Dynamic Behaviour of Materials
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Lecture-36
Plastic Deformation at High Strain Rates 3

Hello everyone, so we are discussing about the dislocation dynamics at high strain rate, so how the plastic deformation happens, how the dislocation moves at high strain rate, so we are discussing about that. So in the last lecture we were discussing the thermally activated deformation mechanisms of thermally activated dislocation motion.

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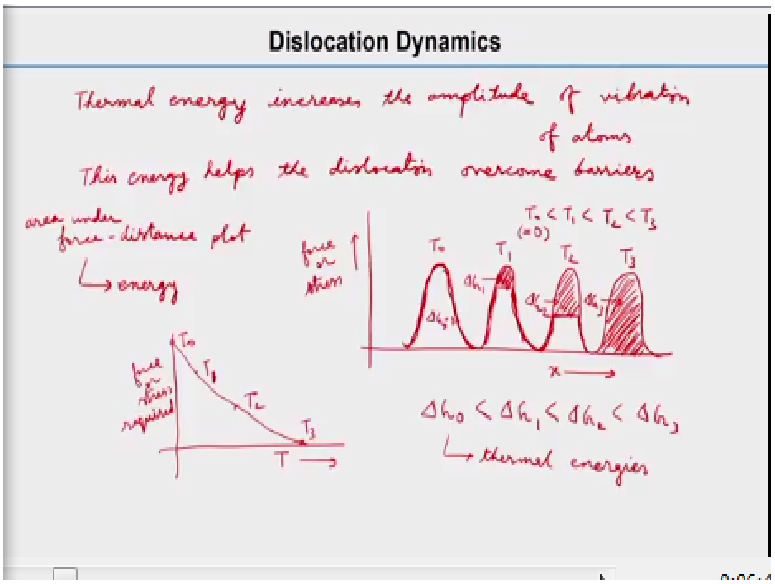

Dislocation Dynamics

Thermal energy increases the amplitude of vibration of atoms

This energy helps the dislocation overcome barriers

area under force-distance plot → energy

$T_0 < T_1 < T_2 < T_3$ $(=0)$

$\Delta h_0 < \Delta h_1 < \Delta h_2 < \Delta h_3$ → thermal energies

So the thermal energy increases the amplitude of vibration of atoms as we have discussed even earlier the atoms are vibrates continuously. So this thermal energy can increase that amplitude of vibration. So this energy can help the dislocation to overcome the obstacles or the barriers. So we will see just by plotting this, so in this in the x axis we have X that is distance and then in the y axis we have force or stress.

So what happen is suppose if we talked about a different temperatures let us say we are talking these plots at different temperatures t1, T0, T1, T2, T3 and here let us say T1, T2 and T3, so T3 is the highest temperature and T0 is let us assume this is equal to 0. So now what will happen is this force versus distance plot. The area under this plot area and the false displacement plot it represents energy, we need to have these much of energy.

The area under let us say you know one part of this first part, so that is the energy required to overcome across an obstacle or barrier. We will write the energy the thermal energy as this thermal energy which are as you know in the same order as that temperature, so these are thermal energy**.** So here the thermal energy in the first plot will be equal to 0 and in the second plot the thermal energy this part is the thermal energy delta G1, here actually G0 yeah.

Then again this one is delta G subscript 2 and here delta G subscript 3, so that means in the first case so the dislocation to overcome the barrier, it needs high energy the entire energy which is like a blank portion blank area under this curve force distance curve. And in the second case we can see that the blank portion, so in this region blank means not the hats portion.

So that will represent the energy required and in the third case the energy required would be this portion. So hats portion is the thermal energy, so the total energy required - the thermal energy will give us the energy required to overcome the dislocation. In the third case you can see that the thermal energy so high that we do not need extra energy to overcome the dislocation.

So we can plot this in another plot that is we can have temperature and the x axis and force or stress required for the dislocation to overcome an obstacle, it will decrease like this, it will decrease. So if you take let us say T0 here T1, T2 and T3, T3 we do not need extra energy the thermal energy will only work.

