Creep Deformation of Materials.
Indian Institute of Technology, Madras.
Transitions in Creep Mechanisms and Creep Constitutive Equation.

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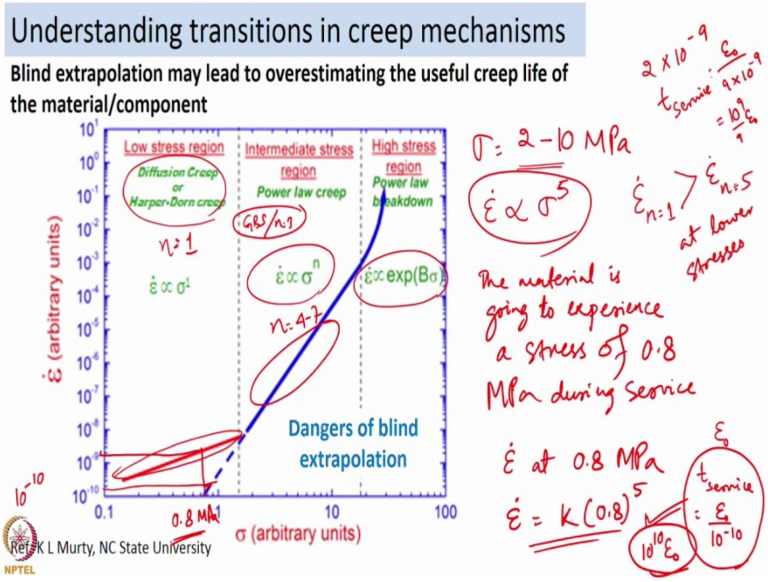

So, the next portion that we are going to talk about is transitions in deformation mechanisms. So the point is why is it important to understand the transitions in deformation mechanisms. So to explain that, I would take you to this particular slide or to this particular curve so as this particular graph is basically summarising the different types of deformation mechanism that one could expect. Of course I have ignored grain boundary sliding and viscous creep in this particular slide.

But let us talk about low stress region, intermediate stress region and high stress region and say low stress region that is equal to n is equal to1, you have either diffusion creep or Harper Dorn creep as the rate controlling mechanism. And then we said Epsilon dot proportional to Sigma to the power n, so let us said power law creep and let say it is n equal to 4 to 7. And then at higher strain rates of, higher stresses, you could have Epsilon dot proportional to exponentially, of the B Sigma.

So basically you have seen transitions in deformation mechanism. Now say you are designing a component for a particular high-temperature application, let us take a gas turbine engine blade. So you have an engine blade and you want that the blade to survive a certain number of hours or survive a certain stress level for a certain number of hours. And that is what you have in mind. Now as an engineer, you decided to conduct all your creep tests, say within this stress region.

So say you carried out all your creep tests in the range of Sigma is equal to 2 to 10 Mpa. So let me tell you, this is just for the sake of illustration, this is not real data, this is just a graph for the sake of illustrating the dangers associated with a blind extrapolation. So towards that end, this is what I am talking about. So towards that end, this is an example saying, let us say you have carried out as an engineer you have carried out your creep tests in the range of Sigma is equal to 2 to 10 MPA. And you found out that in that stress range, Epsilon dot is proportional to Sigma to the power 5.

So since in that stress range you are in the power law creep regime, so you found this kind of a correlation. Now why did you choose to do only 2 to 10 Mpa and not lower? Well as you go down in stress levels, the time to carry out that creep test also goes up. So generally when people when agencies are developing components, the generally try to carry out accelerated test, so that they can bring down the time required for the product development. So in such a scenario, say as an engineer, you are running an accelerated program to understand the creep behaviour of a material which is going to be used in a gas turbine engine.

And you carried out tests in the range of 2 to 10 MPA and you found strain rate proportional to Sigma to the power 5. However your interest, so basically you decided that the material is following that and you said that if, if the stress, that the material is going to experience during service is say 0.8 Mpa. So, the material is actually going to, so based on your accelerated test, you said okay I can find out the strain rate of deformation and 0.8 Mpa by basically plugging it 0.8 to the power 5.

So you decided that the strain rate of deformation at 0.8 Mpa, applied stress will be somewhere in this range. So that is what you concluded will be the strain rate of deformation based on your high stress tests. Now this is only valid, so this equation is valid only if the material continues to deform by power law creep, even at 0.8 Mpa stress levels. But as I mentioned earlier, as you go down in stress values, materials could undergo a transition in deformation mechanism.

So typically at low stressors you could actually be in the diffusion creep regime and what people have noticed the strain rates of deformation associated with diffusion creep are very different compared to the strain rates of deformation associated with power law creep. So there is a big probability that the strain rates of deformation actually the strain rates of deformation with in diffusion creep or in the lower stress regime are higher than that a back extrapolation of a power law creep would provide.

So if the material actually translates into a diffusion creep or Harper Dorn creep regime, then the strain rates associated with that, it is going to be higher than the strain rates associated with n is equal to 5 at lower stresses. But since you decided to design your component based on your extrapolation, so basically you are over estimating the useful creep life of the material. So at 10 to the power -10 strain rates, to achieve a strain of some value Epsilon, let us say the strain value Epsilon0 is what you are going to allow your material to experience before you remove it from the turbine engine.

