# Creep Deformation of Materials.
# Indian Institute of Technology, Madras.
# Deformation Mechanism Maps - Part 2.

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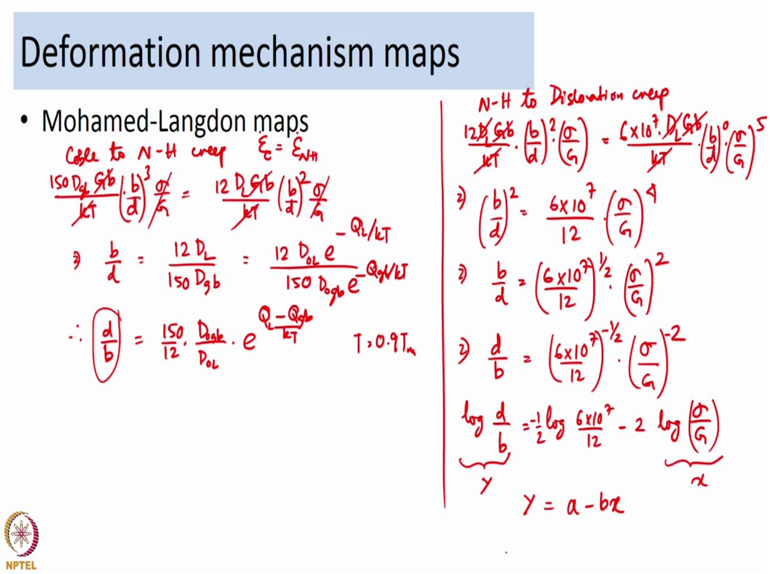


Deformation mechanism maps

- Mohamed-Langdon maps

Coble to N-H creep $\dot{\varepsilon}_c = \dot{\varepsilon}_{NH}$

$$\frac{150 D_{gb} \cancel{Gb}}{\cancel{kT}} \left(\frac{b}{d}\right)^3 \cancel{\frac{\sigma}{G}} = \frac{12 D_L \cancel{Gb}}{\cancel{kT}} \left(\frac{b}{d}\right)^2 \cancel{\frac{\sigma}{G}}$$

$$\Rightarrow \frac{b}{d} = \frac{12 D_L}{150 D_{gb}} = \frac{12 D_{0L} e^{-Q_L/kT}}{150 D_{0gb} e^{-Q_{gb}/kT}}$$

$$\therefore \boxed{\frac{d}{b}} = \frac{150}{12} \cdot \frac{D_{0gb}}{D_{0L}} \cdot e^{\frac{Q_L - Q_{gb}}{kT}} \qquad T \approx 0.9 T_m$$

N-H to Dislocation creep

$$\frac{12 \cancel{D_L} \cancel{Gb}}{\cancel{kT}} \cdot \left(\frac{b}{d}\right)^2 \cdot \left(\frac{\sigma}{G}\right) = \frac{6\times10^7 \cdot \cancel{D_L} \cancel{Gb}}{\cancel{kT}} \cdot \left(\frac{b}{d}\right)^0 \cdot \left(\frac{\sigma}{G}\right)^5$$

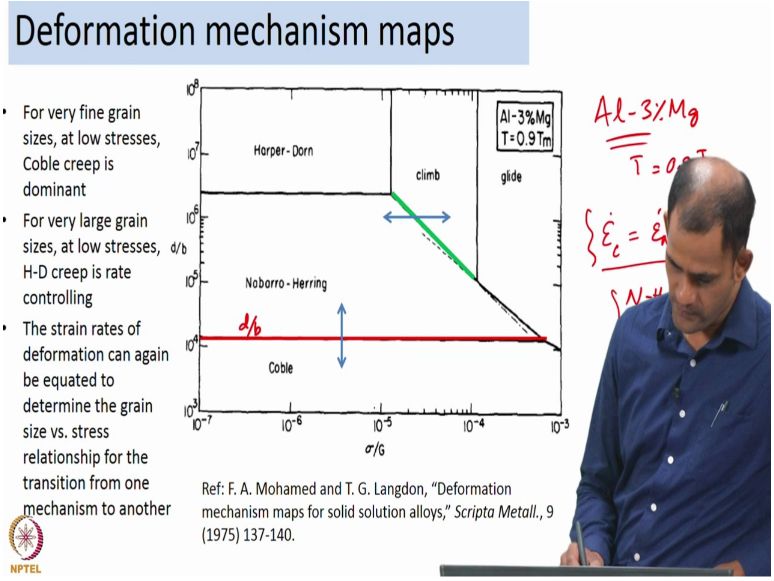
$$\Rightarrow \left(\frac{b}{d}\right)^2 = \frac{6\times10^7}{12} \cdot \left(\frac{\sigma}{G}\right)^4$$

$$\Rightarrow \frac{b}{d} = \left(\frac{6\times10^7}{12}\right)^{1/2} \cdot \left(\frac{\sigma}{G}\right)^2$$

$$\Rightarrow \frac{d}{b} = \left(\frac{6\times10^7}{12}\right)^{-1/2} \cdot \left(\frac{\sigma}{G}\right)^{-2}$$

$$\underbrace{\log \frac{d}{b}}_{y} = -\frac{1}{2} \log \frac{6\times10^7}{12} - 2 \underbrace{\log \left(\frac{\sigma}{G}\right)}_{x}$$

$$y = a - bx$$



Deformation mechanism maps

- For very fine grain sizes, at low stresses, Coble creep is dominant
- For very large grain sizes, at low stresses, H-D creep is rate controlling
- The strain rates of deformation can again be equated to determine the grain size vs. stress relationship for the transition from one mechanism to another

Ref: F. A. Mohamed and T. G. Langdon, "Deformation mechanism maps for solid solution alloys," *Scripta Metall.*, 9 (1975) 137-140.

Now, Coble to Nabarro Herring creep. Again, it is 150, so you are doing epsilon dot c is equal to epsilon dot nh, so 150 kt into b by d into sigma by g is equal to 12 dl gb over kt by g. So sigma by g and sigma by g cancel out, kt, kt cancel out, gb, gb cancel out. So what you have is b by d is equal to 12 dl by 150 d gb. And if we expand this, so this is 12 dol e to the power - ql by kt by 150 d0 gb. So therefore d over b is equal to 150 by 12 into do gb by dol into e to the power ql - q gb over kt.

So here since the temperature is already taken as t is equal to 0.9 tm, so the boundary is only dependent on the grain size, there is no dependence on stress. So the transition from Coble to Nabarro Herring creep is not dependent on stress but it is only dependent on the grain size, especially when the temperature is fixed. So, that is why if you look at the map, you see a certain value of d by b. So this is d by b for a given temperature, and that is what it means the transition from Coble to Nabarro Herring, there is no dependence on stress.

