because this is the log, log plot so.

But this is the conclusion they actually come to that conclusion that the slope will decrease as a velocity will increase. If you see that some of the materials for these let us say we told about some equations the Rohde and Pitt equation this equation although it looks complex. But the same data can we fit into a simpler equation like this also. So if you these experimental results of the Rohde and Pitt can be you know fit to this equation as well this will also we give some approximation.

So different equations mathematical equations, mathematical relations are proposed but the overall trend you can see from here this plot this was compiled from different references. And I think that is they have been published in the Mark Meyer’s and K.K. Chawla’s book mechanical metallurgy, so this is the trend.

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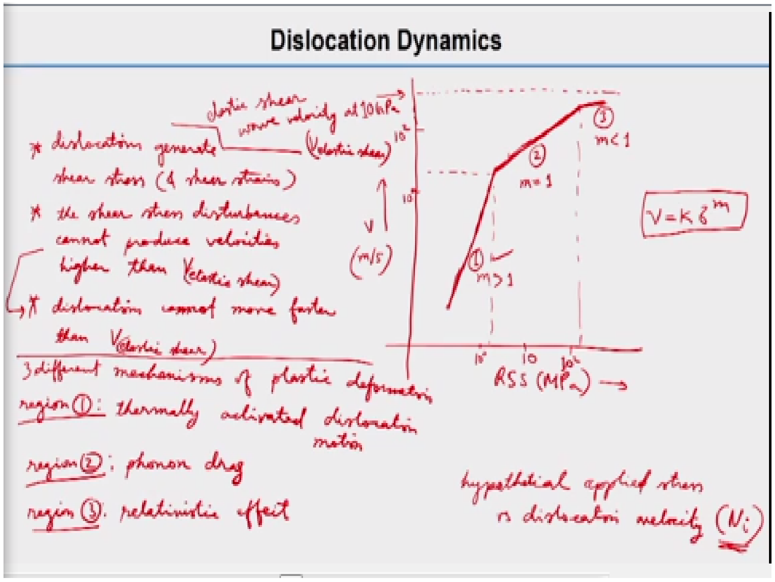

Dislocation Dynamics

* dislocation generate shear stress (& shear strains)

* the shear stress disturbances cannot produce velocities higher than $V_{(\text{elastic shear})}$

* dislocation cannot move faster than $V_{(\text{elastic shear})}$

elastic shear wave velocity at 10 GPa $\rightarrow$ $V_{(\text{elastic shear})}$

3 different mechanisms of plastic deformation

region ①: thermally activated dislocation motion

region ②: phonon drag

region ③: relativistic effect

$\boxed{V = k\sigma^m}$

hypothetical applied stress vs dislocation velocity (V_i)

And then we can draw a hypothetical applied stress versus dislocation velocity. This is they have drawn it for nickel, how it looks like is, so this is the resolve shear stress in mega Pascal and this is the dislocation velocity in meter per second. So what happen is if you see for nickel so I will not write the scale here, so maybe we can write the straight line behavior, so it looks something like this.

So I think this point will be probably somewhere in between 10 to the power 0 to let us say 10 square. And then this point is somewhere probably in between 10, 0, 10 and this point is probably somewhere above 10 square. So now there are 3 phases, 3 regions you can see that region 1 and region 2 and then region 3. If you check the earlier equation if it is earlier equation one of the earlier equations V = k sigma to the power m.

So in here, so if you use these relations, so here actually for the first region, so m is greater than 1 and here m = 1 and then here m is smaller than 1. So if you use this relation, so you can have the coefficients of m like this and there will be a limiting velocity by the way, this limiting velocity. So that limiting velocity is your shear wave velocity actually elastic shear wave velocity at 10 Giga Pascal.

So what happen is because this dislocation this is all about dislocation dynamics we are talking about the dislocations whether it is a screw dislocation edge dislocation they generate shear stress and also shear strain. So these shear stress, so the shear stress disturbance the shear stress if you consider them as the disturbance, that means we are talking about the wave propagation, so cannot produce velocities higher than the V elastic sheer.

