Creep Deformation of Materials.
Indian Institute of Technology, Madras.
Deformation Mechanism Maps - Part 1.

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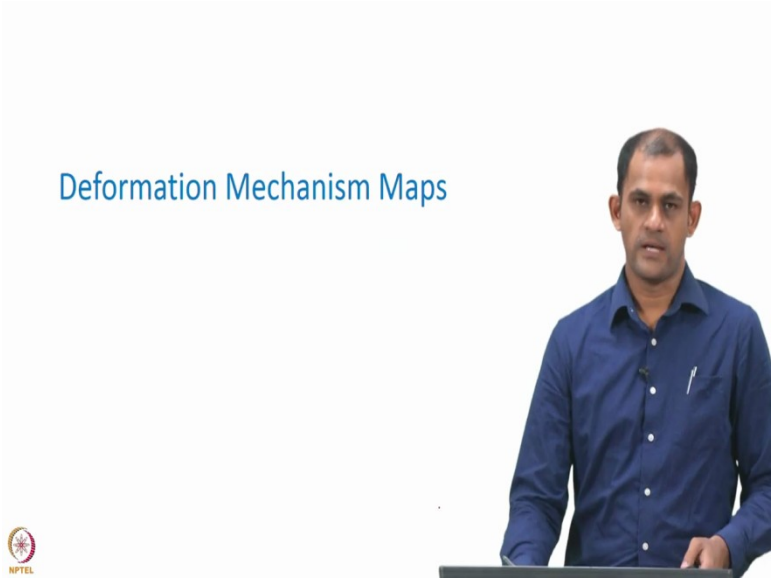

So, we were talking about the mechanisms of creep when they operate either in parallel or in series, how does the activation energy change, how does the contribution of each of the mechanisms towards the activation energy change, depending on the temperature in which the deformation is taking place. So, we are talking about that, so, so far we have covered the different mechanisms of creep, we talked about Newtonian viscous creep, grain boundary sliding, viscous glide, power law creep, power law breakdown and all that.

And we talked about them operating in series or in parallel. Now we are going to talk about the concept of deformation mechanism maps. So just like a normal map, which tells us the different directions or the direction in which, direction and distance of one place from another comment similarly these maps are also as a guide. Just like normal maps are guides for human beings to be able to locate a certain place in a vast area, similarly deformation mechanism maps are basically maps which help us, help engineers and scientists locate the bounds of stress and temperature in which a particular mechanism of creep would be dominant.

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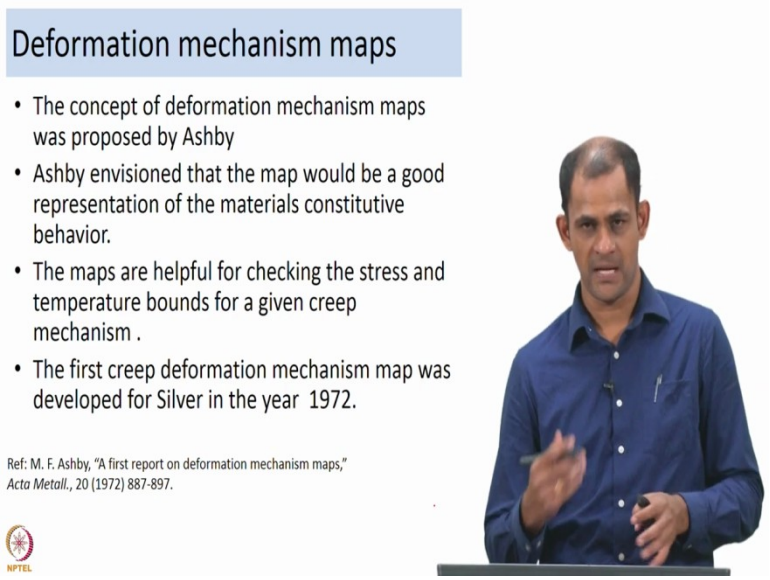

So we are going to talk about these maps in detail. So the concept of deformation mechanism maps was first proposed by Ashby, MF Ashby. So Ashby envisioned that the map would be a good representation of the materials constitutive behaviour. So, when you talk of constitutive behaviour, we talk about these different mechanisms of creep deformation that can be active for different combinations of stress, temperature and microstructures. And Ashby said, envisioned, that if we have a single map where all of these mechanisms are located, then we will know for a given material with a given grain size or microstructure what mechanism of creep will be dominant for a certain combination of stress in certain region.