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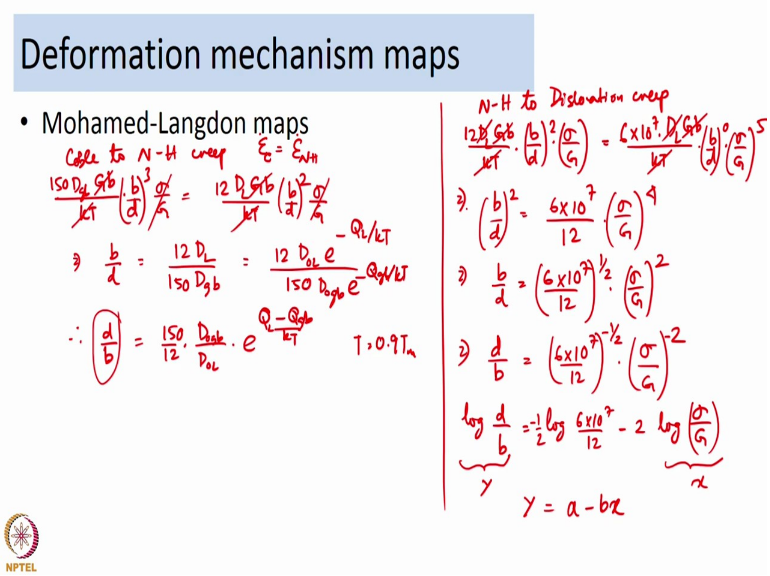

## Deformation mechanism maps

- Mohamed-Langdon maps

Coble to N-H creep $\dot{\varepsilon}_c = \dot{\varepsilon}_{NH}$

$$\frac{150 D_{gb}\, G\cancel{b}}{\cancel{kT}}\left(\frac{b}{d}\right)^3 \cancel{\frac{\sigma}{G}} = \frac{12 D_L\, G\cancel{b}}{\cancel{kT}}\left(\frac{b}{d}\right)^2 \cancel{\frac{\sigma}{G}}$$

$$\Rightarrow \frac{b}{d} = \frac{12 D_L}{150 D_{gb}} = \frac{12 D_{0L}\, e^{-Q_L/kT}}{150 D_{0gb}\, e^{-Q_{gb}/kT}}$$

$$\therefore \boxed{\frac{d}{b}} = \frac{150}{12} \cdot \frac{D_{0gb}}{D_{0L}} \cdot e^{\frac{Q_L - Q_{gb}}{kT}} \qquad T = 0.9 T_m$$

N-H to Dislocation creep

$$\frac{12 \cancel{D_L}\, \cancel{Gb}}{\cancel{kT}} \cdot \left(\frac{b}{d}\right)^2 \cdot \left(\frac{\sigma}{G}\right) = \frac{6\times10^7 \cdot \cancel{D_L}\, \cancel{Gb}}{\cancel{kT}} \cdot \left(\frac{b}{d}\right)^0 \cdot \left(\frac{\sigma}{G}\right)^5$$

$$\Rightarrow \left(\frac{b}{d}\right)^2 = \frac{6\times10^7}{12} \cdot \left(\frac{\sigma}{G}\right)^4$$

$$\Rightarrow \frac{b}{d} = \left(\frac{6\times10^7}{12}\right)^{1/2} \cdot \left(\frac{\sigma}{G}\right)^2$$

$$\Rightarrow \frac{d}{b} = \left(\frac{6\times10^7}{12}\right)^{-1/2} \cdot \left(\frac{\sigma}{G}\right)^{-2}$$

$$\underbrace{\log \frac{d}{b}}_{y} = -\frac{1}{2} \log \frac{6\times10^7}{12} - 2 \underbrace{\log\left(\frac{\sigma}{G}\right)}_{x}$$

$$y = a - bx$$

Now let us look at the 2nd case, which is Nabarro Herring to dislocation creep. So, again we have 12 dl gb by kt into b by d square into sigma by g is equal to 6 into 10 to the power 7 dl gb by kt. We know there is no grain size dependent, so b by d to the power zero into sigma by g to the power 5. So, what we get is kt, kt cancel out, gb, gb, dl, dl cancel out each other. So you have b by d square is equal to 6 into 10 to power 7 divided by 12 into sigma by g to the power 4. So the rest of the top cancel each other, so this is what you have.

So now if you do b by d is equal to 6 into 10 to the power 7 by 12 half into sigma by g square. So this implies d over b is equal to 6 into 10 to the power 7 by 12 - half into sigma by g -2. Now if you look at the map, they have plotted it on the log log scale, so if you take log d over b, so what you will have is log of - half log of 6 into 10 to the power 7 by 12 - 2 log sigma by g. So with, so this is going to be your x and this is going to be y. So if you see it is a - bx kind of line. So you have a negative slope, so the d by b is dependent on the stress that is used. And so you have a straight line equation of state and with a negative slope.

So if you look at the map, that is what it is. So, Nabarro Herring creep to climb, especially see there is a straight line, the transition is a straight line with a negative slope. So that is how you can determine the bounds for Nabarro Herring creep and Coble. So, this is the concept behind the generation or development of deformation mechanism maps. So you can use this way, you can use this approach to create maps of any material that you want. Of course you need to have the details of the microstructure, the applied stress and the temperature, etc. For creating these maps.

So that brings me to an end, to the end on the portion of deformation mechanism maps. So, now we will quickly go through some tutorials. So the objective is to solve some problems related to the portions on creep mechanisms. So all the portion that we covered about newtonian viscous creep and power law creep and in the deformation mechanism maps and things like that, so we are basically going to solve few problems to develop our concepts further. So, the first question is as follows, problem 1. So, i will be, in the next slide i will be showing you creep data.

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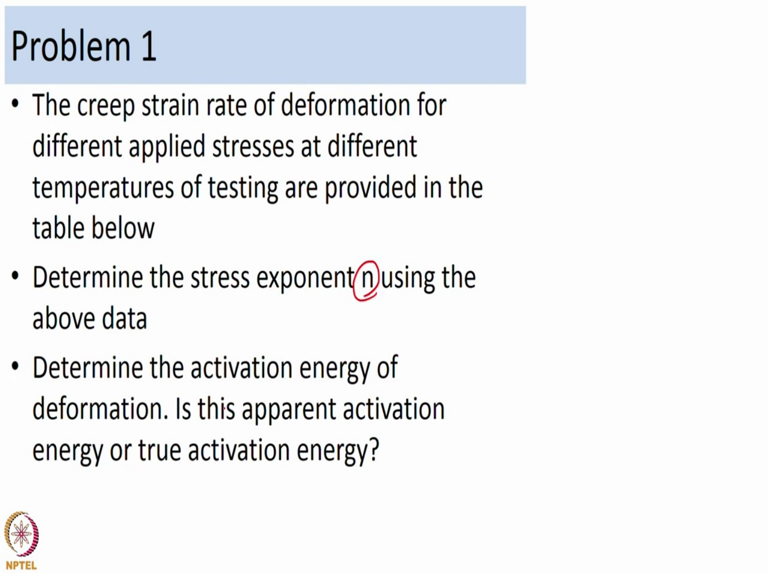

## Problem 1

- The creep strain rate of deformation for different applied stresses at different temperatures of testing are provided in the table below
- Determine the stress exponent n using the above data
- Determine the activation energy of deformation. Is this apparent activation energy or true activation energy?

