Mechanical Behavior of Materials-1
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Lecture - 15
Effect of Strain-rate and Temperature

Okay, so welcome back. And today's topic is, we will try to understand the effect of strain-rate and temperature on flow stress. So you have seen that strain of course has effect on the flow stress and that is reflected very nicely by the use of that power law equation, where we see that as the strain increases flow stress increases, which is also called as work hardening or strain hardening.

Today, we will in this particular lecture, we will look at the effect of strain rate and temperature and then we will also see the combined effect of strain-rate and temperature.

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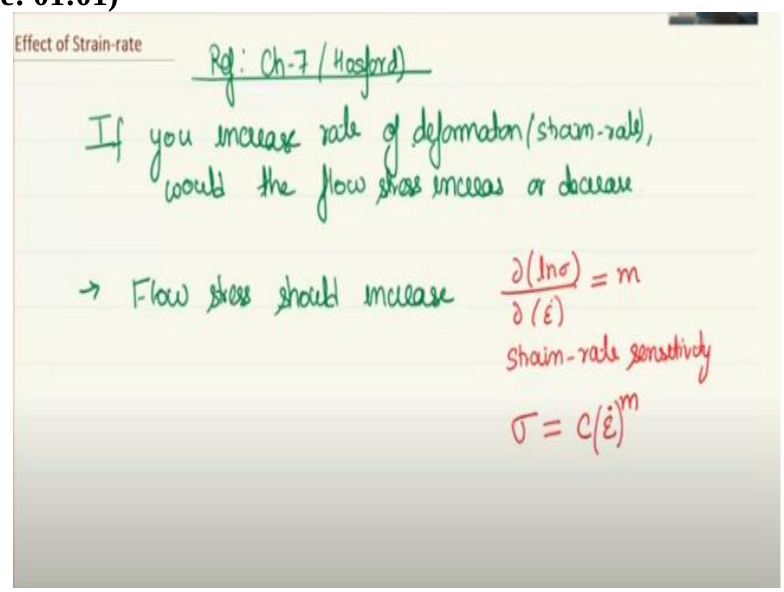

So the reference for this topic is chapter 7 from Hosford. Okay, so now let us start with a question. If you increase the rate of deformation do you expect to observe more resistance to flow stress or less resistance to flow stress assuming that the total strain remains the same? Rate of deformation is what translates to strain rate. Imagine that when you are deforming and there will be dislocations which have to move.

So we have not talked about the dislocations, but yes we will come to that. But for now, we know that there is something called as dislocation which lead to whose movement lead to deformation. Now if you are doing the deformation at a much higher rate, then the dislocations need to move at a much faster rate. They will need to overcome the resistance much faster and therefore, extra energy would be spent on that.

And therefore, you can qualitatively say that yes the flow stress should increase. In fact, you can have a relation which is described like this and this is given by a constant m which is also called as strain rate sensitivity and you can write it in other form which would be like this, $\sigma = C\dot{\varepsilon}^m$

where c would be a constant, m is the strain rate sensitivity and not the strain hardening coefficient strain hardening exponent.

So this is not the strain hardening exponent, this is a strain rate sensitivity. And this relation shows how flow stress would change with change in the strain rate.

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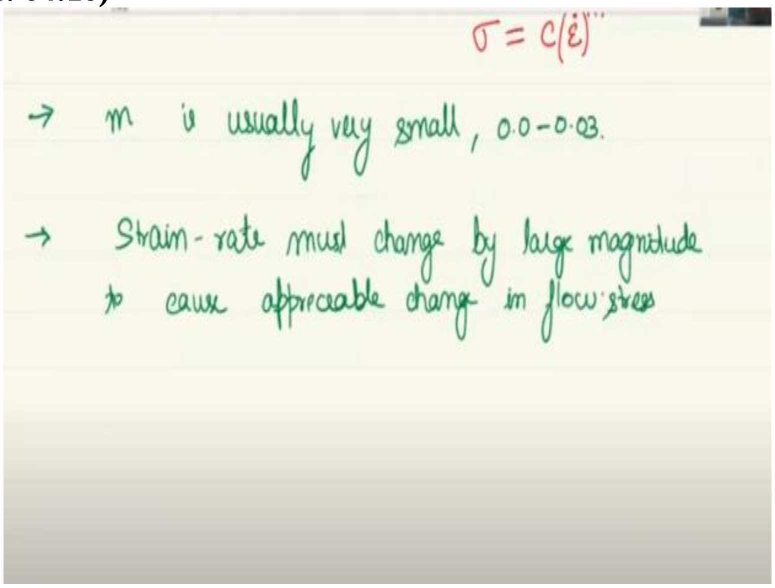

What is the value of m? m is usually very small, typically 0.0 to 0.03 at lower temperatures. However, things change drastically when you increase the temperature, particularly if you go above 0.5 T m. We will come back come to that in a moment. And when you have such a low value of m, what it means is that strain rate has to change by a very large factor for it to cause appreciable change to flow stress.