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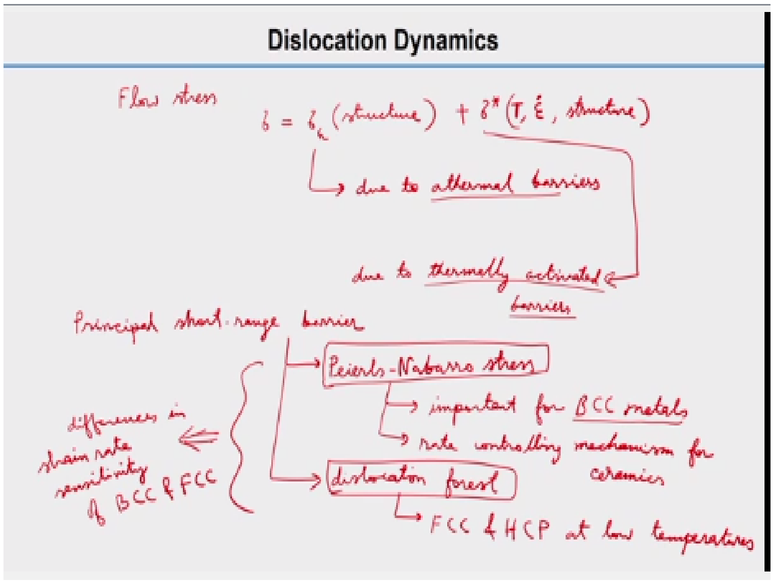

Dislocation Dynamics

Flow stress

$\sigma = \sigma_G(\text{structure}) + \sigma^*(T, \dot{\varepsilon}, \text{structure})$

→ due to athermal barriers

due to thermally activated barriers

Principal short-range barrier

→ Peierls-Nabarro stress

→ important for BCC metals

→ rate controlling mechanism for ceramics

→ dislocation forest

→ FCC & HCP at low temperatures

differences in strain rate sensitivity of BCC & FCC ⇐

The flow stress we can express the flow stress sigma equal to sigma G which is due to attermal barriers that is the function of structure**.** And then another contribution is from thermally activated barriers, so this is change it structure sorry. So what it means is the sigma G is due to the stress required due to attermal barriers. And the other one sigma star is due to thermally activated barriers, so these are the stresses required to overcome the barrier.

So as you can see that what we discussed now is thermally activated barriers the stress required to overcome the thermally activated barriers. And then you can see that it depends on temperatures, strain rate and structure. So it depends on the strain rate as well. So we did not discuss that much, but temperature we have just discussed. And the other part the flow stress due attermal barriers that does not depend on as you can understand on temperature or strain rate, that is depend on only on the structure.

So the principle short range barrier is we know that the pulse Nabarro stress that is the main one pulse Nabarro stress, this is very important for BCC metals body centered cubic. And then also this pulse Nabarro stress is important for ceramics is the rate controlling mechanism for ceramics. However for FCC and ACP metals the primary short range barrier is the dislocation forest.

So for these BCC metals the principle short range barrier is pulse Nabarro stress. And for FCC it is dislocation forest, a forest dislocation we discussed about that, so dislocation forest and that is important for FCC and hexagonal close pack. Basically at low temperatures, that is important low temperatures, so this different nature of these barriers, so the barrier is pulsed Nabarro stress for BCC metals and dislocation forests for FCC and HCP, that is very important.

So that is why because of this we are getting that differences in strain rate sensitivity of BCC and FCC. So as we know that the BCC metals have higher strain rate sensitivity, so that is because of the pulse Nabarro stress.

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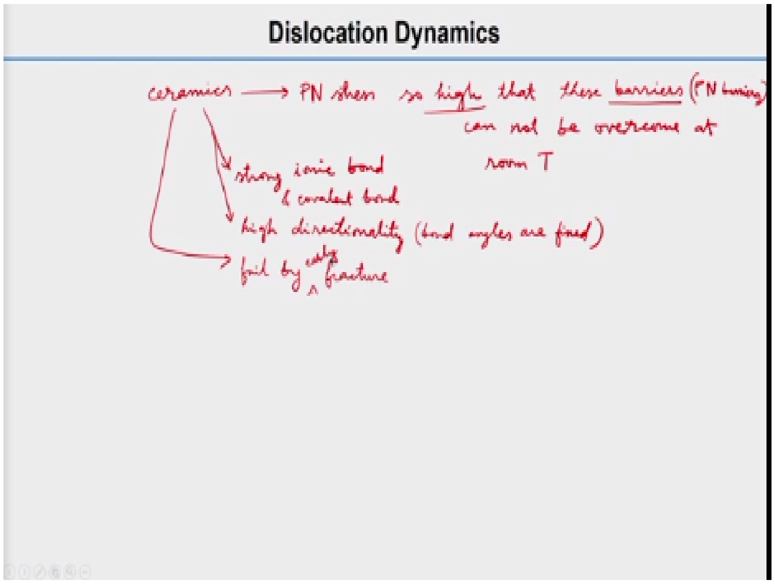

