Creep Deformation of Materials
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Basics of plastic deformation and characteristics of dislocations

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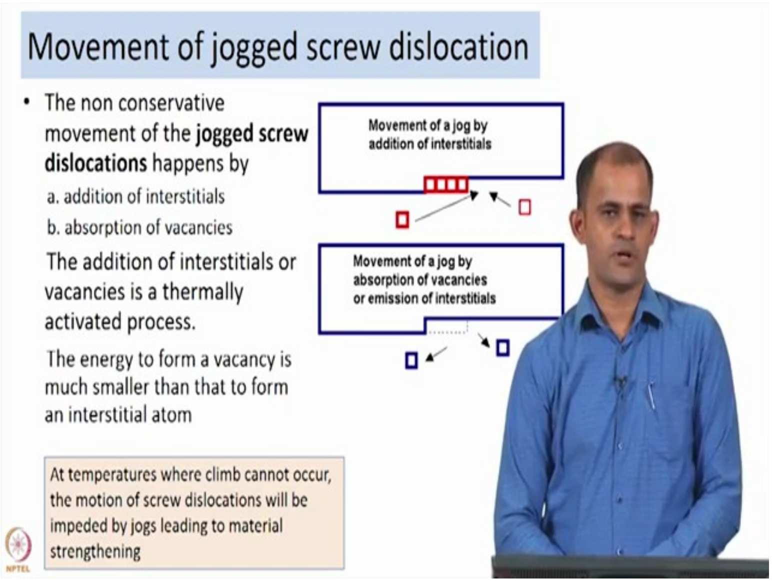

So we were talking about the behavior of jogged screw dislocations, we were talking about how jogged screw dislocations move by either the addition of interstitials or the absorption of vacancies to the dislocation core region and the jogged screw dislocation is a non-conservative motion of dislocation, so with this knowledge we will go on to the next set of slides which is about some characteristics of dislocations.

So we are going to talk about the kind of forces that exist between dislocations, the energy of a dislocation and the strain rate of deformation produced by the motion of a dislocation and things like that, again this is all important because it will help us in understanding in depth creep behavior of a material because like I mentioned the beginning creep behavior involves the motion of defects and dislocation is an important defect that contributes towards plastic deformation or creep deformation.

Characteristics of dislocations, so what are the different characteristics, we already spoke about the nature of dislocations, the type of dislocations such as screw dislocations, the motion of dislocations for example edge dislocations move by climb, screw dislocations move by cross slip and temperature has a role to play, stress also has a role to play in how the dislocations behave.

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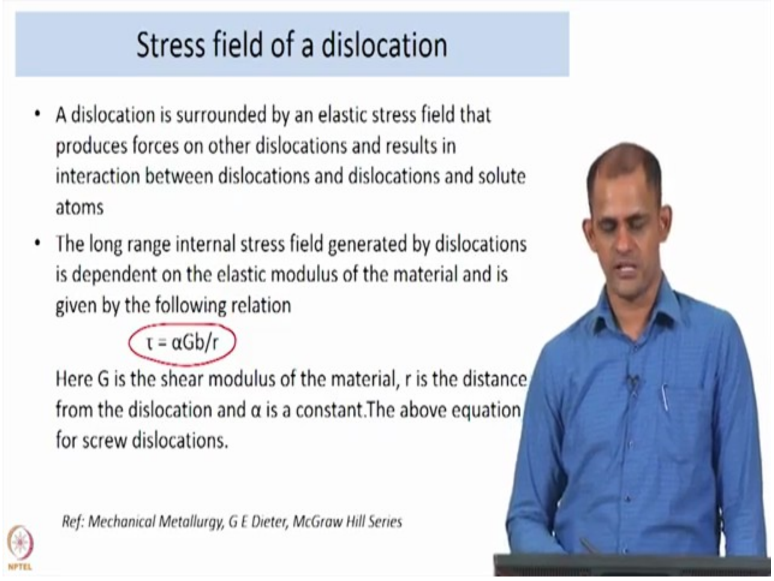