Then the time of service of this material is going to be Epsilon0 divided by 10 to the power -10. So this is the value you are going to get based on your extrapolation. But in actuality at that stress level, most probably the material is creeping at 2 into 10 to the power 9. So, which means the true correct service life of the material should be, will be Epsilon0 divided by 9 into 10 to the power -9. So it is approximately 10 to the power 9 by 9 Epsilon0.

Which is lower than what you are going to get from just blind extrapolation. So the whole objective of this slide is to tell you that you should understand the deformation behaviour of the material over difference stress and temperature ranges, and not rely on blind extrapolation because you might significantly overestimate the useful creep life of your material by relying only on blind extrapolations.

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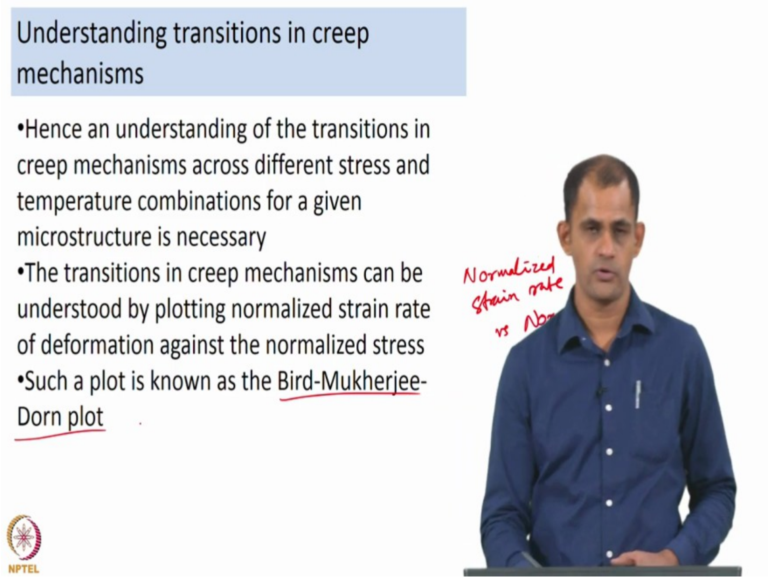

So hence an understanding of the transitions in creep mechanisms across different stress and temperature combinations for a given microstructure is necessary. Now the transitions in creep mechanisms can be understood by plotting normalised strain rate of deformation against the normalised stress. So we are saying, if you want to understand the transitions in creep mechanisms, then it is important that you have one single plot where you use normalised strain rate and plot against the normalised stress.

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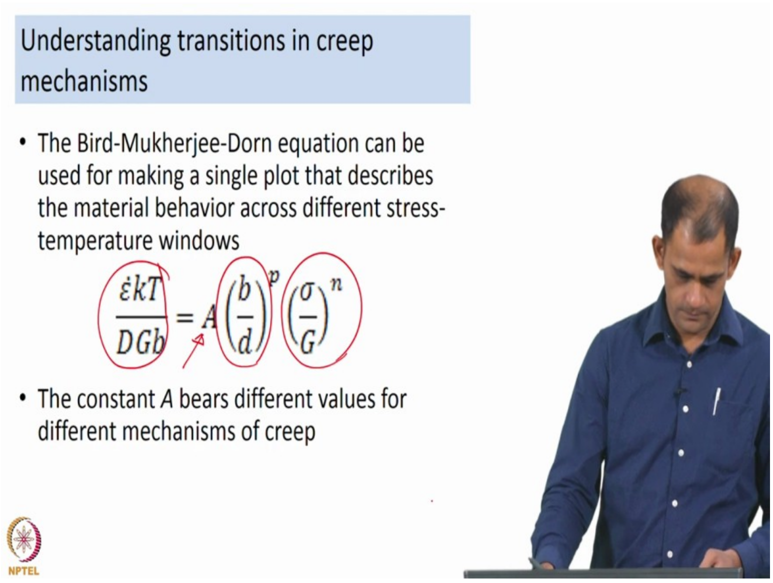