Dislocation Dynamics

ceramics → PN stress so high that these barriers (PN barriers) can not be overcome at room T

→ strong ionic bond & covalent bond

→ high directionality (bond angles are fixed)

→ fail by early fracture

So for ceramics just I want to mention it because we do not discuss about ceramics much in this course. So just to mention that with the PN state the pulse Nabarro stress is very very high, so pulse Nabarro stress is so high that these barriers cannot be overcome at room temperatures, so these barriers cannot be overcome at room temperatures room T, T means temperature.

So barriers here means PN barriers pulse Nabarro barriers, we are talking about. So and the it is because it is ceramic has strong ionic bond and even the covalent bond it has also strong, strong ionic and covalent bonds. And also it has high directionality of the bonds, high directionality means that the angles are fixed by electronic structures sorry the bond angles, so bond angles are fixed, so because of the ionic structure.

So because of that the PN stress is very high, so that is why as you know that the ceramic fail by different mechanism and that is by fracture crack nucleation and growth or we can write the fail by early fracture without any plastic deformation.

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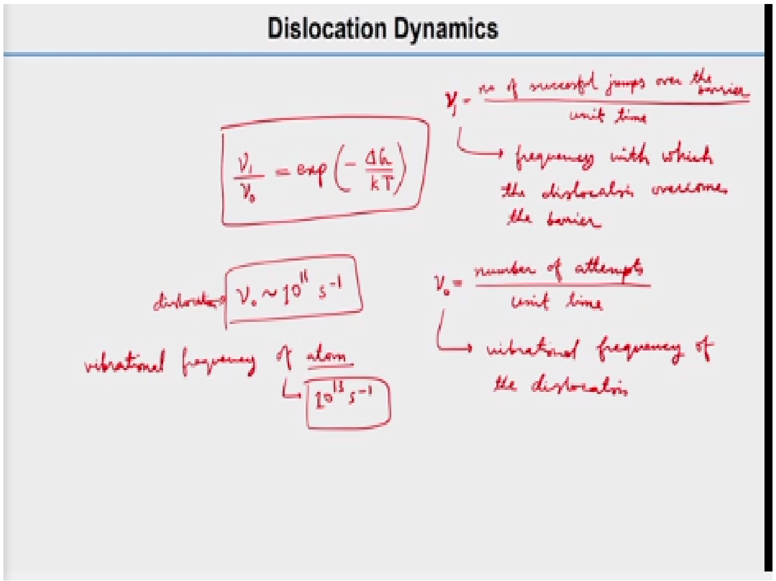

Dislocation Dynamics

$$\boxed{\frac{\nu_1}{\nu_0} = \exp\left(-\frac{\Delta G}{kT}\right)}$$

$\nu_1 = \frac{\text{no of successful jumps over the barrier}}{\text{unit time}}$

→ frequency with which the dislocation overcome the barrier

$\nu_0 = \frac{\text{number of attempts}}{\text{unit time}}$

→ vibrational frequency of the dislocation

dislocation → $\boxed{\nu_0 \sim 10^{11}\ s^{-1}}$

vibrational frequency of atom → $\boxed{10^{13}\ s^{-1}}$

So we are not discussing each and everything whatever discussed in the book Mark Mayer's. So if you want to know about the details please follow the book Mark Mayer, so only the important topics we are covering and some of them are as we have very less time. We are just giving the glimpse or you know just to show you that these some relationship or these you know we can see from this point of view.

So please go through the book for detailed analysis, so we will now see the probability that a dislocation can jump or dislocation can overcome a barrier, there is a mathematical relationship. So we want to show this is nu subscript 1 by nu subscript 0 which will be equal to exponential - delta G KT. So delta G is the free activation energy and T the temperature and K the Boltzmann constant.