So here you know what we talked about V elastic shear, shear wave velocity elastic shear wave velocity, so I would write like this. So this, so what happens is that, so dislocation cannot move faster than thus. So this means dislocations cannot move faster than V elastic shear, so the velocity should be less than that. Now coming to these T region, so what happens why this for the nickel alloy, so this has I told you this is for nickel.

So for this material why this is like a hypothetical one but this although it is hypothetical but the trend is similar. So what happened is this 3 region represent 3 different mechanisms of plastic deformation. So that is number 1, that number 1 is thermally activated, so I would write here 3 different mechanisms ends of plastic deformation, so I would write region 1, that means this region ok.

And then that gives us this is thermally activated dislocation motion. Then region 2, that mechanism is called phonon drag we will discuss about that phonon drag and then region 3 is the relativistic effects, so we will discuss all 3 mechanisms.

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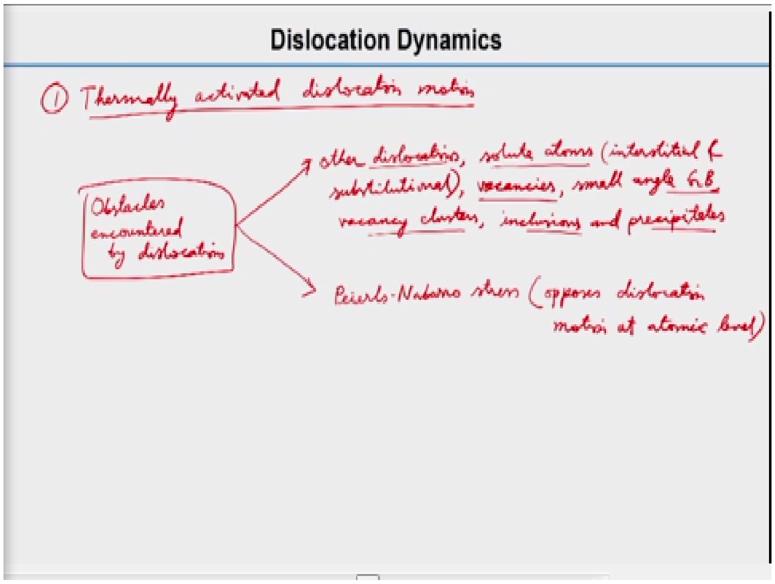

Dislocation Dynamics

① Thermally activated dislocation motion

Obstacles encountered by dislocation

→ other dislocations, solute atoms (interstitial & substitutional), vacancies, small angle G.B, vacancy clusters, inclusions and precipitates

→ Peierls-Nabarro stress (opposes dislocation motion at atomic level)

The thermally activated dislocation motion**,** so dislocations continuously encounters obstacles. So **so** dislocation needs to cross those obstacles to continue the plastic deformation. So you will see what are the obstacles encountered by dislocations ok. So we will see the first category is like other dislocations, other dislocations that means dislocations interact with dislocation.

And then solute atom, we have discussed about that in the material science basic class that lecture. So what we discussed that dislocation the interstitial and substitutional impurity or solute atoms. So what we discussed are different crystal defects and also strengthening mechanism. So where we discussed that the dislocations encounter some obstacles and that way the material got you know get strengthened.

So and then vacancies, then small angle grain boundary I will write GB to grain boundary. And then vacancy clusters number of vacancies group together and then inclusions and precipitates, these are 3 dimensional defects. So that we have discussed earlier, so these are all you know the facts here whatever we discussed all are defects. So other dislocations that is these are one dimensional defects solute atoms, vacancies, grain boundaries, vacancy clusters, inclusions, precipitates they are all defects.

But there is another one which we did not discussed earlier, so that is called pulse Nabarro of stress so pulse Nabarro stress, so that is another obstacle. So this pulse Nabarro stress opposes dislocation motion at atomic level. So we will see what is that is atomic level as you know that others are also like vacancies or dislocations or grain boundaries they are also probably you can think that is it is kind of a atomic level.