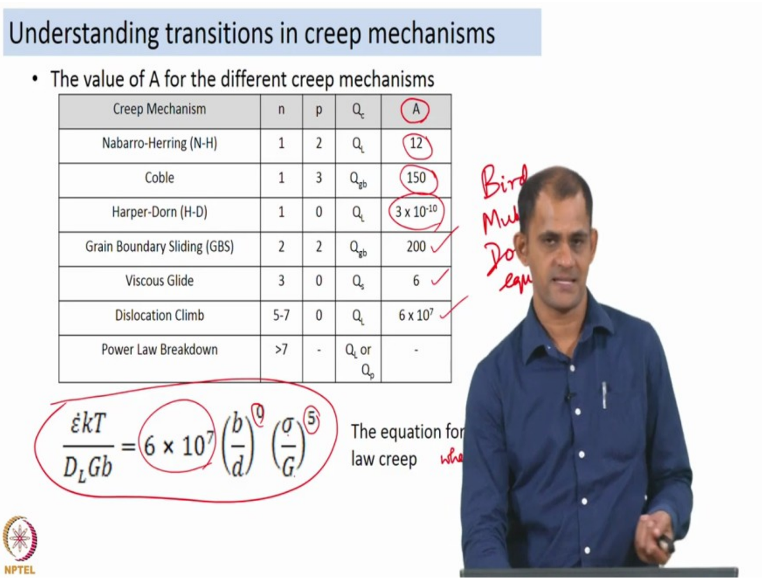

So a plot like that is known as the Bird Mukherjee Dorn plot, so this is what I am going to talk now. So the Bird Mukherjee Dorn plot has its roots in the following equation. So the bird Mukherjee down, they propose an equation of this form. So this form is basically a dimensionless equation between normalised strain rates and normalised stress and even grain size is also made dimensionless by bringing in the Burger's vector factor. So it is a dimensionless equation, so and it can be used for making a single plot, that describe the material behaviour across the different stress, temperature and microstructure windows.

And one of the key point here is the constant A and this constant A has different values for different mechanisms of creep. So, here is a different mechanisms of creep that we have discussed so far and the values of A that one could note for these different mechanisms. For Nabarro Herring creep, people have noticed that the letter a value is 12, for Coble creep 150, 4 Harper Don creep, it is in the range of 10 to the power -10, grain boundary sliding around 200, viscous glide creep, 6 and dislocation climb is around 6 to the power, 6 into 10 to the power 7.

So just as an example if we want to represent dislocation climb as per the Bird Mukherjee Dorn equation, then this is how the creep equation would look like. So you will have Epsilon dot KT by DL because we generally know that power law creep is controlled by climb of dislocation. So you have diffusivity corresponding to lattice diffusion. So Epsilon dot KT by DL Gb and K value is 6 into 10 to the power 7, so that is included here. And we know there is no grain size dependence, that is because in power law creep, the deformation behaviour is grain size independent. So p is equal to 0.

And then you have normalised stress with that of shear modulus, so Sigma by G and then the value equal to 5. So this is the equation for power law creep, where dislocation, dislocation climb is rate controlling. So this is how the Bird Mukherjee Dorn equation would look like. And the similar exercise can be carried out for the different, other mechanisms shown here.

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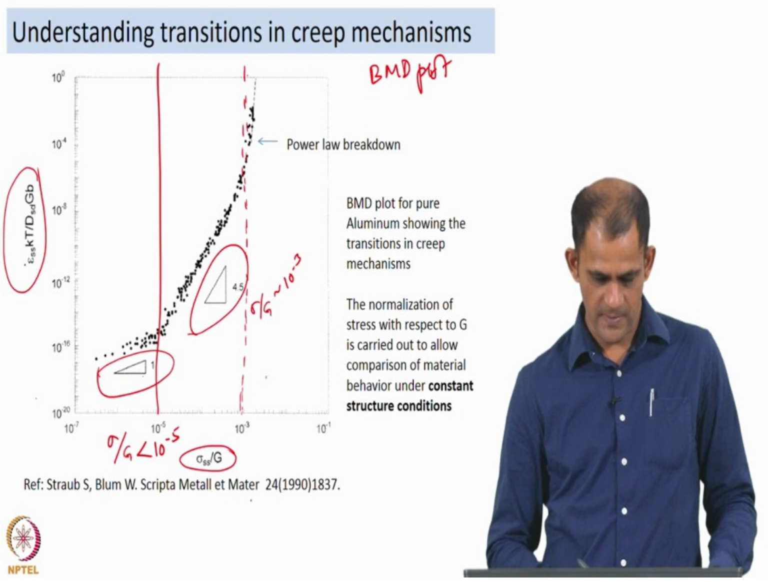

Now, so if you plot the normalised strain rate, so this is a normalised strain rate versus normalised stress in a BMD plot. So this is a plot that I had shown earlier as well, so here if you see there is a transition in creep behaviour. So you are going from an n equal to one region to n equal to 4.5. And then you are going into the power law creep region and where interesting if you see the power law creep region is close to sigma by G value of 10 to the power -3. The power law breakdown region I mean.

So the power law creep region and is at somewhere close to that stress level. And beyond that you are basically moving into the power law breakdown region. So, this plot is basically showing you the transitions in deformation mechanisms that are happening as a function of the normalised stress value. So at Sigma by G, lower than 10 to the power -5, you are in n is equal to one region and then between 10 to the power -5 and 10 to the power -3, approximately, you are in the n is equal to 4.5 region. And so on at higher stresses you go on into the power law breakdown region.

Now one key aspect here is the normalisation of the stress with respect to shear modulus. So why is the stress normalised with that of shear modulus? So we are going to talk about the importance of normalising the stress with shear modulus. Basically they say that when you normalise a stress with shear modulus, you are ensuring that the material behaviour is being compared under constant structure conditions. So, this brings us to the point about the importance of elastic modulus.