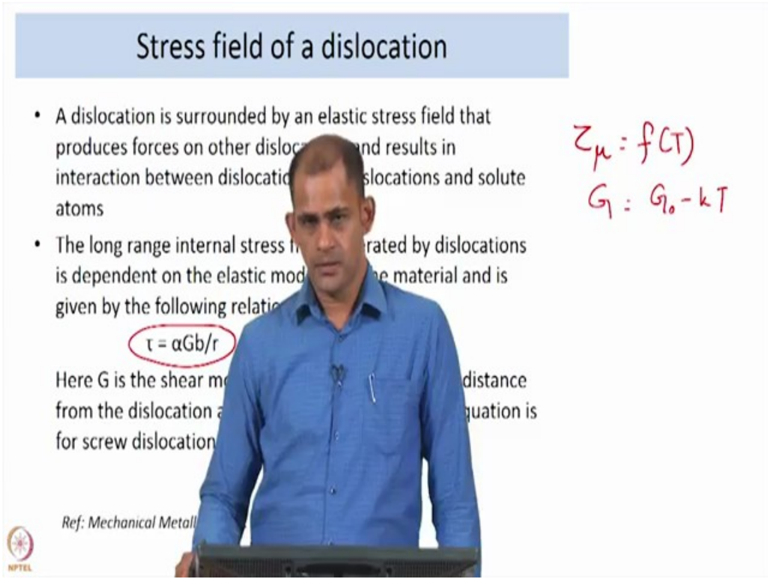

Now talking of characteristics of dislocations, one of the first things is about stress field of a dislocation, so the edge dislocation is basically an extra half plane of atoms and because it is disturbing the area around it so if you understand a crystal, a crystal is basically a periodic arrangement of atoms in 3 directions in the 3 dimensions so a periodic arrangement of atoms is what a crystalline material is and whenever you introduce an extra half plane of atoms you are basically introducing disorder and because of the disorder there is a stress field that is generated around the disorder.

So since the dislocation is bringing about the disorder, so a dislocation is surrounded by an elastic stress field that produces forces on other dislocations and also results in interaction between dislocations and between dislocations and dislocations and solute atoms, so what I am trying to say here is the stress field that a dislocation produces or carries around itself leads to interaction with other dislocations and it is the same stress field that also helps dislocations interact with solute atoms.

So the interaction between dislocations and solute atoms we discussed about it in detail in the slide on dislocation point defects interaction, so we were talking about how point defects such as vacancies or interstitial atoms interact with dislocations. So let us talk about the stress field that a dislocation is surrounded by, so the long range internal stress field generated by dislocations is dependent on the elastic modulus of the material and is given by the following relation.

So what I am trying to say here is the dislocation produces a stress field and this stress field is the reason for the existence of an internal stress field so we were talking about athermal component of stress, internal stress as well as thermal component of internal stress, so the athermal component of internal stress is a result of the stress field generated by the dislocations and this stress field is given by this following relation.

So here G is the shear modulus of the material and r is the distance from the dislocation and alpha is the constant, so this equation is applicable for screw dislocations, the equation for edge dislocation is a little more complicated so I am not covering it here but for the sake of interest, the audience can refer to Mechanical Metallurgy by George E Dieter and where he has discussed in more detail the stress field around an edge dislocation.

But the important point here is whether it has screw dislocation or an edge dislocation the stress field is dependent on the shear modulus of the material, so what is the significance of this? Well, the significance is that the stress field or the athermal component of the internal stress is dependent on the shear modulus and when you are trying to determine the athermal component of the internal stress field it is important to understand that as a function of temperature the shear modulus is going to change.

So if you are looking at tau mu as a function of temperature you will have to account for the fact that G decreases as the temperature increases, so G is approximately given by that relation and so as the temperature increases there is a change in G which means if you are going to evaluate the athermal stress component you will have to account for the change in G, what this also tells us is as a function of temperature the dislocation arrangements might change.