But this is even at the smaller length scale it is only one atomic distance, so Pulse Nabarro stresses corresponds to only in the displacement of and the barrier of only one atomic displacement ok. So Pulse Nabarro stress is called at an atomic level, it opposes the dislocation at atomic level because it involves the obstacle or barrier of let us say 1 atomic distance.

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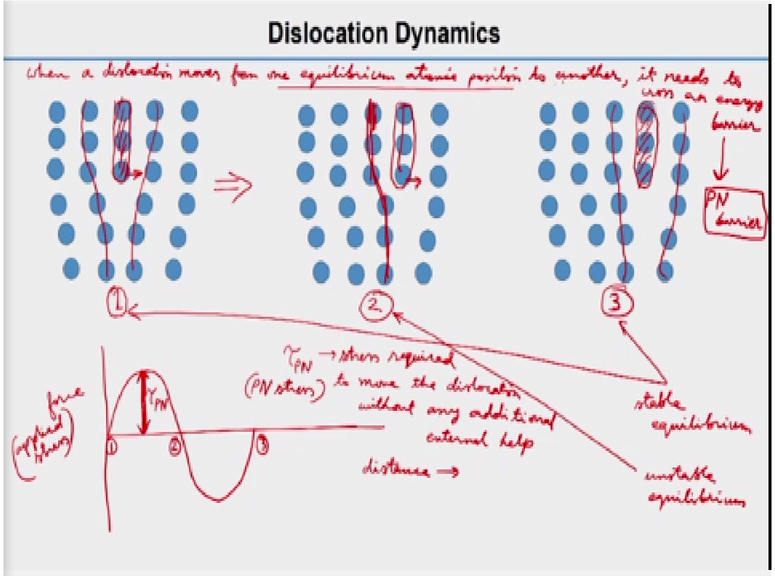

Dislocation Dynamics

when a dislocation moves from one equilibrium atomic position to another, it needs to cross an energy barrier → PN barrier

τ_{PN} → stress required (PN stress) to move the dislocation without any additional external help

So we will see what is that Pulse Nabarro stress, so to see the Pulse Nabarro stress, so we need to understand that when the dislocation I will write somewhere here , I hope it is clear when 1 dislocation moves from 1 equilibrium atomic position to another. So it needs to cross an energy barrier and that is called Pulse Nabarro barrier, it is Pulse Nabarro stress the dislocation need to overcome, and that is called Pulse Nabarro barrier.

So what is happening here is let us say this is the extra half plane in this case and then after some time, so what will happened dislocation wants to go move towards right. So what will happen after some time the extra half plane will move to this distance. But if you can see that, if you see the configuration, so it is not totally shifted to these position. In here you can see that from the this is we can call is a position equilibrium position 1 and then this is position 2 and this is position 3.

So the number 1 and number 3, number 1 I will write like this number 1 and number 3 they are equilibrium position and they are stable, these are stable equilibrium. But if you see the number 2 this little different, this is unstable equilibrium. So why it is unstable equilibrium because if you see this if you consider all these planes like, this plane or this plane, so they are not at a stable position.

Here if you see in a number 1 case, so these extra half plane is in between these 2 rows of atoms and even in if you go to the third case also this extra half plane is in between these 2 rows of atoms. But in this case it is unstable, so this wants to go on the right side and then what happens these atom rows of atoms wants to align with this one.

So that is why it is not a stable equilibrium, so what happen is that we what will happen to the force which respect to distance. So we want to plot it now, so the applied force or you can write like even applied stress in terms of applied stress. So and if you plot distance on x axis or (()) (29:06), so what happen is this will look something like this. So position 1 position 3 will be here position 2 will be here.

So as you know the force versus distance will give you energy what will happened is the force required to move the dislocation will be tau PN, so that is the stress required. So I would write here so tau PN will be the stress required to move the dislocation, dislocation means dislocation on the above figure, dislocation without any additional help**.**

And also means that there are no interaction from other dislocations or other defects without any external help is called a PN stress that is a PN or Pulse Nabarro stress. So you can see here that is the barrier, that means it needs to have that much of force to cross the barrier and so that from position 1 to position 3 it can move from one stable atomic position . So where I wrote here that 1 equilibrium atomic positions to another, so what happens when the dislocation moves on a slip plane.