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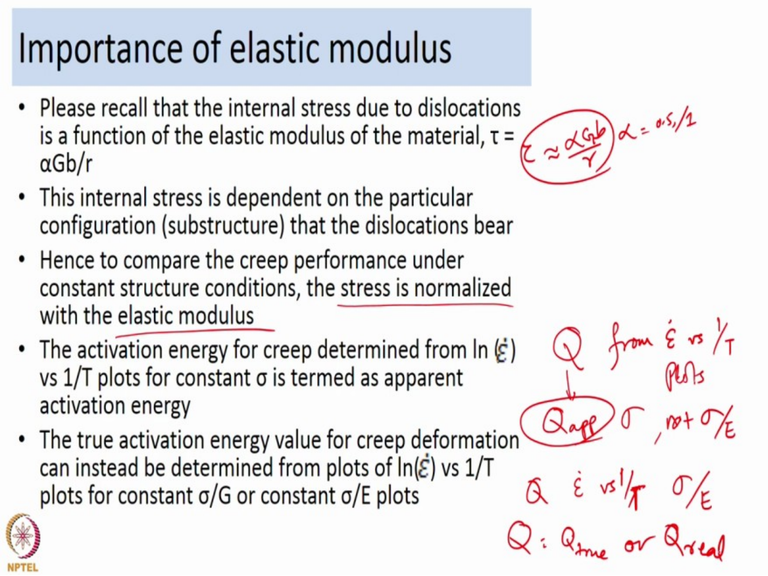

So here we are talking about the normalisation of stress which shear modulus or the elastic modulus, either case it is fine. You can do Sigma by G, you can make a plot of normalised stated against Sigma by E or Sigma by G, it will still be the same. Now the normalisation with E or G is important because if you recall in one of the first few portions that we were talking about, importance of stress, temperature, we said that the internal stress that are generated due to dislocations is a function of the elastic modulus of the material. So, approximately Tao is some Alpha Gb by r, where Alpha can be 0.5 or 1 or something like that.

So you have a dependence on the shear modulus or elastic modulus of the material and r is the distance from the dislocation. So the dislocation forcefield is dependent on the elastic modulus of the material. And what people have noticed is the stress field generated due to a certain dislocation substructure, so assume the dislocations have a certain substructure, they have a certain configuration and so now the stress felt or the forcefield that the dislocation configuration is generating is dependent on the nature of the configuration.

So if you want to, now if you want to compare the creep performance under constant structure conditions, so now you will say you have applied a certain stress and as a result of that, you have a certain configuration. And if you want to maintain the configuration, then you will have to remove the effect of the elastic modulus. So, if you now want to compare the behaviour of the material at a different stress and temperature values, then you have to account for the elastic modulus, change in elastic modulus with temperature.

So elastic modulus is going to change the temperature in order to account for the change with temperature under constant structure conditions, it is necessary to normalise the stress with the elastic modulus. Now what that helps is, so if you normalise the space with the elastic modulus and then if you determine the different parameters, especially people have noticed that the activation energy Q, that can be determined after normalisation is known as the true activation energy.

So if you are determining Q from strain rate versus temperature plots, but if you are using only Sigma and not Sigma by E, then the Q that you will get will be known as Q apparent. So it is not the real activation energy of the material. On the other hand if you determine Q from Epsilon dot versus 1 by T plots, 1 over it T plots, and use Sigma by E for the determination, then the activation energy that you will get will be known as the true activation energy or the real activation energy.

So I will give you a numerical in support of this concept, so that is something we will cover in that at a later stage. So I will give you a couple of, one numerical at least to explain this, the difference in activation energy values that you achieve based on whether the plot of strain rate versus one over T was carried out at constant Sigma or whether it was carried out at constant Sigma over T.

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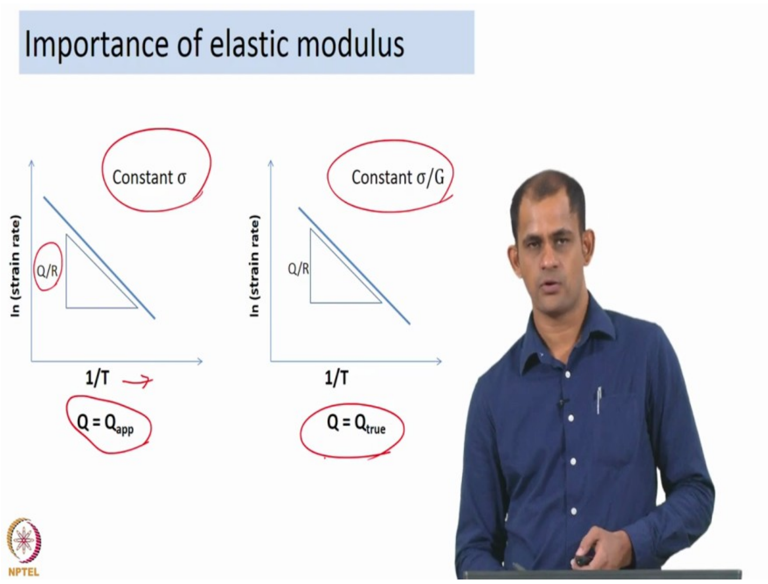

So just an illustration of this point, so here you have an Arrhenius plot, so you have natural logarithm of strain rate versus one over T. And just for the sake of illustrating, so you used a constant Sigma and activation energy that you are getting as a result of that is basically the apparent activation energy. In the 2nd case you actually carried out your comparison at constant Sigma over G and the activation energy you are getting is known as the Q activation energy. So that is the kind of role elastic modulus plays in the analysis of your data and for determining the different creep parameters, especially the activation energy. And the importance of elastic modulus is also understood from the following plot.