And the change in dislocation arrangements and configuration is something I am going to talk in subsequent slides and it also means that when you are evaluating this internal stress field or athermal component of the internal stress field will have to account for the fact that the dislocation sub structure or the dislocation configuration should not have changed.

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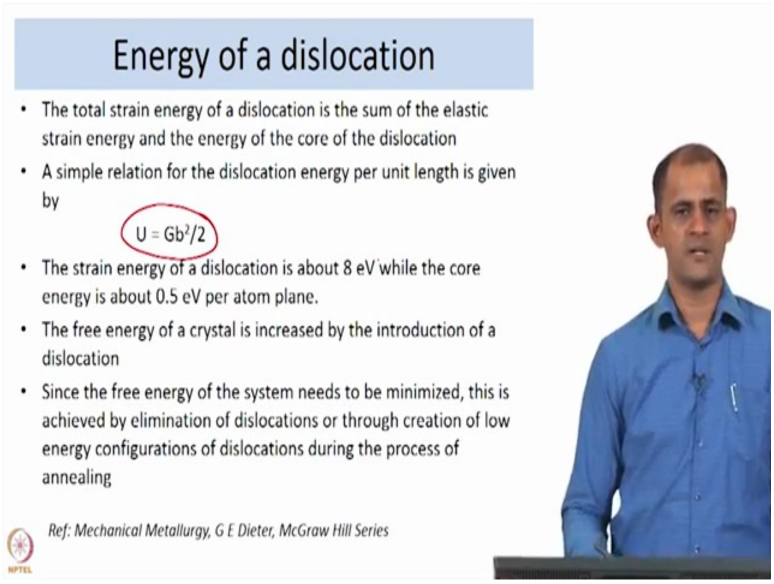

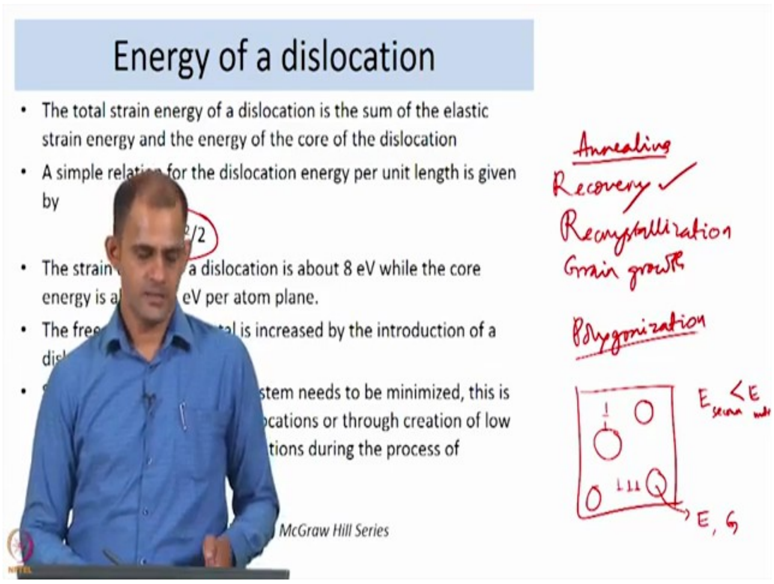

So the energy of a dislocation so we are talking about how temperature can play role on changing of the dislocation configuration and something the temperature has a role, the role of temperature can be understood by discussing the energy of a dislocation.

So there is a stress field around a dislocation and the strain associated with this stress field results in the development of a strain energy so the total strain energy of a dislocation is the sum of the elastic strain energy and the energy of the core of the dislocation, so this energy is basically discussed in terms of energy per unit length and it is given by the following relationship.

Again this relationship shows that the energy, the strain energy of the dislocation is dependent on the shear modulus of the material as well as the Burgers vector b of the material, it has been found out that the strain energy of a dislocation is around 8 electron Volts and whereas the energy of the core of the dislocation is about 0.5 so the total energy of the dislocation will be around 8.5 electron Volts per atom plane.