So we would like to know what is nu 1, so that is basically the number of successful jumps over the barrier divided by per unit time. So that means it is a frequency, so this is the frequency with which the dislocation overcomes the barrier. And then nu 0 is another frequency, so what is that the total number of attempts the dislocation makes to jump the barrier per unit time.

So that is nothing but the vibrational frequency of the dislocation, so this nu 0 is about the order of 10 to the power 11 per second this frequency. So this you can see that the frequency of that we know that frequency of atomic vibration or we would right vibrational frequency of atom is 10 to the power 13 per second. So it is 100 times less, so this is a for dislocation, so you can see that dislocation vibrational frequency is 100 times less and this is for atom.

So now as you can understand here that whatever rate it will jump, so dislocation will have a vibrational frequency it will jumped let us say 10 to the power 11 per second. But not every jump will be successful, so how many jumps per unit time are successful that is the nu 1, the first term nu 1. So that is one important expression, so we are not going to details about this or any derivation or we are not going to do that. But just for your knowledge or information, so we have discussed that.

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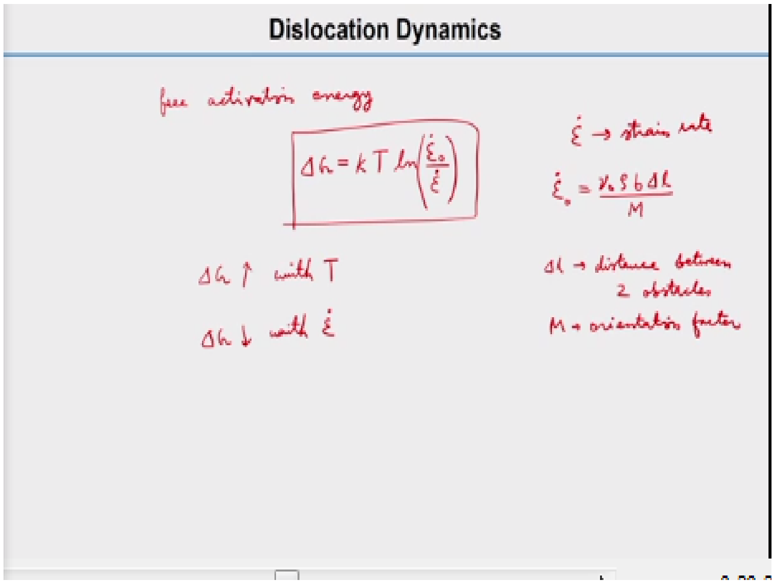

Dislocation Dynamics

free activation energy

$$\boxed{\Delta G = kT \ln\left(\frac{\dot{\varepsilon}_0}{\dot{\varepsilon}}\right)}$$

$\dot{\varepsilon} \rightarrow$ strain rate

$\dot{\varepsilon}_0 = \frac{\nu_0 \rho b \Delta l}{M}$

$\Delta G \uparrow$ with T

$\Delta G \downarrow$ with $\dot{\varepsilon}$

$\Delta l \rightarrow$ distance between 2 obstacles

$M \rightarrow$ orientation factor

So another important relationship is the free activation energy delta G = Boltzmann constant temperature and then natural logarithm of epsilon dot epsilon 0 dot and this equal to epsilon dot. So here you know T is the temperature and so this epsilon dot is strain rate but what is the other term other symbol this is equal to this is nu 0 which is the vibrational frequency of dislocation rho is the dislocation density.

I will not write because you already know this, B is the magnitude of the burgers vector and delta l. We never encountered it delta l is the distance between 2 obstacles or barriers and M you know, M we already discussed M is the orientation factor. So this is also one important relationship for details you can study Mark Mayer's, but here what the important information you should you know have from here is delta G will increase with temperature and delta G will decrease with you know strain rate. So that is important result we can get it from this relation.