So i will give you data of temperature, stress, applied stress and strain rate of deformation and the goal of this is to determine the, stress exponent n using the data given in the table and you also have to determine the activation energy of deformation. And the question that you also have to answer is, is this activation energy using the approach that we are using, will that be apparent activation energy or true activation energy. So, that is the purpose of this work, of this question.

So the table contains the data, the creep data, so tests were carried out, creep tests were carried out at 3 different temperatures, 350 degrees centigrade, 400 degrees centigrade and 450 degrees centigrade. And the stresses that were used were varied from 10, 50 and 100. So, 3 different temperatures and 3 different applied stresses and the creep strain rate, basically the minimum creep data or the steady-state creep rate, that data is also given in this table. So the question is how do you find out stress exponent n from this data.

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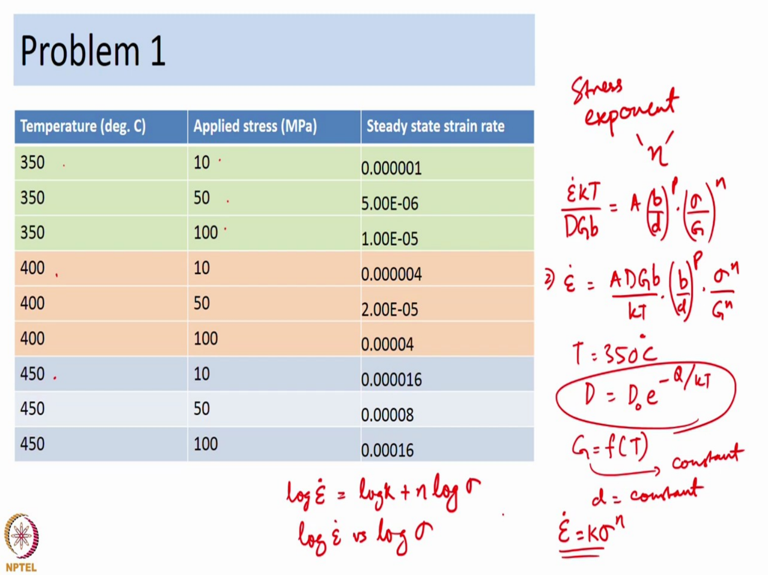

## Problem 1

| Temperature (deg. C) | Applied stress (MPa) | Steady state strain rate |
|---|---|---|
| 350 | 10 | 0.000001 |
| 350 | 50 | 5.00E-06 |
| 350 | 100 | 1.00E-05 |
| 400 | 10 | 0.000004 |
| 400 | 50 | 2.00E-05 |
| 400 | 100 | 0.00004 |
| 450 | 10 | 0.000016 |
| 450 | 50 | 0.00008 |
| 450 | 100 | 0.00016 |

Stress exponent 'n'

$$\frac{\dot{\varepsilon}kT}{DGb} = A\left(\frac{b}{d}\right)^p \cdot \left(\frac{\sigma}{G}\right)^n$$

$$\Rightarrow \dot{\varepsilon} = \frac{ADGb}{kT} \cdot \left(\frac{b}{d}\right)^p \cdot \frac{\sigma^n}{G^n}$$

T = 350°C

$$D = D_0 e^{-Q/kT}$$

$G = f(T) \xrightarrow{} \text{constant}$

$d = \text{constant}$

$$\dot{\varepsilon} = k\sigma^n$$

$$\log \dot{\varepsilon} = \log k + n \log \sigma$$

$\log \dot{\varepsilon}$ vs $\log \sigma$

So to understand that we can look at the Bird Mukherjee Dorn equation again. So you have epsilon kt by dgb is equal to a b by d to the power p and sigma by g to the power n. So if you take the relation, if you take all the terms onto the other side, so you have a dgb by kt into b by d to the power p into sigma to the power n by g to the power n. Now for a given temperature, so say if temperature is 350 degrees centigrade, d, which is, we do not know the activation energy, we do not know whether it is grain boundary diffusion controlled or later diffusion controlled.

But what we know is that he is going to be some t0 into e to the power – Q over kt. And for a given temperature, this is going to be constant, okay. And we also know g is a function of temperature and for a given temperature G is also a constant. The microstructure, the grain size d is a constant, at that temperature and also we are assuming that there is no grain growth happening.

Typically if you remember, we said that your grain size should be stabilised at a temperature higher than the test temperature. So assuming that, so d is also a constant. So there are only 2 variables here, epsilon dot and sigma. So the rest of the terms can be taken as constant k and so essentially this becomes epsilon dot is some constant k times sigma to the power n. So for a given temperature and given microstructure, if you make a lot of log epsilon dot, if you take locks, then this becomes log k + n log sigma.

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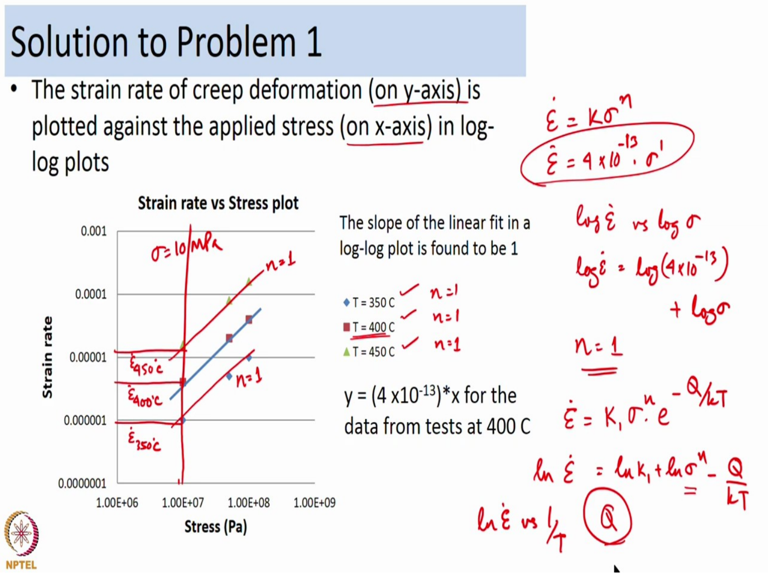

## Solution to Problem 1

- The strain rate of creep deformation (on y-axis) is plotted against the applied stress (on x-axis) in log-log plots