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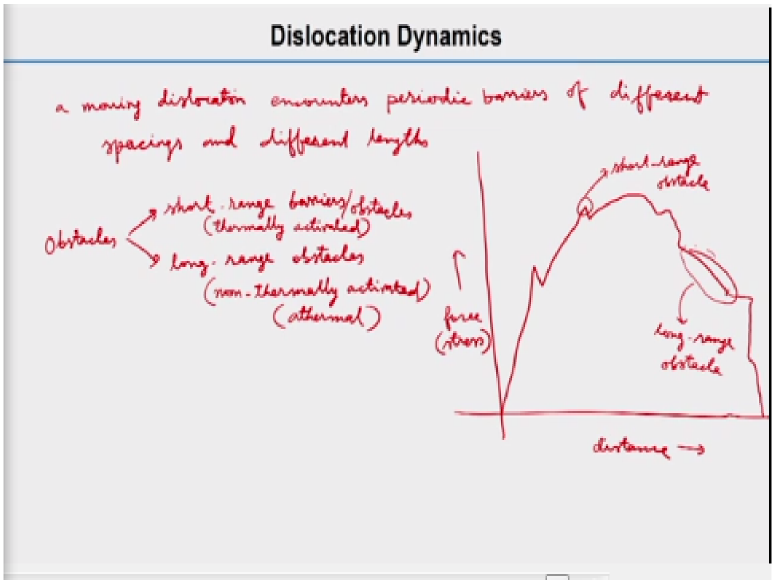

Dislocation Dynamics

a moving dislocation encounters periodic barriers of different spacings and different lengths

Obstacles → short-range barriers/obstacles (thermally activated)

Obstacles → long-range obstacles (non-thermally activated) (athermal)

As we discussed that there are other defects but there are several dislocations also will influence the movement of dislocation. Suppose this is a slip plane on which the dislocation move, so we call it as a primary slip plane there are some secondary slip planes also. We do not need to discuss much about it but let us say there is a dislocation line. So this is dislocation line or we will simply call it dislocation and dislocation is moving towards this direction.

And then there can be some dislocations, so these dislocations I will tell what these dislocations are, these are called forest dislocations. And these dislocations are perpendicular to the plane of this slip plane. So you have the slip planes sorry this is dislocation line, so you have this slip plane, I am trying to take it in the line. And so and then so what direction the dislocation is moving is the slip direction.

So and these dislocations are the forest dislocations are perpendicular to the plane of the paper whereas there is other dislocations. This lines as I told you earlier this dislocation may not be a straight line, so it can be like a Maggi noodles. So what happen is like these dislocation now which is on the slip plane, so this dislocation is moving and I will write just moving dislocation here and this is on the slip plane.

And these are not on the slip plane that means it is crossing the slip plane at some points. So what will happen now, so this dislocation will fails from you know will need to overcome these forest dislocations. So the forest dislocations are the barrier here or obstacle here for the moving dislocation barrier for moving dislocation. A moving dislocation encounters periodic barriers of different spacings and different lengths.

So there can be 2 types of barriers, so there are different types of obstacles or barriers. So first we can classify them as short range barriers or obstacles and then another one is long range obstacles. If you plot them force or stress is applied, if you plot them with distance it will look something like this. So there can be a short range obstacle and then long range obstacle will look something like this portion has a long range obstacle.

So important to note that the short range obstacle which are smaller and narrower barrier, that can be thermally activated with the help of thermal energy, dislocation can cross these barriers. And the other barriers, long range barriers are it is called non thermally activated or it is called as attermal barrier. So yeah, so I think we will discuss more on this in the next lectures.

So we will continue this discussion John dislocation dynamics and we will discuss more about different mechanisms of dislocation movement. So we are here discussing the thermally activated the mechanism and the other mechanisms we will discuss in the next lecture, thank you.