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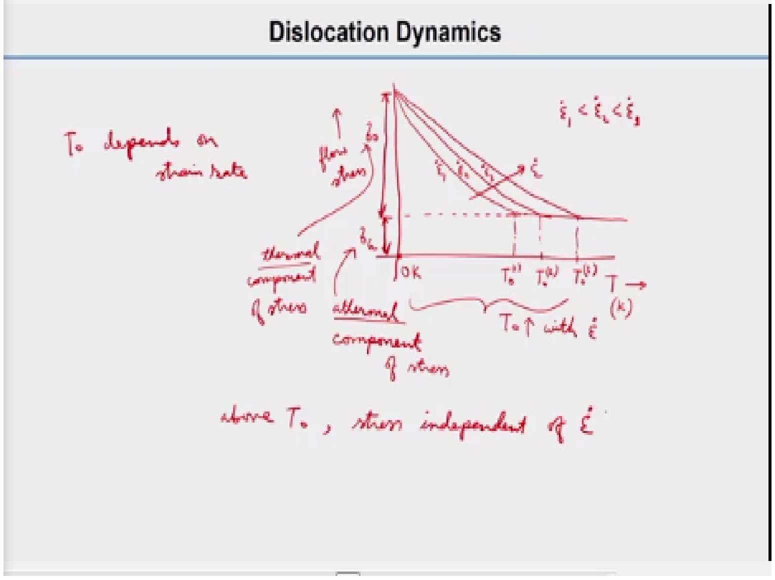

Dislocation Dynamics

T_0 depends on strain rate

above T_0, stress independent of $\dot{\varepsilon}$

So this earlier relation we can have a plot related to that, so this plot is temperature in the x axis let us say temperature in Kelvin and then we can have flow stress on the y axis flow stress. So we will see this at different strain rate, so what will happen is this is one strain rate, this is another strain rate and this is another strain rate. So let us say first one is epsilon dot 1, epsilon dot 2 and epsilon dot 3.

So here this order of the strain rates are like this, so epsilon dot 3 is the highest strain rate. So **so** here this temperatures corresponding to this is written as we can write T0 corresponding to strain rate 1, T0 corresponding to strain rate 2, T0 corresponding to strain rate 3. So this T0 depends on strain rate, so here we can see that this is actually 0 Kelvin**.**

So what happens when we increase the strain rate, so we are increasing the strain rate in this direction that you can see that for more duration for that at T0 sorry T0 is higher, the T0 will increase with epsilon dot strain rate. So it says that this part is the attermal component sigma G and this part is the attermal component of the flow stress, that is sigma 0. So this is attermal component of the flow stress, so and then other one is thermal component.

So you understood now what is thermal means with temperature the stress will decrease. But after it reaches T0 the stress will be equal above the temperature, so that is why it is called attermal component above T0. So the stress is independent of the strain rate.

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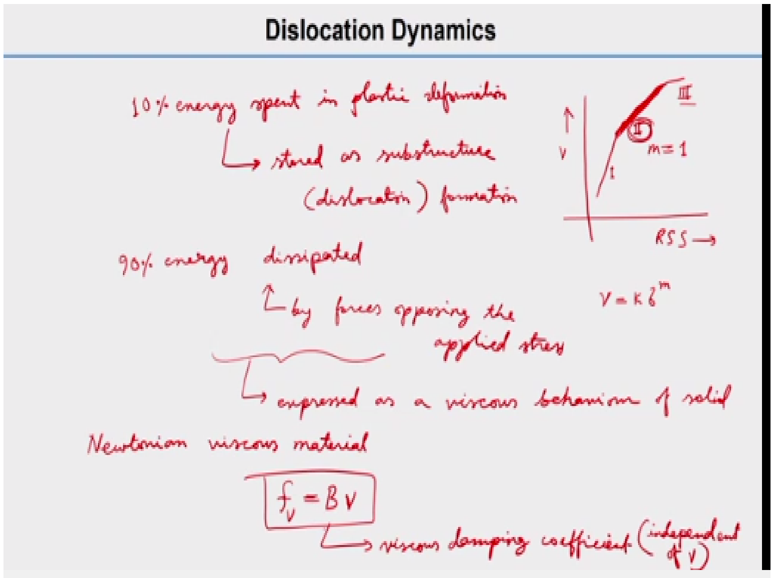

Dislocation Dynamics

10% energy spent in plastic deformation

$\hookrightarrow$ stored as substructure (dislocation) formation

90% energy dissipated

$\hookrightarrow$ by forces opposing the applied stress

$\hookrightarrow$ expressed as a viscous behaviour of solid

Newtonian viscous material

$$\boxed{f_v = B v}$$

$\hookrightarrow$ viscous damping coefficient (independent of v)

$v = k \tau^m$

So what we have discussed is thermally activated dislocation motion, now we will discussed another one. So we earlier discussed that that we have 3 different mechanisms and we have shown that there is a plot like this where we have resolve shear stress on the x axis and dislocation velocity in the y axis. And we have shown that this will look something like this and then this, so the first part, second part and the third part.