The slope of the linear fit in a log-log plot is found to be 1

- ◆ T = 350 C ✓ $n=1$
- ■ T = 400 C ✓ $n=1$
- ▲ T = 450 C ✓ $n=1$

y = (4 x10$^{-13}$)*x for the data from tests at 400 C

$\dot{\varepsilon} = K\sigma^n$

$\boxed{\dot{\varepsilon} = 4\times10^{-13}\cdot\sigma^1}$

$\log\dot{\varepsilon}$ vs $\log\sigma$

$\log\dot{\varepsilon} = \log(4\times10^{-13}) + \log\sigma$

$\underline{\underline{n = 1}}$

$\dot{\varepsilon} = K_1\sigma^n \cdot e^{-Q/kT}$

$\ln\dot{\varepsilon} = \ln K_1 + \underline{\underline{\ln\sigma^n}} - \frac{Q}{kT}$

$\ln\dot{\varepsilon}$ vs $1/T$ ⓠ

And so if you plot log epsilon dot versus log sigma, you should essentially get a straight line, so this is a equation of the straight line. And the slope of that line will give you the stress exponent n. So, that is what i have done here and, so you have strain rate of creep deformation on the y axis and the applied stress on the x axis in a log log plot. And i have taken, i have done that for all the 3 temperatures, 350, 400 and 450. Let us take the case of 400 degrees centigrade, data corresponding to 400 degrees centigrade.

And the plot basically turned out to be something like that. So the strain rate of deformation, so i give it if it, basically power law it because epsilon dot is equal to k sigma to the power n. So if i give, when i gave it a power law fit, what i found was epsilon dot is basically a 4 into 10 to the power -13 into sigma to the power n. So, x is sigma, so this is what i got from the power law fit. And to the data, house course one way of doing it is if you take your log epsilon dot and log sigma values, you could also give it a straight line and fit and then see what are the values.

So what you would have got in that case is log epsilon dot is equal to log of 4 into 10 to power -13 + log sigma. And so n is equal to 1. So what we found out from this is the lowercase and value, so n is equal to 1 for the tests being carried out at 350 degrees centigrade. And if you notice the other data is also, the slopes of the other lines are also parallel to the line that we determined. So the slope is more or less the same in the other case is also and if you do it, if you carry out these exercise on your own, you will notice that n is equal to 1 for the other 2 temperatures also.

So n to 1 at 350, n is equal to 1 at 400 and n is equal to 1 at 450 degrees centigrade. So this shows that the stress exponent is one for the temperatures and the stresses that were used for this case. Now let us look at determining the activation energy of deformation. So again if we go back to this case, so epsilon dot is equal to a DGb by kT into b by d to the power p sigma over G to the power n. Now, if you take, so you have 3 temperatures, so you have to, to get the activation energy, so epsilon dot can also be represented as constant k1 and sigma beta exponential - q over kt.

So in this case if you plot epsilon dot lon of, if you do, if you take, it would take ln of epsilon dot, you will get ln k1 + lon sigma n - Q over kT. So, if you take a plot of ln epsilon dot versus 1 over t, then you will get the ql you as the slope of the line. So but this has to happen at a constant stress because now for this to happen, the stress to be constant. So which means you should take one constant stress value and then look at the strain rates corresponding to these different temperatures.

So in this particular case, we can take the stress of 10 to the power 7 MPa, so basically 10 MPa, so if you take that, so take sigma is equal to 10 MPa and look at the strain rates corresponding to the 3 points. So, this is strain rate corresponding to 350 degrees centigrade, strain rate corresponding to 400 degrees centigrade and strain rate corresponding to 450 degrees centigrade. So these are the 3 levels for a constant stress of 10 MPa. And now if you plot epsilon dot versus 1 over T, so this is what you will get.

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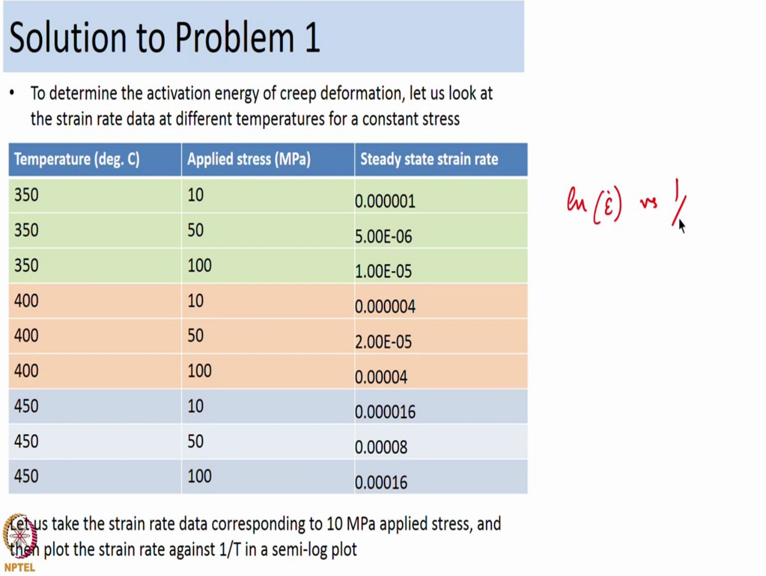


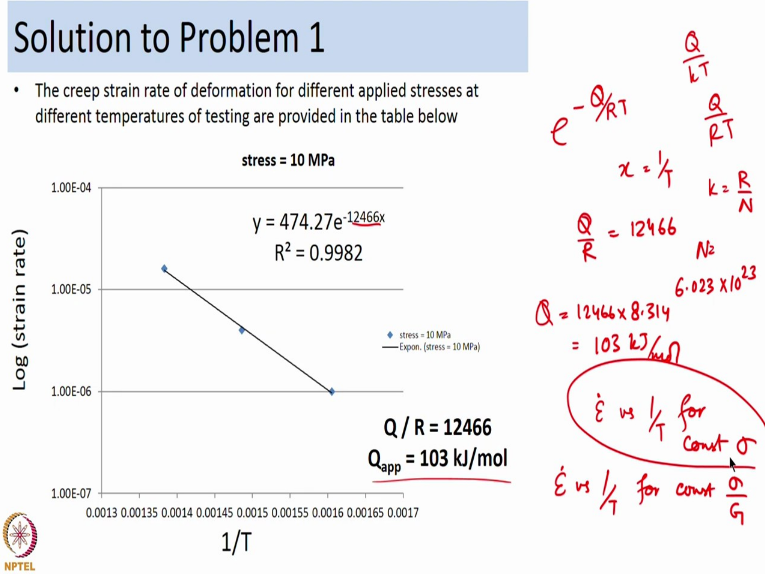
## Solution to Problem 1

- To determine the activation energy of creep deformation, let us look at the strain rate data at different temperatures for a constant stress

| Temperature (deg. C) | Applied stress (MPa) | Steady state strain rate |
|---|---|---|
| 350 | 10 | 0.000001 |
| 350 | 50 | 5.00E-06 |
| 350 | 100 | 1.00E-05 |
| 400 | 10 | 0.000004 |
| 400 | 50 | 2.00E-05 |
| 400 | 100 | 0.00004 |
| 450 | 10 | 0.000016 |
| 450 | 50 | 0.00008 |
| 450 | 100 | 0.00016 |