So, basically the maps are helpful for checking the stress and temperature bounds for a given creep mechanism. In the first creep deformation map, mechanism map was developed for Silver in the year 1972. Now, over the years Ashby and his team, they also developed similar maps for fracture, wear and some other sintering and so some of the other mechanisms which were also covered with the similar concept of maps.

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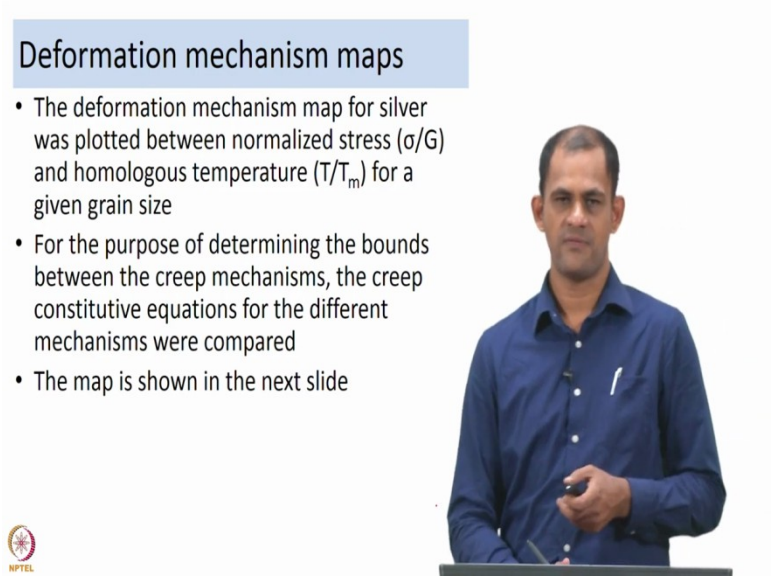

How does a deformation mechanism map for Silver, which was the first one which they developed, was plotted between normal expressed Sigma over G and homologous temperature T over Tm for a particular grain size of the material. And for the purpose of determining the bounds, so I will show you the map that was developed and I will explain how or briefly tell you how these bounds were determined. So essentially the bound within the different creep mechanisms for determining those bounds, the creep constitutive equations were used as well as compared for the different mechanisms.

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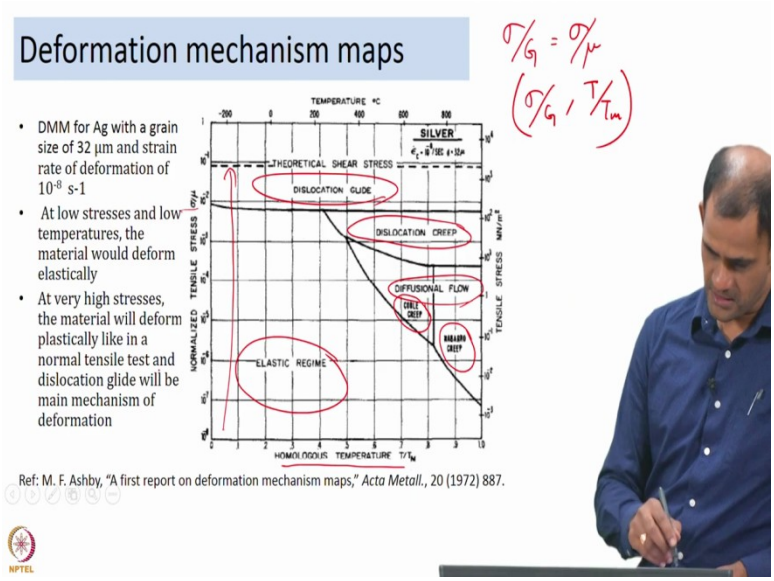

So the map is shown in the coming slide. So, here is a deformation mechanism map of silver, so DMM stands for deformation mechanism map. And this, the material that they had had a

grain size of 32 micrometres and they were comparing all the different mechanisms for a creep strain rate of 10 to the power -8. Now if you look at the map here, so you see the homologous temperature T over Tm is on the x-axis and the normalised tensile stress Sigma over mu also it can also be mentioned as Sigma over G.