So which means, so if that is the energy of a dislocation this means when you introduce a dislocation into a crystal you are essentially increasing the free energy of the crystal, in nature all systems try to minimize their free energy so which means as you introduce more and more dislocations you are basically driving away from stability or you are driving away from equilibrium.

So which means if there is a driving force provided, the system would like to come back to its equilibrium state and this is what happens during the process of annealing, so in order to reduce the free energy of the system dislocation start getting eliminated the dislocations get eliminated by moving from the interior of the crystal to the surface or by annihilating each other, so if you have an edge dislocation, positive edge dislocation, if you have a edge dislocation of one type versus the edge dislocation of other type they may annihilate each other and things like that.

So that can lead to the removal of dislocations or reduction of dislocations in the system or since dislocations tend to arrange themselves in certain configurations so during the process of annealing the dislocations may choose to create a low energy configuration so they may try to develop a new network or a certain type of network or arrangement of dislocations which will have a lower energy contribution.

So that is the effect of annealing, so annealing is basically a high temperature process and annealing can lead to different things within a material, one of them is recovery, it also could lead to re-crystallization of the material or lead to grain growth within material. Now among the three things that is recovery, so recovery is something that leads to creation of low energy configurations.

There is a term called polygonization which leads to the creation of low energy arrangements of dislocations leading to the formation of sub grains within a given grain, so as a concept, so polygonization is a result of recovery and we are going to talk a little bit about recovery and polygonization etc. in the subsequent lecture because this has an importance towards understanding the creep behavior of materials.

So the bottom line here is dislocation there is always an energy associated with a dislocation which is dependent on the shear modulus and the system would like to reduce the energy associated or brought about by the presence of dislocations and the system can do that by during annealing which is basically high temperature process so since the energy of the dislocation is dependent on the elastic modulus or the shear modulus, this concept will help you in understanding why when you have a second phase with higher elastic modulus the dislocation would generally get repelled by the presence of that second phase.

That is because for the dislocation when it is moving in its matrix so assume you have a composite material and this is a second phase and then the dislocation, here let me describe it as an edge dislocation, so assume some edge dislocations moving towards the second phase and if the second phase has a higher elastic modulus and then the dislocation, E or G, the dislocation would rather prefer not to move into that second phase that is because it is going to have a higher energy once it moves into a second phase with a higher elastic modulus.

So what this tells us is that when you have second phases of that type then the material will have a higher strength, similarly if the second phase has a lower elastic modulus than the matrix, if the second phase has lower elastic modulus than the matric then the dislocations would rather be happy moving into the second phase because they will have a lower energy state in the second phase in which case the material is going to be lower in strength compared to the matrix. So this is the importance of the understanding the concept of energy of a dislocation.

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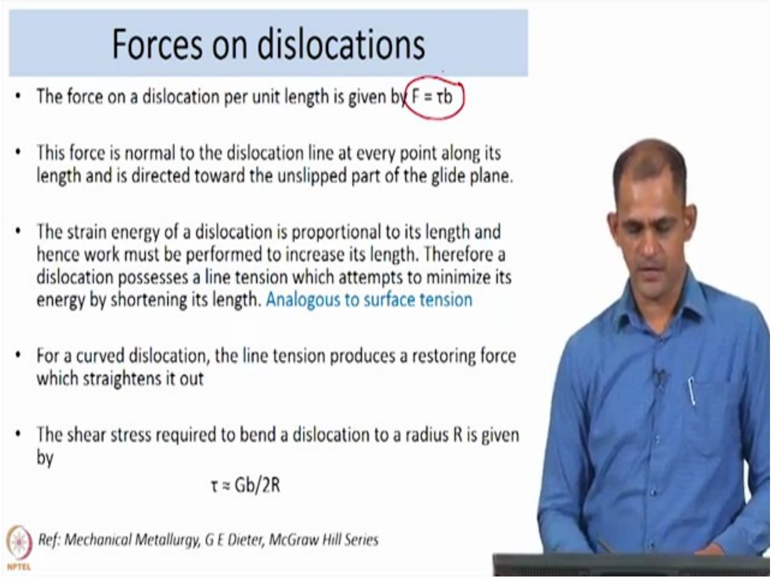

Now the next slide is about forces on dislocations so I already mentioned that there is a stress field that exist around a dislocation and if when you talk about several dislocations in the material the stress field of one dislocation maybe positive versus another dislocation which may be a negative, one analogy that can be drawn is to that of charges, electrical charges, a positive electric charge versus a negative electric charge will have opposite electric fields of opposite sign and that is why there will be attraction towards each other.