Let us take the strain rate data corresponding to 10 MPa applied stress, and then plot the strain rate against 1/T in a semi-log plot

$\ln(\dot{\varepsilon})$ vs $1/$



## Solution to Problem 1

- The creep strain rate of deformation for different applied stresses at different temperatures of testing are provided in the table below

Q / R = 12466

$Q_{app}$ = 103 kJ/mol

$\frac{Q}{kT}$

$e^{-Q/RT}$

$\frac{Q}{RT}$

$x = 1/T$

$k = \frac{R}{N}$

$\frac{Q}{R} = 12466$

$N =$

$6.023 \times 10^{23}$

$Q = 12466 \times 8.314$

$= 103$ kJ/mol

$\dot{\varepsilon}$ vs $1/T$ for const $\sigma$

$\dot{\varepsilon}$ vs $1/T$ for const $\frac{\sigma}{G}$

So, log strain rate versus 1 over T, so you can give it an exponential fit, you can just take the direct data, directly and give it an exponential fit or you convert your strain rate terms, you convert your strain rate data, convert your strain rate data into ln of strain rate and then plot it against 1 over t. In either case, what you will get is, the exponential term, that is e to the power – Q/ kT or Rt, let us say Q over RT. So since you are doing it, x is 1 over T because your plot is against 1 over T, so x is 1 over T.

So, what you are getting here is Q over R is basically 12466. So, if you remember an earlier class, portion i also mentioned, you could either do it as Q over Kt or Q over RT, it would not change because k is basically R over N and N is the avogadro's constant, which is 6.023 into 10 to the power 23. So if you take care of the units, you are always going to get the right value of q. So, here we are taking the universal gas constant r, so q becomes 12466 into 8.314, so that approximately is 103 kilojoule per mole.

So if you remember i asked question that the activation energy that you are determining in this case, is it the true activation energy or apparently activation energy. Well, the answer is it is going to be apparent activation energy and the reason is, you have taken the strain rates versus 1 over temperature for constant sigma. But for determining real activation energy or true activation energy, your strain rate versus 1 over T should be for constant sigma over G.

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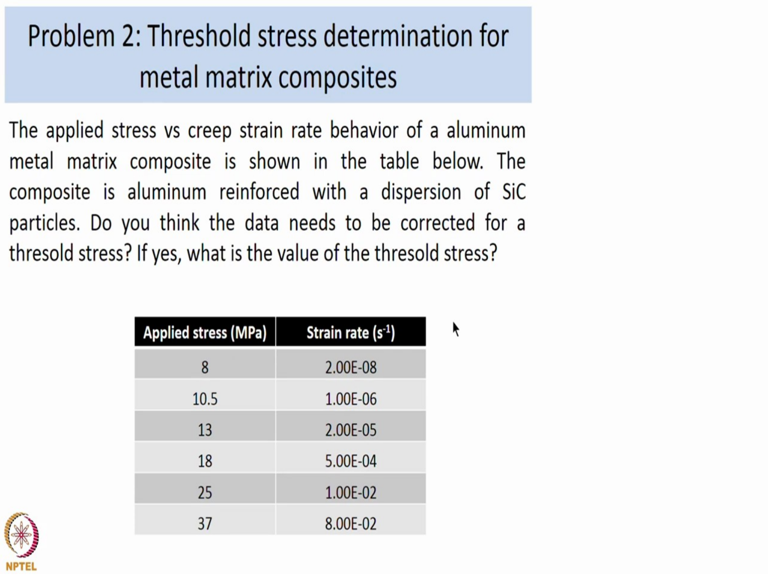

## Problem 2: Threshold stress determination for metal matrix composites

The applied stress vs creep strain rate behavior of a aluminum metal matrix composite is shown in the table below. The composite is aluminum reinforced with a dispersion of SiC particles. Do you think the data needs to be corrected for a thresold stress? If yes, what is the value of the thresold stress?

| Applied stress (MPa) | Strain rate ($s^{-1}$) |
|---|---|
| 8 | 2.00E-08 |
| 10.5 | 1.00E-06 |
| 13 | 2.00E-05 |
| 18 | 5.00E-04 |
| 25 | 1.00E-02 |
| 37 | 8.00E-02 |

Since we chose the first case for our analysis, so the data that we get or record is only apparently activation energy. So this is how you can determine the activation energy from deformation prop creep data. So, let us go to problem number 2, so if you remember we said, in certain cases you can have n greater than 7, although it is not power law breakdown. And n greater than 7 can happen if you are studying metal matrix composites. And for metal matrix composites you have to introduce a threshold stressed up to rationalise the data and to get stress exponent value is close to 5 as is expected for a power law creep behaviour.

So here in this particular problem i am giving you the applied stress versus creep strain rate data for an aluminum metal matrix composite. And the composite is basically aluminum reinforced with a portion of silicon carbide particles. Now, the first question that i have for you is, do you think this data rates to be corrected for a threshold stress. And the 2nd question is if yes, then what is the value of threshold stress. So, there are 2 portions, the first portion is you could tell me whether this data needs to be corrected for threshold stress, if it needs to be then what is the value of the threshold stress so that you get your stress exponents within the range of 4 to 7.

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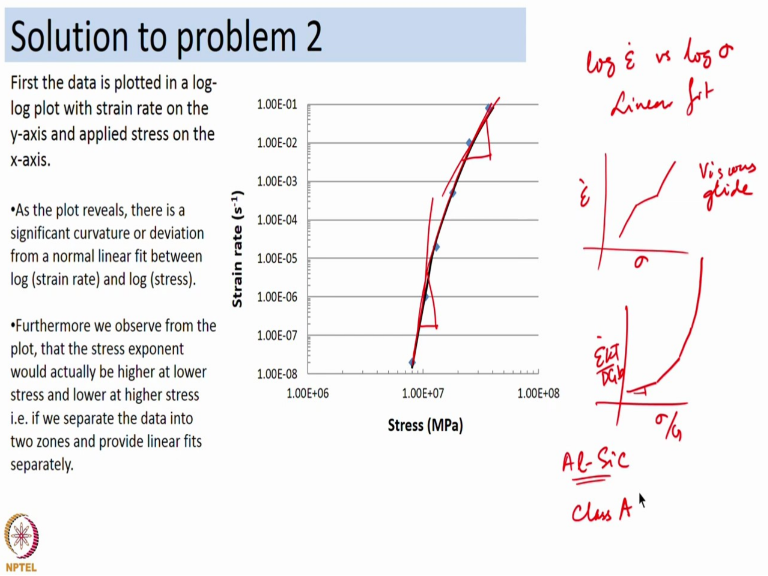

## Solution to problem 2

First the data is plotted in a log-log plot with strain rate on the y-axis and applied stress on the x-axis.