In fact it should change by orders of magnitude. So why would we be so concerned if that is the case if the strain rate has to change by a very large magnitude for it to cause any change in flow stress? The answer is that there are some processes where the strain rates are very high.

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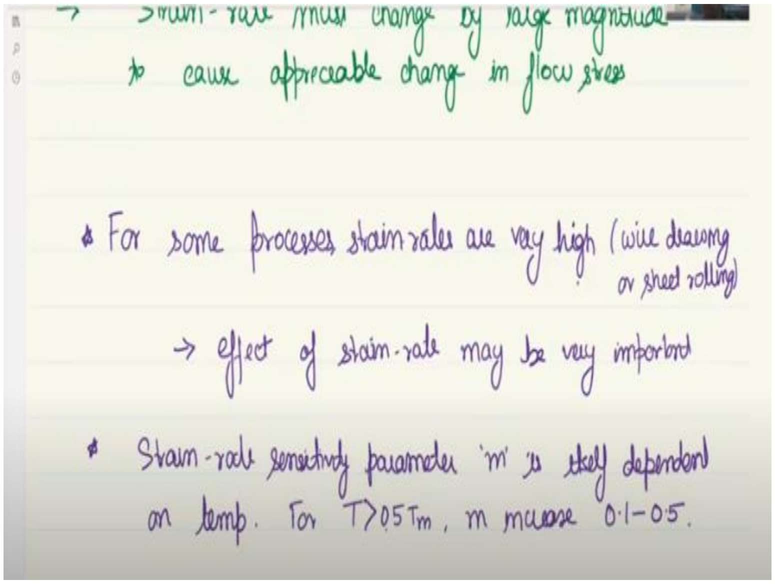

What are such processes? For example, sheet rolling, wire drawing. If you go on the YouTube you can look at some of the videos from industry and you would see that how fast these wires are getting drawn or how fast the sheets are getting rolled. So it is a very high strain rate. So the processes are like wire drawing or sheet rolling. So here, effect of strain rate may be very important.

So you may have calculated the flow stress at very low strain rate, but when you want to design the machine, when you want to understand how much forces would be required, then you say that it is fine that you are under driven you are under power, your machine is under power. And therefore, you need to have understanding of the effect of strain rate on the material.

Then you would be able to design the equipment and peripheral parts accordingly. Another important aspect about strain rate that we were discussing earlier is that strain rates, the strain rate sensitivity parameter m is itself variant or variable depending on the temperature. So is itself dependent on temperature for T greater than 0.5 T m, m increases to 0.1 to 0.15, in the range of 0.1 to 0.5. And that has a very important significance as we will see in a moment.

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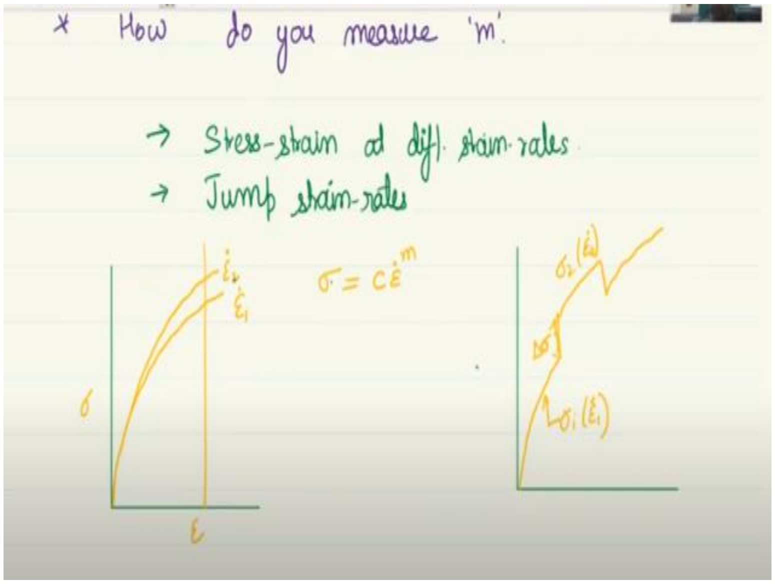