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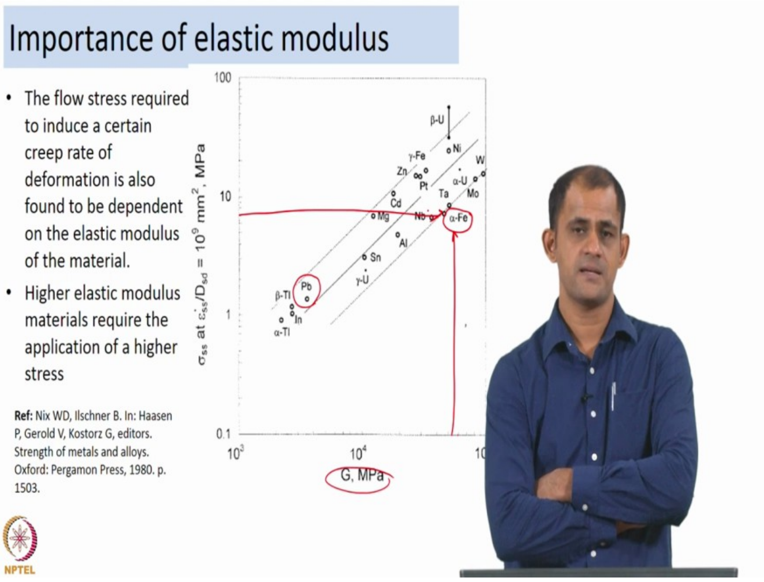

So, this is a plot of flow stress versus shear modulus. And this flow stress corresponds to a certain strain rate of deformation during creep. So if you are interested in achieving a certain creep deformation and if you are, if you need to apply a certain stress to achieve that strain rate, what people have noticed is this flow stress is dependent on the elastic modulus of the material. So if you have no elastic modulus material, such as lead, the stress that you need to apply is low. Whereas if you have high elastic modulus material such as iron, then the stress that you need to apply is accordingly increasing.

So that is, that is the effect of elastic modulus. Higher elastic modulus metal requires the application of a higher stress to achieve the same amount of strain rate of deformation. So, this also tells us that normalising with the elastic modulus in that sense allows us to compare different materials, the behaviour of different materials. So, we were talking about transition in creep mechanisms, service at the Bird Mukherjee Dorn equation helps in understanding helps us in looking at different mechanisms in a single plot. So you could have different mechanisms of deformation shown in a single plot, if you plot normalised strain rate versus normalised stress.

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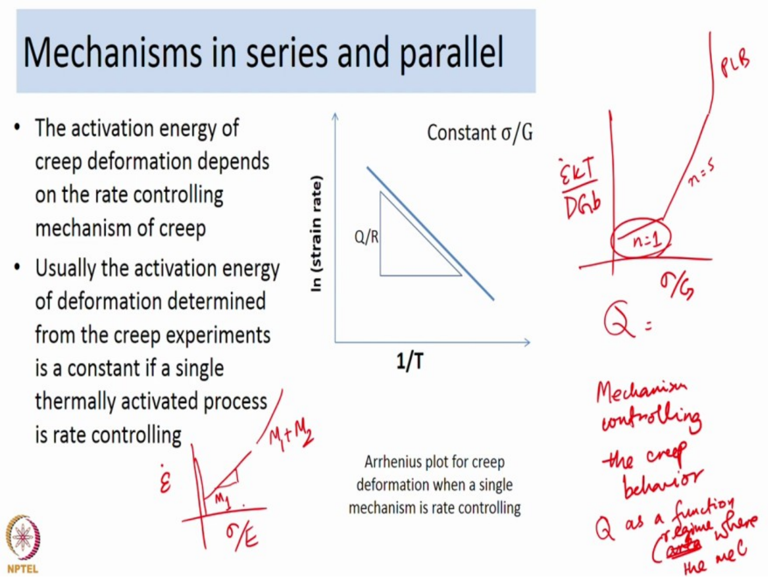

So you would have transitions and mechanism from one mechanism to another as a function of Sigma by E. That works, that concept works, if you have only one single rate controlling mechanism of creep. So say at a lower stress range, you only had Nabarro Herring in creep as an so let us look at this. So, you have Epsilon dot KT by D Gb versus Sigma by G and n is in the lower stress range, your n is equal to1 and you only had Nabarro Herring creep as a rate controlling mechanism and then you had n is equal to 5, you had only dislocation climb control and then you had PLB.

So if you had only one mechanism of creep which was the rate controlling, then you are going to get only one Q value corresponding to that mechanism which is rate controlling. However in many cases, more than one mechanism of creep could be operating at the same time. So, if you have more than one mechanism which is controlling, if you have more than one mechanism which is controlling the creep behaviour, then Q value will vary as a function.