- As the plot reveals, there is a significant curvature or deviation from a normal linear fit between log (strain rate) and log (stress).
- Furthermore we observe from the plot, that the stress exponent would actually be higher at lower stress and lower at higher stress i.e. if we separate the data into two zones and provide linear fits separately.

So, in order to understand whether the threshold stress-based approach is to be taken or not, plot the straight rate of deformation against stress in a log log plot. So, if you look at the plot, there is a significant curvature or deviation from a normal linear fit between log and log stress. But typically when you have log epsilon dot versus log sigma, you expect a linear fit. But in this case if you notice, you have a slightly curved fit, so it is nonlinear fit. Furthermore, we observe from the plot that the stress exponent is actually higher at lower stresses.

So the stress exponent is higher at lower stresses, the slope and lower at higher stresses. The stress exponent is decreasing as you increase the stress level. Now this is not what we expect in a normal creep behaviour because a normal creep behaviour, you typically go from, except for viscous glide creep, where you see something like that, you have higher slopes, that lower slope and then higher slopes, this is for viscous glide mechanism creep. Otherwise you generally of the something like that.

You expect an increase in stress exponent from lower to, lower values to higher values as the stress increases. But here in this case we are not seeing that, you are seeing a reduction in stress exponent as the stress increases. And also you remember, this is a metal matrix composite and not a solid solution like class A alloy where you would have expected a reduction in stress exponent with increasing stress. So since this is the case , so basically this means, you will need to invoke a threshold stress value in order to rationalise this data.

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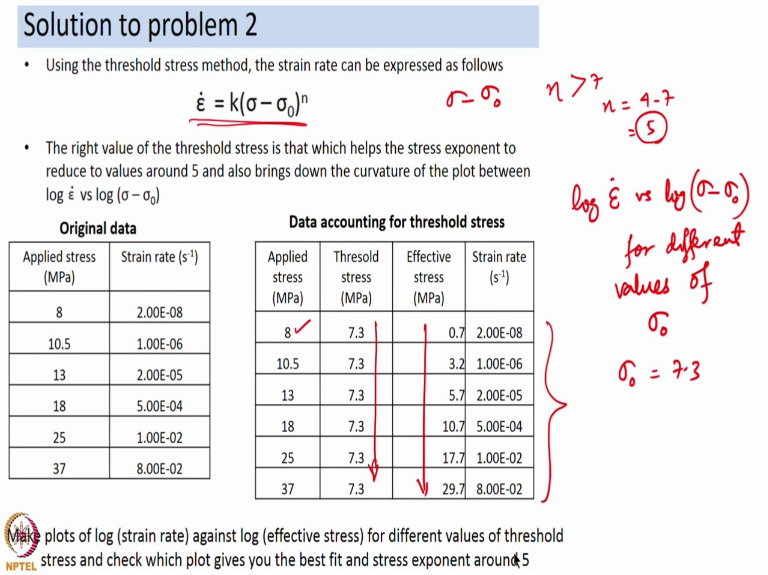

## Solution to problem 2

- Using the threshold stress method, the strain rate can be expressed as follows

$$\underline{\dot{\varepsilon} = k(\sigma - \sigma_0)^n}$$

$\sigma - \sigma_0$

$n > 7$

$n = 4\text{-}7$

$= ⑤$

- The right value of the threshold stress is that which helps the stress exponent to reduce to values around 5 and also brings down the curvature of the plot between log $\dot{\varepsilon}$ vs log $(\sigma - \sigma_0)$

$\log \dot{\varepsilon}$ vs $\log(\sigma - \sigma_0)$ for different values of $\sigma_0$

$\sigma_0 = 7.3$

**Original data**

| Applied stress (MPa) | Strain rate ($s^{-1}$) |
|---|---|
| 8 | 2.00E-08 |
| 10.5 | 1.00E-06 |
| 13 | 2.00E-05 |
| 18 | 5.00E-04 |
| 25 | 1.00E-02 |
| 37 | 8.00E-02 |

**Data accounting for threshold stress**

| Applied stress (MPa) | Thresold stress (MPa) | Effective stress (MPa) | Strain rate ($s^{-1}$) |
|---|---|---|---|
| 8 ✓ | 7.3 | 0.7 | 2.00E-08 |
| 10.5 | 7.3 | 3.2 | 1.00E-06 |
| 13 | 7.3 | 5.7 | 2.00E-05 |
| 18 | 7.3 | 10.7 | 5.00E-04 |
| 25 | 7.3 | 17.7 | 1.00E-02 |
| 37 | 7.3 | 29.7 | 8.00E-02 |

Make plots of log (strain rate) against log (effective stress) for different values of threshold stress and check which plot gives you the best fit and stress exponent around 5

So how do you do that? So, in the threshold stress method, the strain rate can be represented in the following form. So, the strain rate is actually dependent on an effective stress and the effective stress is sigma - sigma zero. And if the threshold stress value, if you identify the right value of this threshold stress, then you will see that the stress exponent, instead of being greater than 7, it will come to in the range of 4 to 7, let us say it comes close to 5. So, this is your original data and what you can do is applied stress, limit certain value of threshold stress, so let us take threshold stress as 7.3.

So the effective stress is it comes 0.7 for an applied stress of 8 MPa and this is how the effective stress will look like for different applied stresses. Please note that the threshold stress is taken as constant. And the strain that of deformation is over here, now make a plot of log strain rate versus log sigma - sigma nought. And for different values of sigma0. So here we said sigma nought is 7.3, when you could have other values of sigma0 and then carry out this, make these plots after taking different values of sigma0.