But for now, let us ask the other question, how do we measure the sensitivity parameter m because now that becomes an important thing or important parameter to define the flow stress and understand related behavior. So how do you measure m and the answer is there are two different ways. One is stress-strain at different strain rates and the other is jump strain rates.

So what happens in the first one what you are doing is you take the flow stress true stress true strain curve at one strain rate, then you again measure it at another strain rate. And for any particular strain value you apply that equation, which we know is sigma equal to c epsilon dot to the power m. So you will be able to get the value of m by applying this at two different points for the same string.

This is one method. The other one is which is called the jump strain rate method. What we do here is you are doing one single test at one particular strain rate, but then suddenly you jump the strain rate and therefore, the floor stress would increase. You do the test for some time, then again maybe you want you are going to come back and continue doing the test.

So this one is at σ_1 at ε_1 and this one is probably at ε_2. So there is a jump in the flow stress which can be easily measured, which I have written here as delta sigma.

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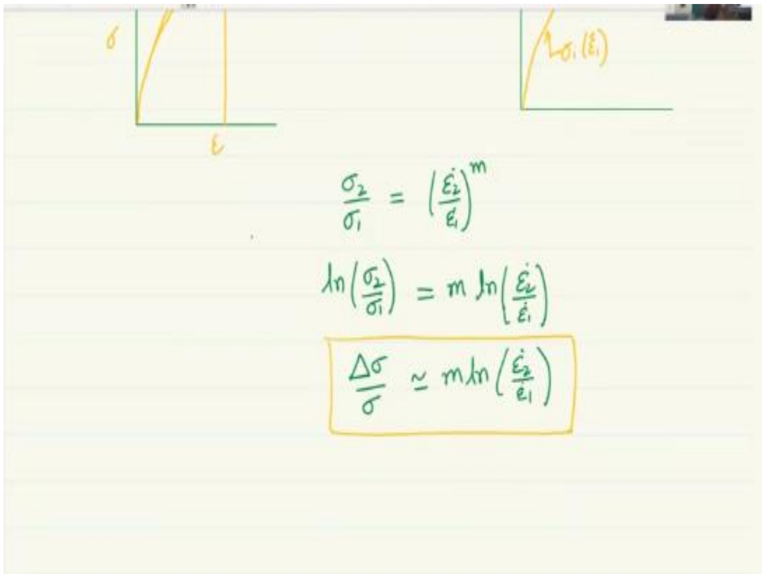

Now again we know the relation that sigma 2 we apply the same relation and the c gets cancelled if you take the ratio and therefore, you have dot to the power m. Now you can take log on both sides. So it is, in this case we already know that when the strain rate changes by a very large magnitude, you may see a small change in the flow stress. So probably you will see a flow stress change or 4, 5%.

And knowing that $\sigma_1$and σ_2 are not very different, it can be easily shown that this will translate to delta sigma by sigma. So whatever is the mean stress that you have at that particular point where it is jumping and the change in the flow stress is equal to approximately, so I will put the sign approximately, m. So this relation can be used to obtain the value of strain rate sensitivity parameter m where delta sigma is what we see over here, the change in the flow stress.

Sigma is the mean stress at which we were doing the test and $\dot{\varepsilon_2}$ and $\dot{\varepsilon_1}$ are the two different strain rates at which you have done the testing, okay. So now with this understanding, let us try to solve one example.