So similar concept can be applied here, forces on dislocations are brought about by the stress field but the first thing to talk about is the force on a dislocation per unit length is given by the following relation F is equal to tau b and this force is normal to the dislocation line at every point along its length and its directed towards the unslipped part of the glide plane.

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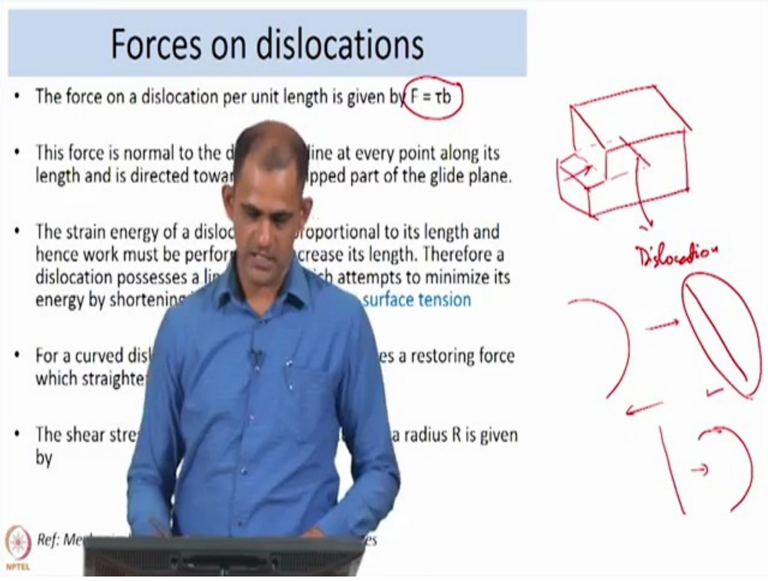

So if this is your dislocation line, so if this is the force acting on dislocation is directed towards the unslipped part of the glide plane, so this is the dislocation here, so the force on a dislocation per unit length is given by the relation F is equal to tau b now the strain energy of a dislocation is proportional to its length and hence work must be performed to increase its length.

So we talked about strain energy of a dislocation and an important point is that the strain energy of the dislocation is proportional to its length and hence work must be performed to increase the length of the dislocation which means therefore a dislocation possesses a line tension which attempts to minimize its energy by shortening its length. So since the strain energy is dependent on the length so the dislocation would not want its length to be increased which means there will always be a resistive force to the increase of a dislocation and this resistive force is basically a line tension and in terms of concept this is very similar to that of surface tension.

So we know a system always tries to reduce its surface energy and the reduction of surface energy is brought about by the presence of a surface tension so the same concept works here so the dislocation wants to reduce its length and minimize its energy and the process, so for a curved dislocation, so a curved dislocation like that would actually prefer to be like that, so for a curved dislocation the line tension produces a restoring force which straightens it out and which means if you want to produce a curved dislocation of a certain radius.

So you will have to apply a stress if you want to go from a straight dislocation to a curved dislocation and the shear stress required to bend a dislocation to a radius r, so if this curved dislocation has a radius of curvature r then the shear stress required to bend the dislocation is given by this following relation.