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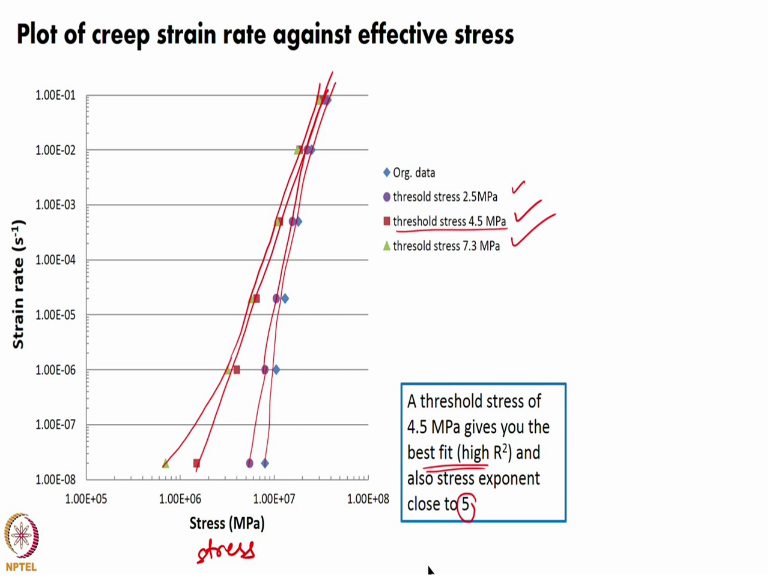

Plot of creep strain rate against effective stress

A threshold stress of 4.5 MPa gives you the best fit (high $R^2$) and also stress exponent close to 5

So if you see in this case, i have made a plot of strain rate versus stress, this is stress for different values of ritual stress. So in the first case i assume 2.5, in another case i assume 4.5, in the 3rd case i assume 7.3. And the original data is indicated here, so this is how the original data had a certain curvature. When i used a threshold stress of 2.5, i still got some curvature, although the curvature has reduced to some extent. When i use the threshold stress of 7.3, it actually went from being convex to concave as the stress increased.

And what i found out, that only at a threshold stress value of 4.5, we get a very good linear fit, so that means with a high confidence and also the stress exponent value can close to 5. So when you chose threshold stress value of 4.5, you got a linear fit between the strain rate and the effective stress. And you also got high, very good fit to the data and that is why for this material cost threshold stress is around 4.5 MPa. So that is the approach to be taken for determining the threshold stress for a metal matrix composite.

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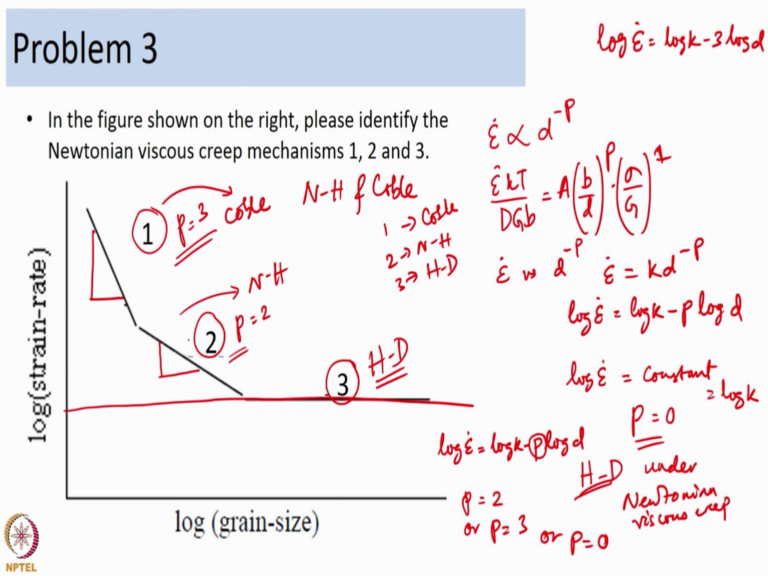

## Problem 3

- In the figure shown on the right, please identify the Newtonian viscous creep mechanisms 1, 2 and 3.

$\log\dot{\varepsilon} = \log k - 3\log d$

$\dot{\varepsilon} \propto d^{-p}$

$\frac{\dot{\varepsilon} kT}{DGb} = A\left(\frac{b}{d}\right)^{p}\cdot\left(\frac{\sigma}{G}\right)^{1}$

$\dot{\varepsilon}$ vs $d^{-p}$   $\dot{\varepsilon} = kd^{-p}$

$\log\dot{\varepsilon} = \log k - p\log d$

$\log\dot{\varepsilon}$ = Constant $= \log k$

$p = 0$

$\log\dot{\varepsilon} = \log k - p\log d$

$p = 2$ or $p = 3$ or $p = 0$

H-D under Newtonian viscous creep

N-H & Coble

1 → Coble
2 → N-H
3 → H-D

Now let us look at another problem, this is problem 3 and here i am talking about newtonian viscous creep mechanisms. This is a plot of log strain rate versus log grain size and what i want you to identify is, tell me what is mechanism, what is mechanism 2 and what is mechanism 3. So, how do you do that, well, if you see epsilon dot is proportional to d over -p, that also comes from the bird mukherjee dorn equation. Since this is newtonian viscous creep, so this is, n is equal to 1, so if you make a plot of epsilon dot versus grain size, so it actually is to epsilon dot versus d to the power - p.

So epsilon dot versus log epsilon dot, so let us say epsilon dot is some constant d to the power - p. So log epsilon dot will be log k - p log d. Now, let us see, let us look at case 3. So case 3 says log epsilon dot is equal to a constant, so if you see log epsilon dot is basically a constant, it does not depend on the grain size. So that could only happen if p is equal to 0. If p is equal to 0, then log epsilon dot will turn out to be log k, which means it is a constant.

So in what case will expect p is equal to 0, well p is equal to 0 only for harper don creep under d over viscous creep mechanism. So harper don creep has p is equal to 0, that is why 3 is harper don creep. Now we have only 2 more newtonian viscous creep mechanisms, nabarro herring and coble. So now let us look at the data here. So between 1 and 2, the higher slope is exhibited by 1, the lower slope is exhibited by 2. Now let us see that it again, so log epsilon dot is equal to log k - p log d.

So if sharper, larger drop-in strain rates will be achieved if p is large, the larger the value of p, later will be the drop in strain rates. So for newtonian viscous creep mechanisms we know p can be 2 or p can be 3 or p is equal to 0. We already found p is equal to 0, so we found that it is harper don creep. Now, between p is equal to 2 and p is equal to 3, if p is 3, so if log epsilon dot is equal to log k -3 log d. So if p is equal to 3, you will see a larger drop in strain rates and if p is equal to 2, you will see a milder drop in strain rates as d increases.

So between 1 and 2, larger drop in strain rates is observed for case 1. So, this has to be p is equal to 3 and a milder drop of stated is observed for p is equal to 2, so this is the difference between 1 and 2. And because we know p is equal to 3 for coble creep, so mechanism one is coble and mechanism is 2 is nabarro herring creep. So, 1 is coble creep, 2 is nabarro herring creep and 3 is harper don creep. So this is a fairly elaborate process that i showed it to come to the conclusion regarding, 2 and 3. But there is also simpler way of looking at this.