So the Q value will vary as a function of the area where, the area, when I say area, basically mean the region or regime, where the mechanisms are operating. So if you have as an example, let us say you have Epsilon dot versus Sigma by E and you have a certain stress range, where only one mechanism, 1 is operating and then you have another stress range where say mechanism 1+ mechanism 2, both are operating, then what you will notice is that the activation energy where only 1 is operating will have an activation energy corresponding to only mechanism one.

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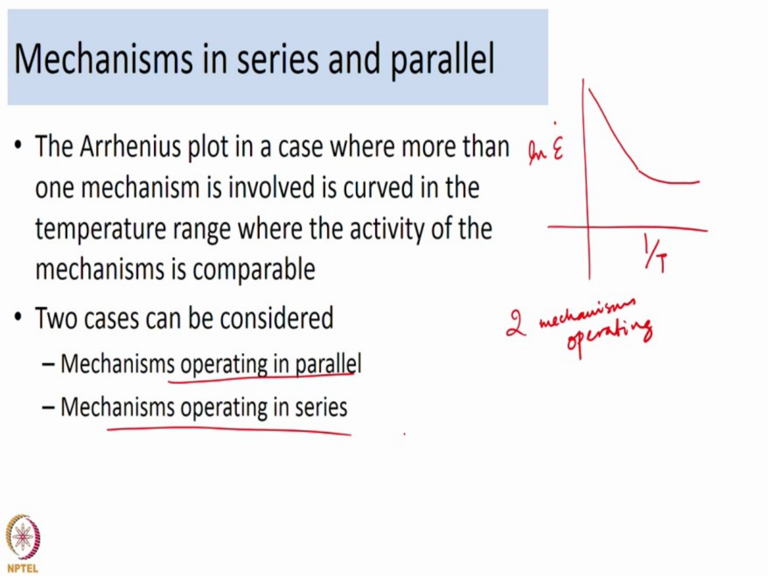

But if you have both, mechanism 1+ mechanism 2, both operating, then you will have an activation energy which will be different than what you get for either mechanism one or for mechanism 2 operating separately. So that is what we will discuss now. So the Arrhenius plot in a case where more than one mechanism is involved is curved in the temperature range where the activity of the mechanisms is comparable. So if you have Arrhenius plot natural logarithm of Epsilon dot versus one over T, what this basically says is that you have only one mechanism operating, then you have straight line.

But if you have 2 mechanisms operating, then you may not see a straight line anymore, you may see a curved line and the curvature of the line will depend on how important, how much of a contribution is coming from both the mechanisms or the multiple mechanisms of creep. Now if you have 2 mechanisms as an example, if you have 2 mechanisms operating, then these mechanisms could actually be operating either in parallel or they could be operating in series. So if you have 2 mechanisms operating, then the operating mechanism, they could be operating in parallel or they could be operating in series.

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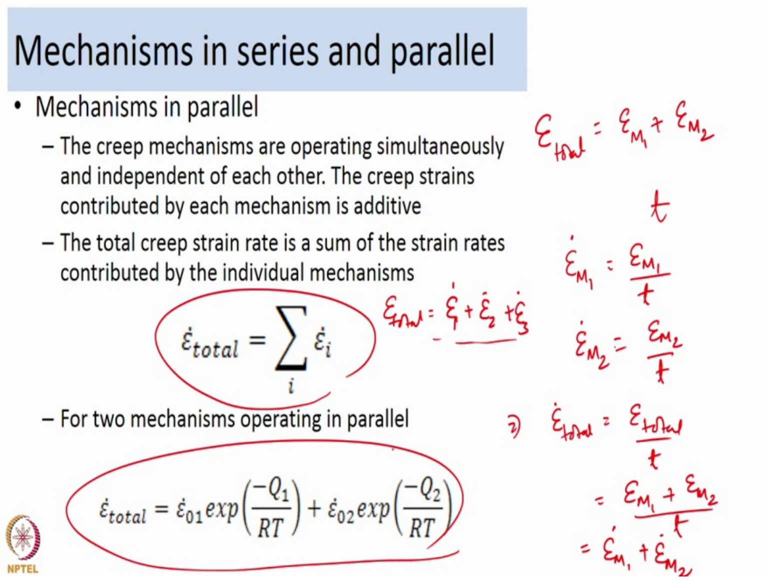

So what is the meaning of operating in parallel or operating in series quest so let us take a look at that. Let us first talk about the case of mechanisms operating in parallel. So, what this means is, the creep mechanisms are operating Simultaneously and independent of each other. So you have 2 mechanisms operating in parallel and mechanism 1, there is no influence of mechanism 1 on mechanism 2 or vice versa. So they have no influence on each other. So they are operating independent of each other, so this, such a case is known as the creep mechanisms operating in parallel.

And here the creep strains contributed by each mechanism is additive. So the total strain, that you will have will be a strain contribution of mechanism 1+ strain contribution of mechanism 2. So and the total creep strains rate accordingly is the sum of the strain rates contributed by the individual mechanisms. Since both mechanisms are operating in parallel and they are going to operate for a given duration of time t, so the strain contribution of mechanism 1 will be equal to the strain of mechanism 1 divided by time t. And similarly mechanisms 2 is equal to divided by time t. So therefore the net total strain rate is equal to strain total part-time total, so that is equal to Epsilon M1 + Epsilon M2 by t, so that makes it Epsilon M1 dot + Epsilon M2 dot.