So Sigma over mu is the same as Sigma over G, so that is on the Y axis. So what you notice here is at low tensile stresses as well as at low temperatures, so if you are carrying out a low temperature test at very low stress, then your material will be in the elastic regime. So the material is going to be elastically and if you unload, then you are going to recover your complete strain. On the other hand if you apply very high stresses at low temperature, so if you are applying very high stresses at low temperatures, then it is more or less like a simple tension test where plastic deformation happens by the glide of dislocation.

So that is why at very, at low temperatures at high stresses or even at for that matter even if you go to very high temperatures, dislocation glide is going to be the deformation mechanism. It is going to determine the extent of plasticity, so the glide of dislocations will do that. In an intermediate temperature and stress range, so if you have a certain combination of stress and temperature, normalise stress and normalise temperature, you can see the other mechanisms coming into play.

So you can have dislocation creep which is basically dislocation climate controlled creep you can have diffusional flow and when we talk of diffusional flow we know of to mechanisms, one is Coble creep any other one is Nabarro Herring creep. So they found out that for different combinations of Sigma by G and T by Tm you could have one mechanism dominant over another or over the others. So, this is basically what we are talking here and now what I want to do is I want you to tell you how or I want to describe how these mechanism maps or these bounds can be identified for these different mechanisms.

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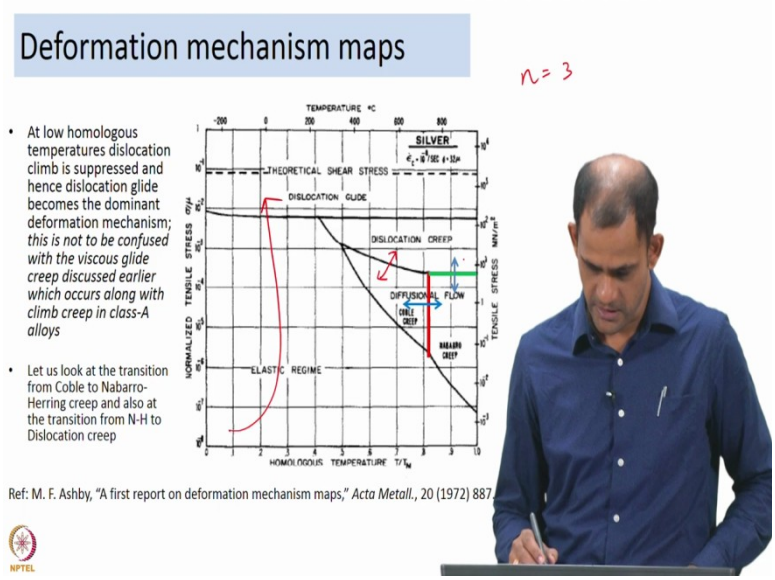

So I am going to talk about the bounds for the following, so I am going to talk about the bounds, how is the bound determined or the boundary determined for a transition from Coble creep to Nabarro Herring creep, how is the boundary determined for Nabarro Herring creep to dislocation creep and even how is the bound determined for dislocation creep to Coble creep. So these are the 3 mechanisms and I am going to talk about the same. Now one point is at low homologous temperatures, dislocation climb is suppressed.

So if you see at low homologous temperatures, we are mainly talking about at high stresses, dislocation glide, that is because that low temperatures dislocation climb is suppressed. And have dislocation glide becomes the dominant deformation mechanism. When we say dislocation glide, let it be clear that this should not be confused with the viscous glide creep mechanism which operates with n is equal to 3. So the width of the glide creep mechanism basically involves the dislocations trapped by the solute atmospheres and the diffusivity of the solute atoms is what will determine the rate of creep.