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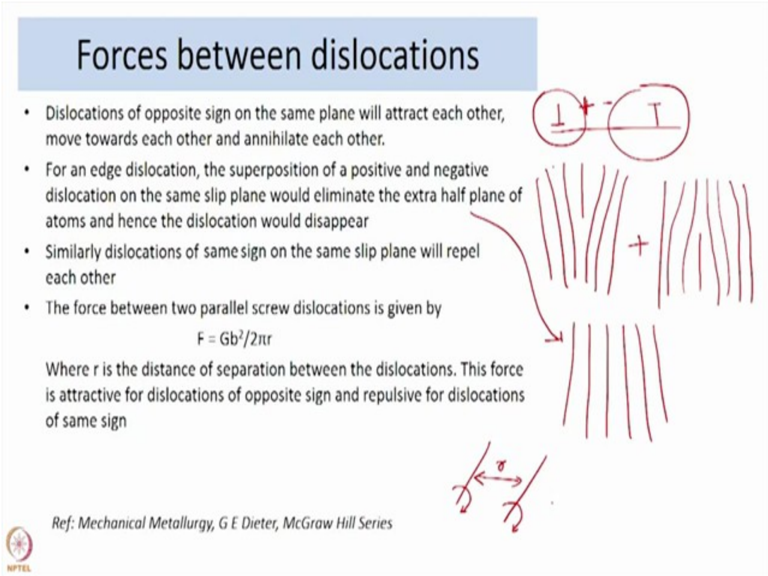

So that was force on a dislocation and forces between dislocation so these forces between dislocations comes about because of the stress field that exists around a dislocation so dislocations of opposite sign on the same plane will attract each other move towards each other and annihilate each other so if see this is a slip plane and you have a dislocation, edge dislocation of that type versus an edge dislocation of that type.

So these are dislocations of opposite nature so the stress field created by this dislocation will have a different sign, so let us assume this is plus and this is minus so the stress field created by this dislocations are opposite in nature and which means they will be an attractive force so a positive and a negative edge dislocation would like to move towards each other and annihilate each other which also makes sense from the fact that the dislocation is basically an extra half plane of atoms which is introducing this order.

So if you have another dislocation of opposite type so then there will be attraction between these two dislocations because that will help in removal of the disorder that was present within the material and basically that helps in reducing the free energy of the system, so for an edge dislocation the super position of a positive and negative dislocation on the same slip plane would eliminate the extra half plane of atom so this is the elimination of the extra half plane of atoms and hence the dislocation would disappear.

Dislocations of same sign on the same slip plane will repel each other, so dislocations of opposite sign attract whereas dislocations of same sign on the same slip plane will repel each other and the force between two parallel screw dislocations is given by the following relation, so we are talking about repulsion between dislocations so if you look at the force between two parallel screw dislocations that would be given by the following relation Gb square by 2 π r so where r is the distance of separation between the dislocations.

So if you have two screw dislocations then the force between the dislocations is dependent on this distance r and it is basically given by the following relation, I am again here I am not covering about forces between edge dislocations, you can refer to the textbook on Mechanical Metallurgy by George E Dieter, again the important point for me here is to tell you how the forces between dislocations depend on the distance between the dislocations and how positive and negative dislocations will attract and whereas two positive dislocations will repel each other.

So that was about forces between dislocations, so now this was basically introducing you to some of the characteristics, so we spoke about the force acting on a dislocation, how it depends on the shear stress as well as the Burgers vector of the dislocation and we also talked about the stress field present around a dislocation and how the stress field leads to interaction forces between dislocations.

And we also talked about the energy of a dislocation and its dependence on the shear modulus and which is why the dislocation would want to and because there is an energy associated with dislocation, it increases the free energy of the system and that is why a system would want to get rid of dislocations or would want them to organize themselves in a fashion which reduces the energy penalty on the system.