So the strain rate, total creep strain rate is a sum of the strain rates contributed by the individual mechanisms. So, that is what you observe for mechanisms in parallel. And so, if you expand for 2 mechanisms, so you could have multiple mechanisms in operating, so you could have Epsilon total as Epsilon one, mechanism one, Epsilon 2 dot + Epsilon 3 dot and so on. But if you have only 2 mechanisms, we could expand the equation into this, surround auto tales equal to Epsilon dot, so that is how the strain rate of deformation would look like for 2 mechanisms operating in parallel.

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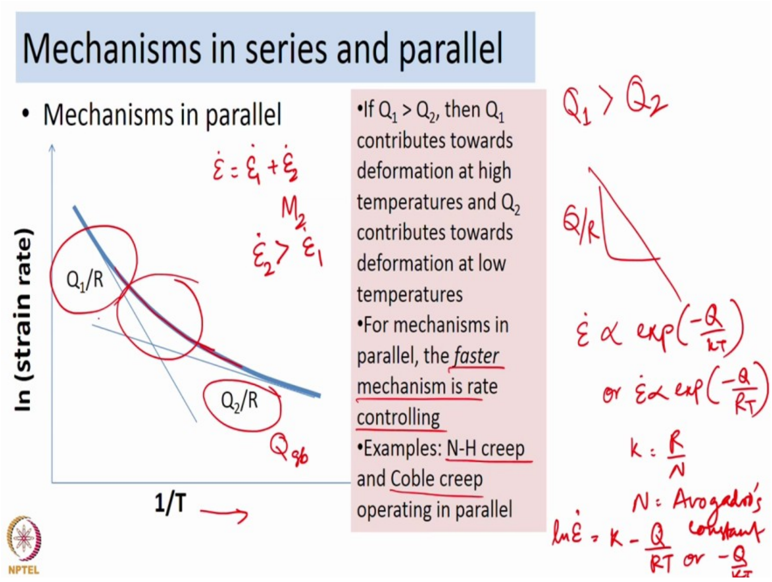

Now when you have 2 mechanisms operating in parallel, then the Arrhenius plot will look like this, so you have ln strain rate versus one over T. And if Q1 is greater than Q2, so say mechanism one, the activation energy corresponding to mechanism one which is Q1 is greater than the activation energy for mechanism 2, which is Q2, then what you will observe is at very high temperatures, the contribution of mechanism 1 towards the information is going to be larger than the contribution of mechanism 2.

So therefore at high temperatures, the activation energy of deformation will be close to Q1. Similarly at low temperatures, very low temperatures, the contribution of mechanism 1 is going to be small and mechanism 2 to is going to dominate over mechanism 1. So the activation energy of deformation at low temperatures, very low temperatures will be close to Q2. So, so if you notice I have mentioned the slope of the lines, so the slope of lines has Q over R and not just Q, that is because strain rate is proportional to exponential - Q over KT or it can also be written as strain rate proportional to exponential - Q over RT.

That is because, K is basically equal to R over N, N is the Avogadro's constant. So you could, if you now do ln Epsilon dot, then that becomes some constant K - Q over RT. - Q over RT or - Q over TT. So the slope of the line will be basically Q over R, that is why I have mentioned the slope of the line as Q over R. So coming back to the point, so depending on the temperature very you are operating, you could have one mechanism completely dominating the other. But there could be an intermediate temperature range where both mechanisms when operating in parallel will have their own contributions to the total strain rate.

And in that case you will see a certain curvature in the line. So, the extent of the curvature, like I said will depend on the contribution of these mechanisms. Now for mechanisms on parallel, so, when you have 2 mechanisms operating in parallel, the observation is that the faster mechanism is the rate controlling mechanism. So, that is because the total strain rate is in addition of the strain rates contributed by both the mechanisms. So whichever has a higher value, so the faster mechanism, say Epsilon 2 or mechanism 2 is the faster mechanism, if mechanism 2 is a faster mechanism, then strain rate 2 is going to be greater than strain rate 1.

So that means the overall strain rate is dependent on the contribution of mechanism 2. So higher the, since mechanism 2 has a higher strain rate, so you can say that mechanism 2 is the rate controlling mechanism in this case. So an example of mechanisms in parallel is Nabarro Herring creep and Coble creep. So these are the 2 mechanisms which can operate in parallel and as you know, at very low temperatures, at low temperatures you have Q is equal to Q Gb, so that is why Coble creep rate controlling and at high temperatures, Q is equal to QL, so Nabarro Herring is rate controlling and that in intermediate temperatures you can have contributions from both.