So this dislocation glide should not be confused with, should not be confused with the viscous glide creep mechanism. So now I am going to derive or established these boundaries between the different mechanisms of creep. So first let us start with the, let us look at the boundary between Nabarro Herring creep and dislocation creep, so this green line. So let us look at how how to determine the boundary between Nabarro Herring creep and dislocation creep.

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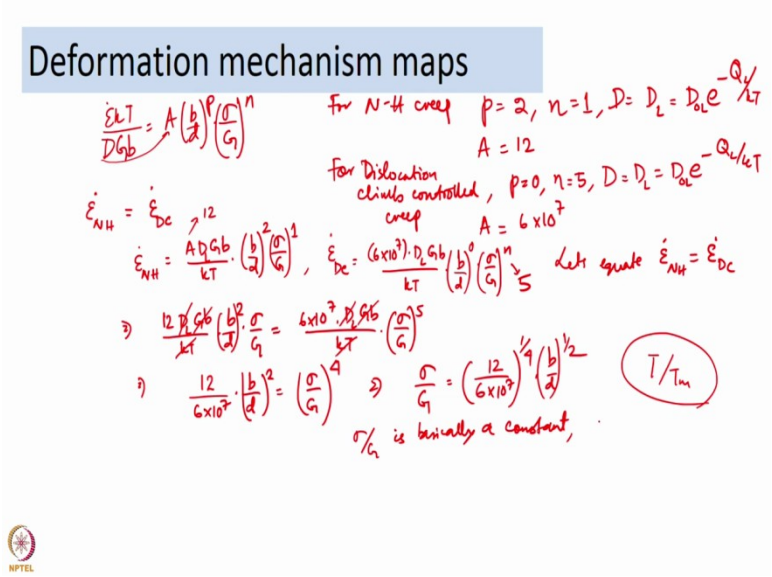

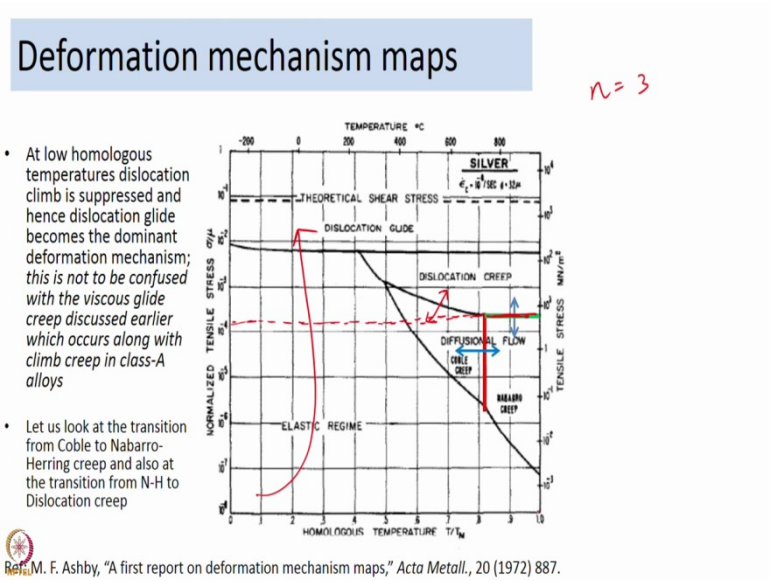

So for determining this boundary we will employ the Bird Mukherjee Dorn equation. So the Bird Mukherjee Don equation is basically Epsilon dot KT by DGb is equal to A b by d to the power P into Sigma by G to the power n. So we basically apply the Bird Mukherjee Dorn equation and for understanding that transition between the different mechanisms of creep. So the Bird Mukherjee Dorn equation if you recall, for Nabarro Herring creep, p is 2, p is equal to 2 and n is equal to 1, D is equal to, lattice diffusivity, so that is equal to D0L a e to the power - QL over KT. And A, the constant has a value of 12.