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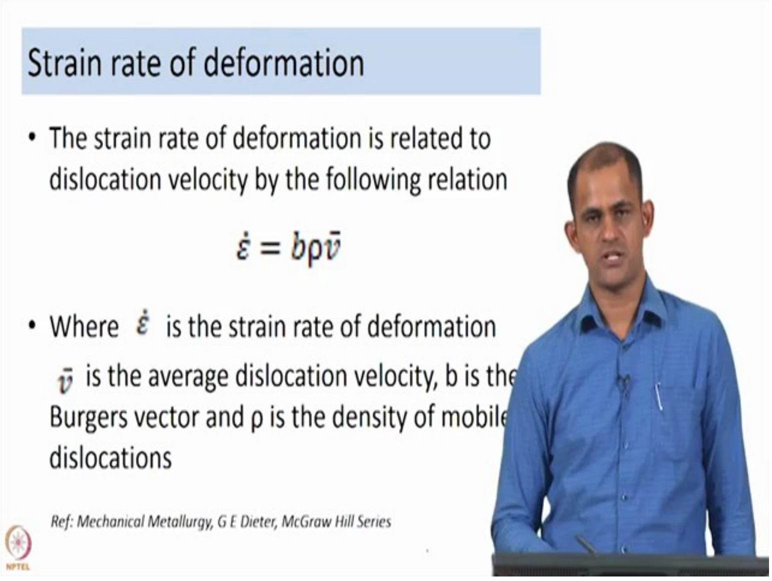

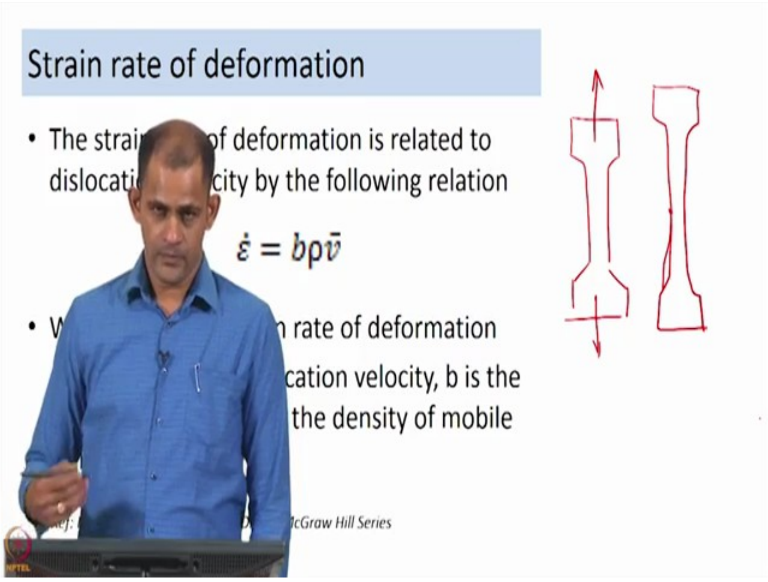

So now a couple of more concepts related to dislocations, so the first concept is about strain rate of deformation and how this depends on the velocity of the dislocation, so when you are doing any mechanical deformations, so let us say, let us take the example of a tension test, so say it is loaded on a universal testing machine and you have applied a certain crossed speed, so the material starts elongating and the process of elongation is introducing certain plastic strain to the material.

Now so the material is also deforming at a certain strain rate of deformation and the strain rate of deformation is related to the average velocity dislocation so the strain rate of deformation is given by the following relation epsilon dot is equal to b rho v bar, so v bar is the average dislocation velocity, b is the Burgers vector and rho is the density of mobile dislocations.

It is important to note this point, the density of mobile dislocations, that is because deformation is going to happen by the motion of dislocations and only those dislocations which are free to move will contribute towards the strain rate of deformation, again the purpose of introducing this slide is to tell you that this relation will be important in understanding the creep rate of deformation and so when we especially talk about power law creep and Weertmans model and etc. this relation will be helpful there.