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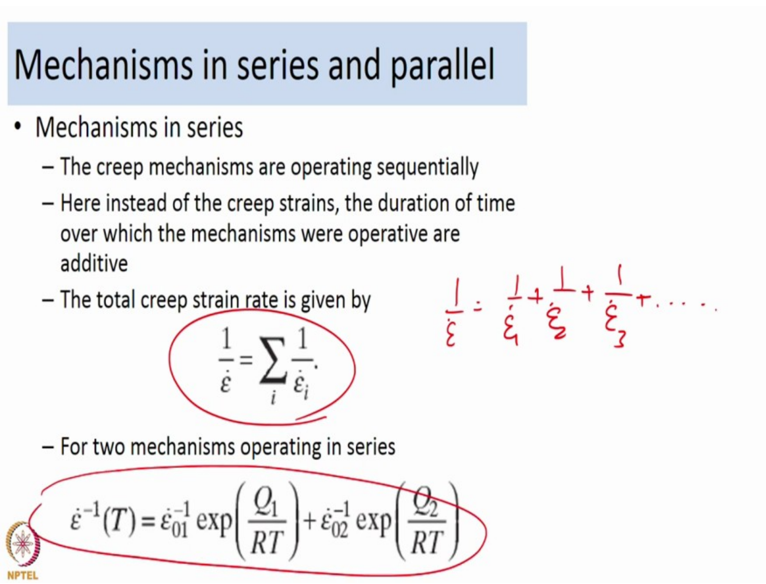

So that was about mechanisms in parallel, now let us talk about mechanisms in series. So, here is a mechanisms are operating sequentially. So one needs to happen for the other to happen. So you have say mechanism 1 and mechanism 2, so for mechanism 2 to operate, it is dependent on mechanism one. So they are operating sequentially and here instead of the creep strains, the duration of time over which the mechanisms are operative, so the time is what is additive. In the previous case it was a strain that was additive, whereas here it is the time that is additive.

And so the total creep strain in this case is given by this equation. So total creep strain rate is given by, is a harmonic mean, so it is one over Epsilon dot is equal to 1 over Epsilon 1 dot +1 over Epsilon 2 dot +1 over Epsilon 3 dot and so on. And if you have only 2 mechanisms, then the equation would look something like that. For 2 mechanisms operating in series, this is how the equation would look like.

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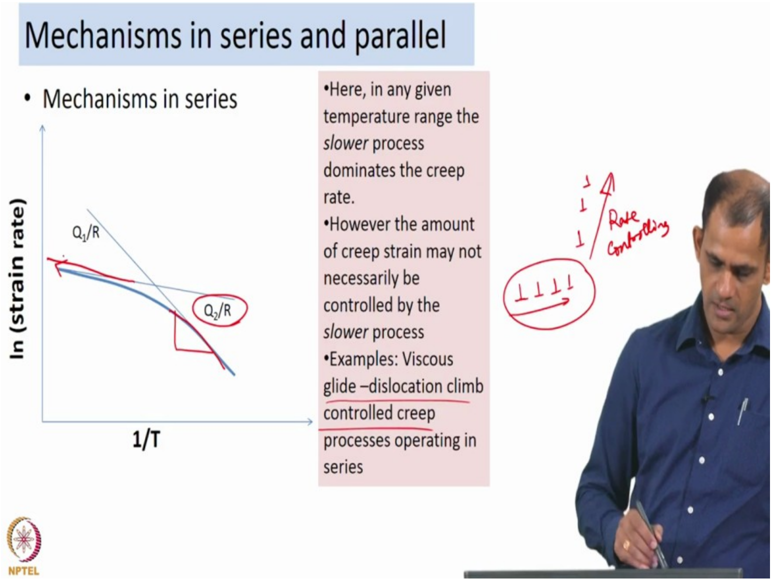

Now let us look at the plot of strain rate, ln of strain rate versus one over T. Now here in any, for mechanisms in series, what is interesting is here unlike for mechanisms in parallel, in series a slower step, the slower process becomes the rate controlling mechanism. So here in any given temperature range, the slower process dominates the creep rate. And however the amount of creep strain may not necessarily be controlled by the slower process. So if you have 2 mechanisms M1 and M2, so if M2 a slower, M2 being slower it will determine the overall creep rate.

However the strain contribution need not be determined by M2, it could still come from M1. So the bulk of the metal deformation could be happening by M1 but the speed at which M2 is happening is limiting the contribution of M1. So that is why the overall deformation process is dependent on the speed of operation of M2 and that is why M2 becomes rate controlling.

So here the slower process, at the creep rates and the creep contribution could still come from the larger process. An example of mechanisms in series is viscous glide and dislocation glide, climate controlled creep process, both are operating in series.

So viscous glide, so you have a glide of dislocations and then the glide of dislocations has to be supported by climb of dislocations for this process to continue. So if the climate of dislocations is not fast enough, then the strain rate, the contribution of glide to the total deformation is going to be limited. So here the climb of dislocations is rate controlling. And if you look at this plot, at lower temperatures, you have, at lower temperatures you have the higher activation energy, the lower activation energy material having less contribution to the total strain rate.

So at lower temperatures you have the higher activation energy mechanism contributing to the strain rates of deformation and at higher temperatures, you have the lower activation energy mechanisms contributing to the strain rate of deformation. So this is how the behaviour is when the mechanisms are operating in series.