So that is for Nabarro Herring creep. For dislocation climb controlled creep, we know it is a grain size independent, the mechanism operates without any grain size dependence. So p is equal to 0 and n can be between 4 to 7, so let us take the n is equal to 5 and then D is equal to

lattice diffusivity which is again D0L e to the power - QL over KT. And the constant A for dislocation climb control creep is 6 into 10 to the power 7, okay. So now when you are looking at the boundary, so the basically the boundary is the point where both strain rates of deformation are going to be equal.

That means the strain rate of deformation due to Nabarro Herring creep is going to be equal to the strain rate of deformation due to dislocation climb controlled creep. So, let us try the relationship for Nabarro Herring creep. So Epsilon dot N H, which is for Nabarro Herring creep will be, so if you take all these 3 terms towards the other side, so it will be A DL Gb over KT into b by d square and Sigma by G to the power 1. Okay and d is basically the grain size if you recall. So and A like I said it is 12.

And the strain rate of deformation for dislocation creep similarly can be written as 6 into 10 to the power 7 into DL Gb over KT and since p is equal to 0, so it is b Over d to the power zero and Sigma by G to the power n. So if you equate both of these, so now let us equate. So what we essentially get is A DL, so instead of A, let me write it as 12 DL Gb Over KT into… Okay. So clearly you will have DL and DL cancelling each other, Gb, Gb cancelling each other, KT, KT cancelling each other. So what you are essentially have is 12 by 6 into 10 to the power 7 into b by d square is equal to Sigma by G to the power 4.

So this implies Sigma by G is equal to 12 by 6 into 10 to the power 7 to the power 1 by 4 into b by d to the power 1 by 2. So, if you look at this equation, Sigma by G does not have any relation with T over Tm. So it is only dependent on the grain size, so Sigma by G has no relation to T over Tm, that is means it is independent of T over Tm. So for this transition the only dependency is on the grain size. So, if the grain size is already given, so in this case for severity 32 micron, so what you essentially know is that Sigma by G is basically a constant and there is no dependence on T over Tm.

That is why if you look had the map, for Nabarro Herring creep, for Nabarro Herring creep to dislocation creep, you basically have a stress value, that is a stress value at which the transition happens and there is no dependence on the temperature. So, that is about the transition between the dislocation cream on Nabarro Herring creep. Now let us look at the transition between Coble creep and Nabarro Herring creep. So a Coble creep and dislocation creep.

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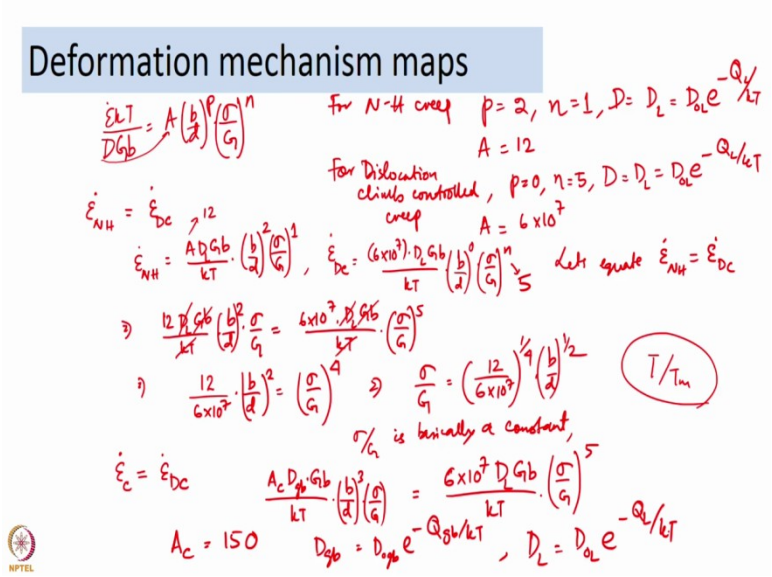

So if similar method can be used, so we are going to do Epsilon dot C equal to Epsilon dot DC and for Coble creep we have AC DGb into KT, AC DGb into Gb by KT into b by d to the power 3 into Sigma by G again for Coble creep it is a Newtonian viscous creep mechanisms, so Sigma by G power 1. And dislocation creep like we wrote earlier, to 6 into 10 to the power 7 DL Gb over KT into Sigma by G to the power 5. So the constant AC the concert AC for Coble creep, AC is 150, so what we get here is, we expand it, so you get, so DGb, now DGb is D0 is Gb e to the power - Q Gb over KT. And DL as we know is D OL e to the power - QL over KT. Okay.