So what we have talked about it the first part is the thermally activated dislocation motion and the second part is for phonon drag or we will discuss about that the drag mechanisms in the second part now. In the third one is we mentioned this is for relativistic effects that we will discuss later. So we are now focusing on the second part, so now what is this dislocation drag**.**

We discussed that this equation the V dislocation velocity has a relationship with applied stress or resolve stresses s to the power m. In this case here the m = 1 and that is a kind of dislocation velocity, the proportional to the applied stress. So we know that only around 10% of the energy spent in plastic deformation will convert to or sorry will be stored as substructure you know like dislocations and other structures or defects formation.

So the remaining 90% it is around 90% energy will be dissipated**,** so this dissipations done by the forces opposing the applied stress. So this can be expressed or described as a viscous behavior of the solid. So that is why we can assume that Newtonian viscous model for Newtonian viscous material, so please check the details in we cannot discuss much on this course because we do not have much time.

So the force will be equal to the viscous damping coefficient that and then velocity of the dislocations. So this is the viscous damping coefficient it is called viscous damping coefficient, so this is independent of dislocation velocity V that is for a Newtonian fluid, so this is independent.

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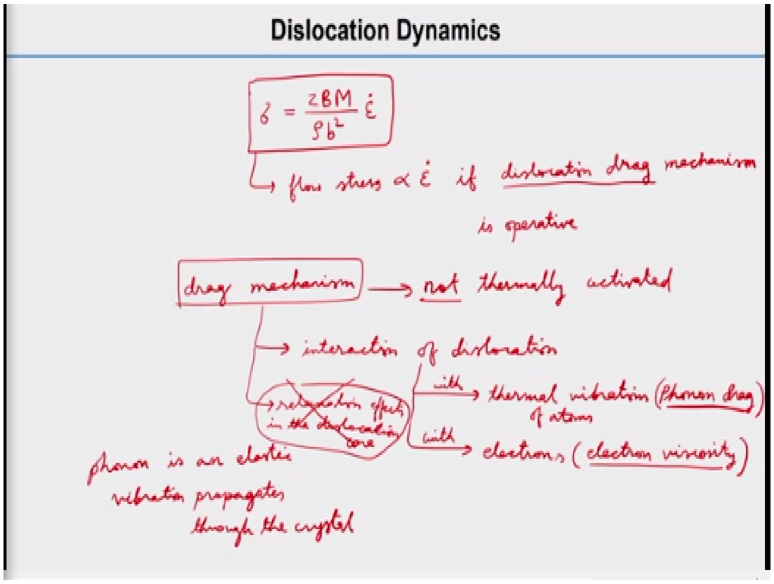

Dislocation Dynamics

$$\boxed{\sigma = \frac{2BM}{\rho b^2}\dot{\varepsilon}}$$

→ flow stress $\propto \dot{\varepsilon}$ if dislocation drag mechanism is operative

drag mechanism → not thermally activated

→ interaction of dislocation
with → thermal vibration of atoms (Phonon drag)
with → electrons (electron viscosity)

→ ~~relaxation effect in the dislocation core~~

phonon is an elastic vibration propagates through the crystal

So this relation from this relation what we can finally can arrive at some other relations which is like sigma = twice BM rho b Square multiplied by epsilon dot. So we are not going to details how we arrived at equation all the symbols you know M is the orientation factor, rho is the dislocation density, b is the magnitude of burgers vector. And capital B is the as we discussed just now the viscose damping coefficient.

So here it means the sigma the flow stress, so this means that the flow stress is proportional to the strain rate. If the dislocation drag mechanism is drag dislocation drag mechanism is operative, so what is this drag mechanism. So this drag mechanism is not thermally activated, so this is mostly the interaction of dislocations with the first one is the thermal vibrations, vibrations of atoms, so that is called as phonon drag or rather I would write of atoms so that is called phonon drag.