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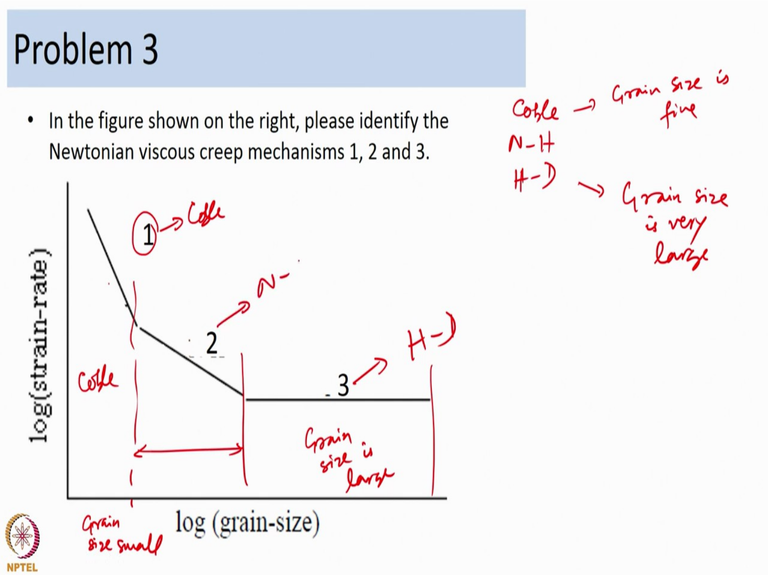

Problem 3

- In the figure shown on the right, please identify the Newtonian viscous creep mechanisms 1, 2 and 3.

Coble → Grain size is fine
N-H
H-D → Grain size is very large

Now if you see newtonian viscous creep mechanisms, the mechanism that would discussed in the lectures so far have been 3. There are 3 newtonian viscous creep mechanisms, coble, nabarro herring and harper don. And what we have also understood so far is that coble is dominated when the grain size is fine and nabarro, harper don is dominated when the grain size is very large. And nabarro herring creep falls in between coble creep, the grain sizes of nabarro herring creep is dominant for somewhere in between coble creep and harper don creep grain sizes.

So in that sense that if you see here, mechanism 1 has to be coble because we are talking about very fine grains sizes. Here the grain sizes are small, so this has to be coble. Whereas here, the grain sizes are the largest, in this particular plot, the larger grain sizes are belong to mechanism 3. So obviously this should be harper don and since the intermittent grain sizes, they will then correspond to nabarro herring creep. So mechanism 2 is coble, mechanism 2 is nabarro herring and mechanism 3 is harper don. So this is just another way of looking at this problem.

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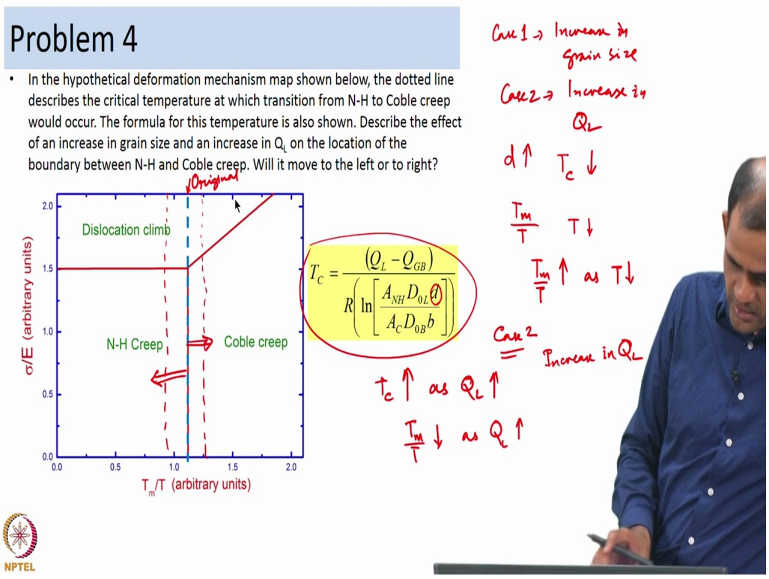

Problem 4

- In the hypothetical deformation mechanism map shown below, the dotted line describes the critical temperature at which transition from N-H to Coble creep would occur. The formula for this temperature is also shown. Describe the effect of an increase in grain size and an increase in $Q_L$ on the location of the boundary between N-H and Coble creep. Will it move to the left or to right?

$$T_C = \frac{(Q_L - Q_{GB})}{R\left(\ln\left[\frac{A_{NH} D_{0L} d}{A_C D_{0B} b}\right]\right)}$$

Case 1 → Increase in grain size

Case 2 → Increase in $Q_L$

$d \uparrow \quad T_c \downarrow$

$\frac{T_m}{T} \quad T \downarrow$

$\frac{T_m}{T} \uparrow$ as $T \downarrow$

Case 2

Increase in $Q_L$

$T_c \uparrow$ as $Q_L \uparrow$

$\frac{T_m}{T} \downarrow$ as $Q_L \uparrow$

And the last problem in the tutorial is related to the deformation mechanism map. So this is a hypothetical deformation mechanism map that I have shown below. And there is a dotted line, so there is a blue dotted line, this dotted line describes the critical temperature at which transition from nabarro herring creep to coble creep would occur. Now, the critical temperature, the formula for the critical temperature is also shown here. What I want you to tell me is what will be the effect of an increase in grain size and an increase in Ql.

So let us take 2 cases, one case 1 increase in grain size and case 2 is increase in Ql. So you have to tell me what happens when there is an increase in grain size? Will the line move to the left or to the right, secondly if you have an increase in Ql, will the line move to the left or to the right? So these are the 2 cases that you have to discuss and you have to tell me how does the line move based on case, for case 1 and case 2. Now let us look at case 1. So d increases, case 1 increase in grain size.

If you see in this equation, Tc is dependent on grain size d and d is in the denominator. So if d increases, Tc is going to come down. So, if Tc is coming down, on the x-axis we have Tm over T. So if d is coming down, so the critical temperature at which the transition happens is coming down, then what will happen if the line will move to do right. So Tm by T increases as T comes down. So the line will move to the right. So, what this tells us is as we increase the grain size, the domain in which coble creep operates is actually shrinking and the domain or the boundaries within which nabarro herring creep operates is actually expanding.

So that is the effect of increase in grain size. So nabarro herring creep is becoming more dominant as the grain size increases. So that was case one, now let us look at case 2 which is increase in Ql. So, when Ql increases, again Tc, Tc increases as Ql increases. So if Tc increases, Tm by T is going to come down. So Tm by T is going to come down as Ql increases. So what would happen is that now the line would actually shift to the left. So this original location, for the line is going to shift to the left as the Ql, activation energy lattice diffusion increases.

And that is because as the activation energy of lattice diffusion increases, it is going to be more difficult for diffusion of vacancies to happen through the lattice. So they would rather prefer to move through the grain boundaries because Qgb has not changed, it is only Ql which has increased. So, which means the contribution of coble creep to the strain rate strain rate of deformation is going to expand whereas the contribution of number herring creep is going to shrink.

So that is why when you have an increase in Ql, nabarro herring creep, domain of operation nabarro herring creep is going to shrink, and the domain of operation of coble creep is going to expand. So that is how the line would move depending on the value of the grain size as well as the value of your activation energy. So with that I come to the end of the tutorial, thank you.