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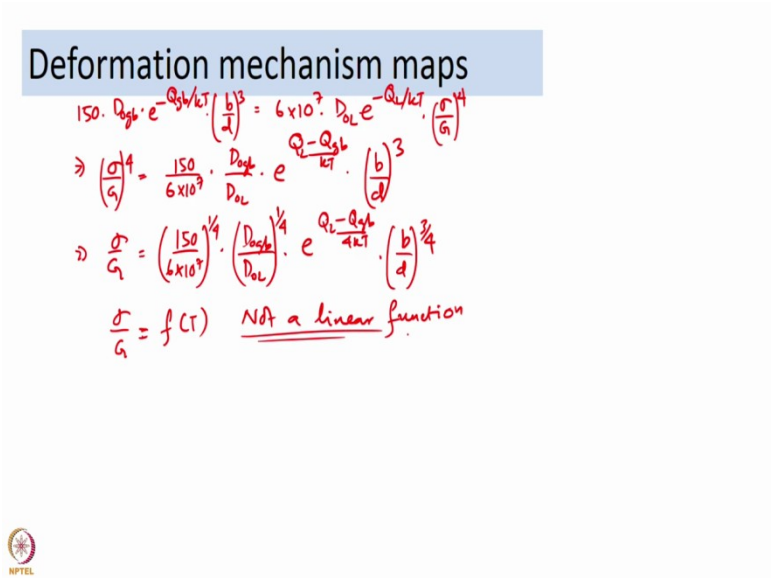

So when you equate these, what you end up is with 150 D0 Gb into e to the power - Q Gb over KT into b by d to the power 3 is equal to 6 into 10 to the power 7 D0L e to the power - Q and over KT into Sigma by G to the power 4. So, this implies Sigma by G to the power 4 is equal to 150 by 6 into 10 to the power 7 into D OG b by D OL and into exponential of QL - Q Gb over KT into b by d to the power 3. So, what is coming out from here is that Sigma by G has a dependence on temperature. So if it take the, if we write it in terms of Sigma by G, then Sigma by G is equal to 150 by 6 into 10 to the power 7 to the power one by 4 into D OG b by D OL.

Again for silver, we know the grain size D And then QL and Q Gb comes, okay, is known and D OG b by D OL is also known. And that rest of the things are known, so Sigma by G has a non-linear essentially non-linear dependence on the temperature. So Sigma G, Sigma by G is a function of temperature but it is not a linear function. So the bounds between, so accordingly, since it is not a linear function, so the bounds between dislocation creep and Coble creep. And that is why if you look at the map, it is not a straight line, so the boundary between Coble creep and dislocation creep is, it is curved because of the non-linear function, knowledge dependence of Sigma by G over T over the temperature.

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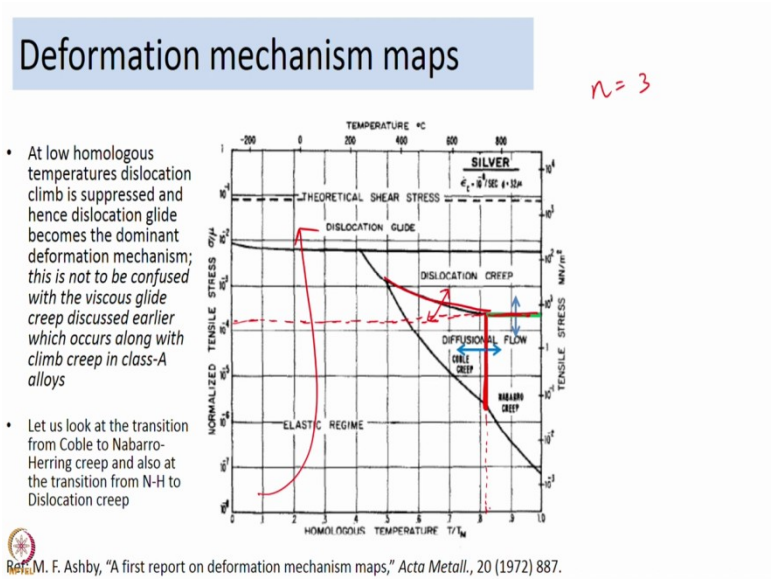