And also with electrons, so I should write interaction of dislocations with thermal vibration and with electrons, so that is called electron viscosity. So phonon as you know the phonon is an elastic vibration that propagates through the crystal. And the there can be these drag mechanisms can be due to another you know aspect as well, so this we will not discuss much about it.

So this is also includes relaxation effects in the dislocation core, that we will not discuss, so this we will not discuss. So by the way I did not tell you what is dislocation core I think many of you know that. So basically what we need to understand is the phonon drag and electron viscosity both are included in the drag mechanism and that is one of the mechanism of plastic deformation in metallic or crystalline material.

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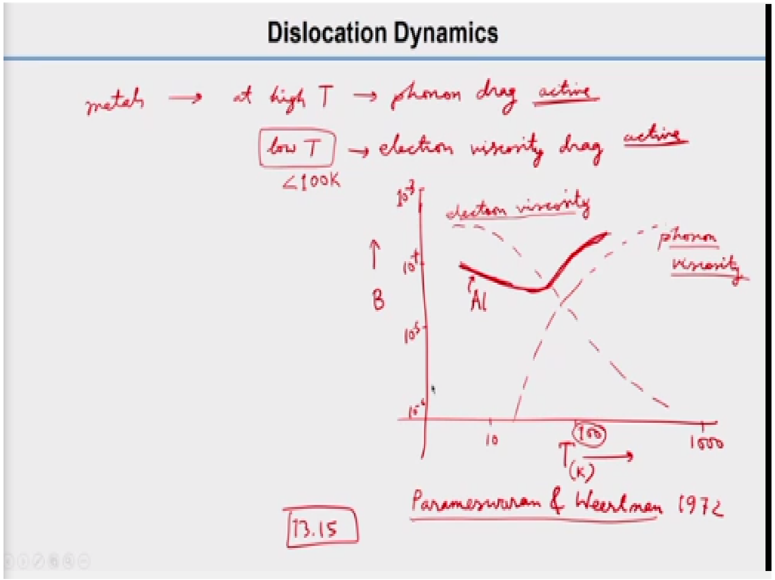

Dislocation Dynamics

metals → at high T → phonon drag active

low T → electron viscosity drag active

<100K

Parameswaran & Weertman 1972

13.15

And that you know for metals we should understand that for metals at high temperatures at high T. So phonon drag mechanism will be active and at low temperatures that electron viscosity **be** drag will be active viscosity drag, so I would write active ok, so active. So we can see with the help of a plot that is mostly from 1972 publication by Parameswaran and Weertman 1972.

So this plot is temperature this is in Kelvin and damping coefficient B is in this direction, so here is 10 to the power – 6, 10 to the power – 5, 10 to the power - 4 and 10 to the power – 3, please refer to the book. This is figure number 13.5, so sorry 13.15 in the Mark Mayer's book, so because my scales will not be appropriate here. So this is kind of these scale 100 and 1000 in a logarithmic scale we are having here.

So we will draw this, so there are 2 curves we are drawing here dashed lines, so it is something like this. So this first line is theory from the electron viscosity theory. And the second one is phonon drag or we can write even phonon viscosity or yeah simply we can write phonon viscosity drag. So you can see that you know above 100 Kelvin which is a low temperature.

So at low temperatures the as I told that at very low temperature that means below 100 Kelvin you can write below 100 Kelvin. The electron viscosity is drag is active and the phonon drag at higher temperatures it is active. So now what they found out that the Parameswaran Weertman, so they plotted for aluminum. So they plotted for aluminum the results are coming out something like this.

So the dashed lines are from the theory and their experiments you know their experiments gave this is for aluminum. So you can see that how whatever we just mentioned is very much correct. Because at a lower temperatures it is showing similar to the electron viscosity trend and at higher temperatures it is showing the phonon viscosity kind of trend.

So this is whatever we just mentioned is it is verified by the Parameswaran and Weertman experiment. So we have discussed about dislocation dynamics what we discussed is thermally activated dislocation motion mechanism. And also we have discussed about the dislocation drag mechanisms which includes phonon drag and electron viscosity drag.

So with that we are closing today, and in the next lecture we will discuss the third mechanism of dislocation motion. That is relativistic motion mechanism of dislocation and so that is all for today, thank you.