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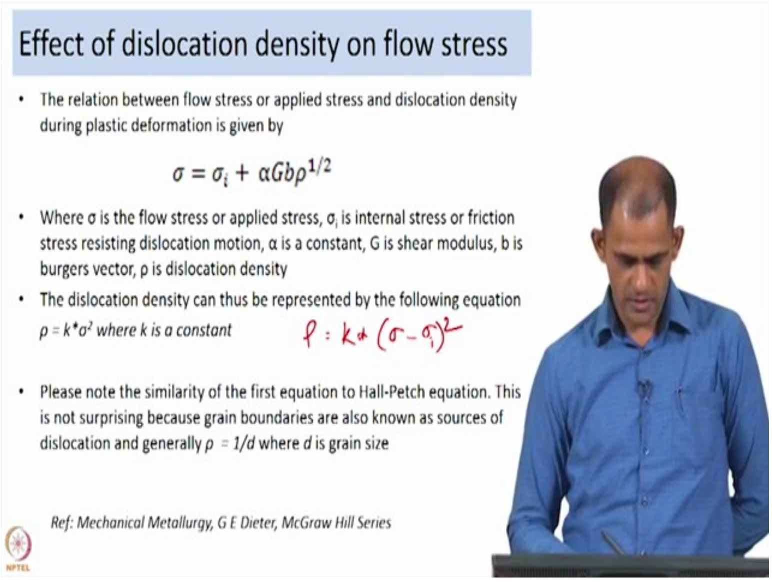

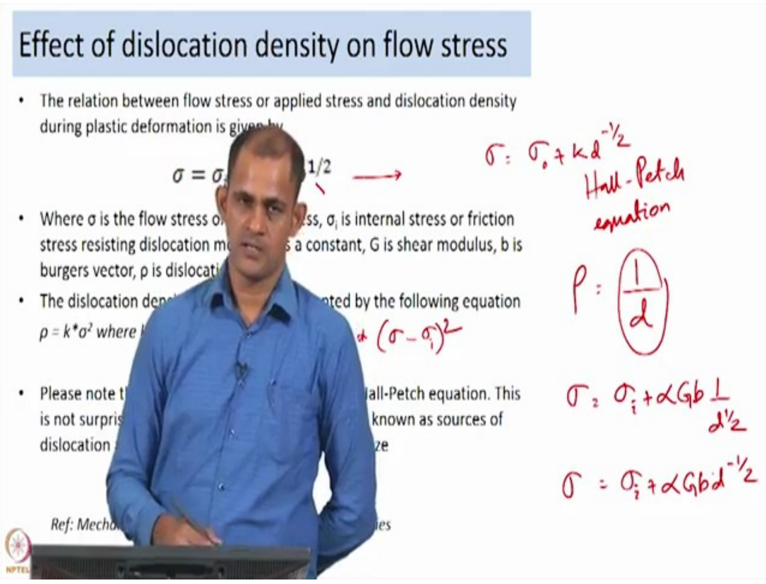

The other relation which will be of importance is the relation that exists between dislocations density and the flow stress of the material so the relation between flow stress or applied stress and dislocation density during plastic deformation is given by the following relation sigma is equal to sigma i plus alpha Gb rho half, so sigma is the flow stress or applied stress and sigma is the internal stress or friction stress resisting dislocation motion, alpha is a constant, G is the shear modulus and b is Burgers vector and rho is the dislocation density.

So basically what this relation says is if the dislocation density is high then the flow stress will also be higher, the inverse of this relation would be that the dislocation density can then be represented by the following equations, so then one can say rho is approximately a constant times sigma minus sigma i square so which means the dislocation density is dependent on the square of the applied stress.

So one of the things to note here is the similarity of the first equation of this equation to the Hall Page equation, so we know sigma is equal to sigma0 plus k d minus half, so this equation bears some similarity to the Hall Page equation and it is not surprising because grain boundaries are known as sources of dislocations and generally it is been observed that the dislocation density is inversely proportional to the grain size which means if you use this relation and substitute it in this equation then you would get sigma is equal to sigma i plus alpha Gb 1 over d half which is what, which can also be written as, so this equation converts into Hall Page equation.

Again the relation between dislocation density and applied stress is something we will use to explain power law creep and to relate strain rate of deformation to applied stress so that was the purpose of introducing this concept here. So with that I would come to end of this set of lecture, this set of slides basically, in this set of slides or in this portion of lecture I have talked about dislocation.