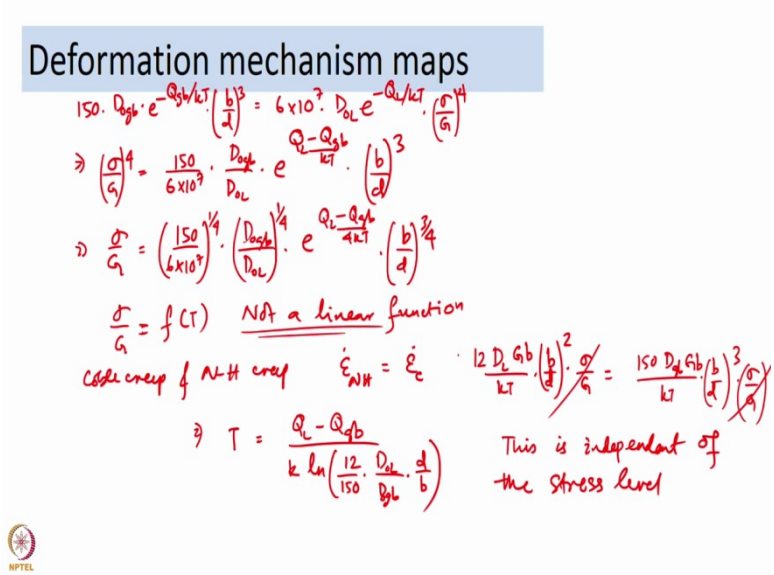

Now let us look at the last case, which is the transition between Coble creep and Nabarro Herring creep. So this is the last case, so again frequently Nabarro Herring strain rate is equal to Coble creep strain rate. So what we end up is 12 into DL into Gb over KT into b by d square into Sigma by G is equal to 150 into 150 DGb over KT b by d 3 into Sigma by G. So Sigma by G and Sigma by G cancel out each other, so what you have here is temperature which ends up as QL - Q Gb by K Lon 12 by 150 into D OL by D Gb into d by b.

So, here the temperature is basically independent of the stress level. So it is only dependent on the value of the temperature and is independent of the stress level. So that is why if you see in the map, it is basically a straight line giving the temperature value at which there can be a transition from Coble creep to Nabarro Herring creep, there is no dependence on stress. So, this basically through these equations, by using these equations you can determine the bounds of the different, the bounds of the different mechanisms.

So you can find out at what temperatures will Coble creep be dominant and at what temperatures will Nabarro Herring creep be dominant, at what combinations of stress and temperature will dislocation creep be dominant over Coble creep. So, that is something, that is how you can go about this and determine the boundaries and create the map. So this is how Ashby and his team, this is how they developed their mechanism maps.

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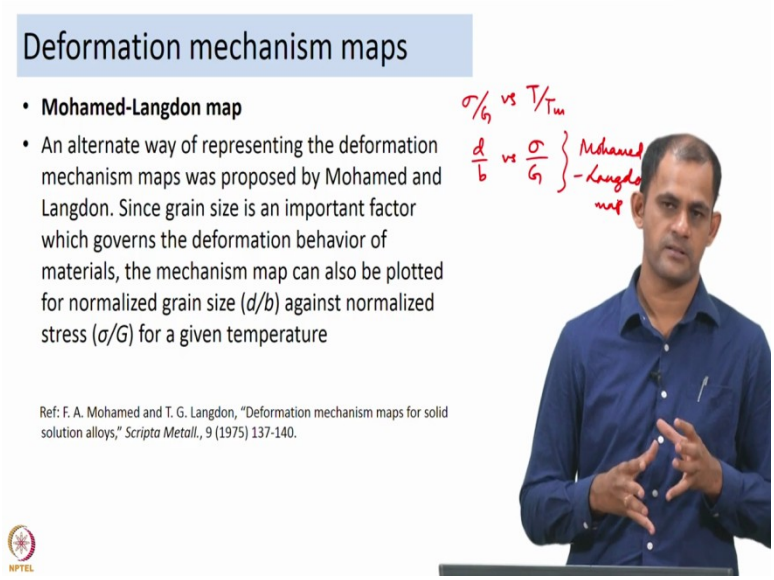

In subsequent years, there was a different type of map, it is also a deformation mechanism map but it is different from the Ashby map. So this map was developed by Mohammed and Langdon. And we can call it as Mohammad Langdon map so this is basically an alternate way of representing the deformation mechanism maps where instead of Sigma by G versus T over Tm, the map is d Over b versus Sigma by G. So this is the Mohammad Langdon map. The reason they chose d by b or the grain size because we know the mechanisms of creep are also a function of the grain size of the material.

For example we know Harper Don is independent of grain size, dislocation creep mechanism will be independent of grain size, whereas Nabarro Herring creep, grain boundary sliding, Coble creep, etc., they are dependent other grain size. So we can use this knowledge, the fact that some mechanisms are dependent on grain size and some are not, this knowledge can be used and the map can be created and that is where exactly Mohammad and Langdon have done.

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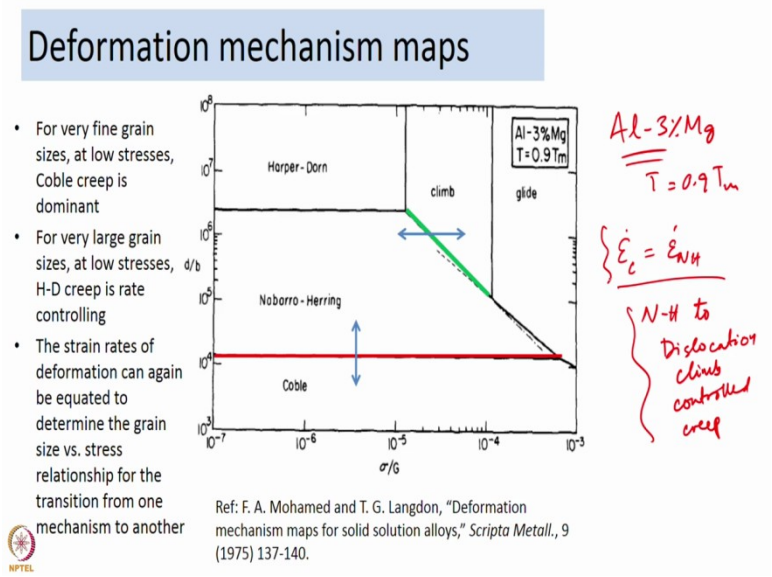

So they plotted normalised grain size d Over b against normalised stress for a given temperature. So this is how the Mohammad Langdon map looks like. This map was created for aluminium 3 percent magnesium at a temperature of 0.9 times the melting point of the material. So, if you see it is d by b over Sigma by G and what we see here is at fine grain size, so when you have fine grain size, you have lower values of d by b, today are saying Coble creep is dominant, as you increase the grain size, Nabarro Herring and if you further grow up, go up in grain size, we know that Harper Don creep becomes dominant at very large grain sizes.

And this is at low stresses but if you go high in Stresses, we know that dislocation based mechanisms, that is power law creep starts coming into play at high stresses. So now you start seeing dislocation climb control creep appearing in the deformation map and also at higher stress levels you can also have dislocation glide controlling the creep deformation. So these are the different mechanisms that they showed in aluminium 3 percent magnesium.

Again the strain rates of deformation, the bounds for determining the bounds you can equate the strain rates of deformation of the different creep mechanisms. So we will do that for Coble to Nabarro Herring creep, so to show how these bounds look like, we will do it for Coble to Nabarro Herring creep and also Nabarro Herring creep to dislocation climb controlled creep. So these are the 2 bounds that I will determine for the purpose of illustrating how the map will look like, why are there some lines parallel to the x-axis and why are some lines at an angle to the x-axis, that will be clear when we carry out this exercise.