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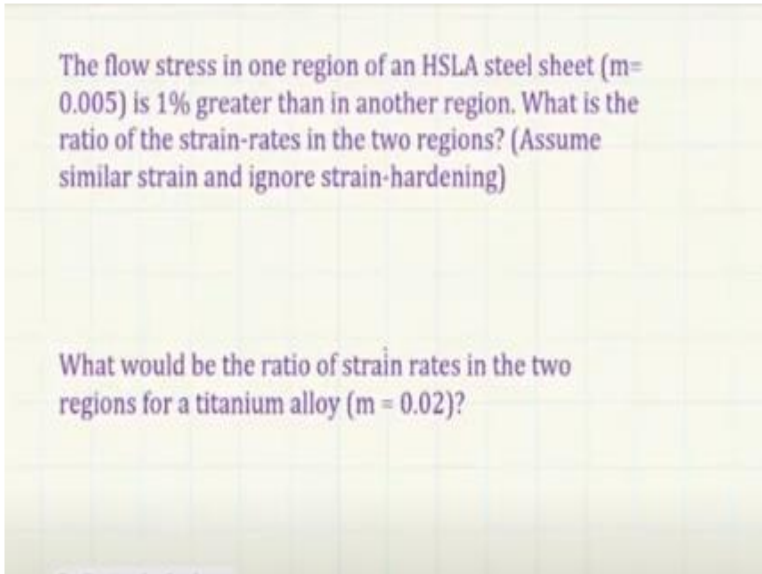

It is given or you are asked the flow stress in one region of an HSLA steel sheet, so you are given a steel sheet. And in one region, the stress the flow stress that is acting is 1% greater than in another region. So the amount of stress that is to be applied is 1% greater in one region than the other. What is the ratio of strain rates in the two region? Assume similar strain and ignore strain hardening.

So it is given that you can assume that the amount of strain is constant and what is changed what is different in the two places is only strain rate. And you can also assume that this difference is not because of strain hardening, because anyways they are going to the same amount of strain, but even otherwise, you may assume that there is no effect of strain hardening. So we have to find the ratio of strain rates in the two region. So what a ratio of strain rate would cause a change of 1% in the flow stress.

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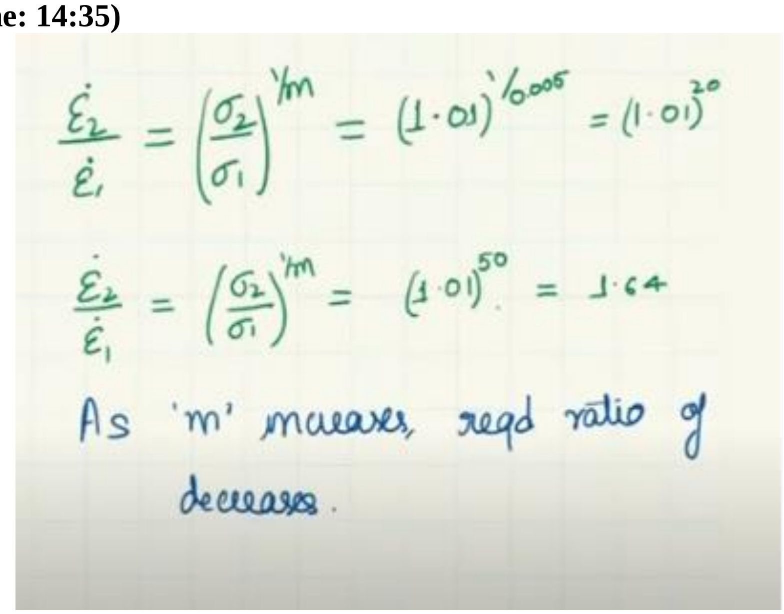

Now again from the equation that we know, we can write, we know that $\frac{\dot{\varepsilon}_2}{\dot{\varepsilon}_1}$ and this is equal to σ_2 / σ_1 and there should be power m but I will since we already know the this is what we are trying to find. So I will take the power m over here so it becomes 1 over m. And since sigma 2 is 1% higher, so I can say σ_2 / σ_1 is equal to 1.01.

And m is given as 0.005. So this becomes 1 by 0.005 which is equal to 1.01^{200}. And you would see that this comes to approximately 7.3. So strain rate of 10, strain rate ratio not even a fact, not even percentage change, the strain rate 2 should be 7.3 times that of strain rate 1 for you to obtain a flow stress difference of 1%. Now let us go to the next part of the problem.

Here we are asked what would be the ratio of strain rates in the two regions for a titanium alloy. So now the material has been changed. Earlier it was HSLA steel for which the m was 0.005. Now m is this little smaller value, m is equal to 0.02. So we will have to do the same thing. So assuming that we that everything else is same meaning 1%, the flow stress has increased by 1%.

So here the only thing that has changed is m. Now with that

$$\frac{\dot{\varepsilon}_2}{\dot{\varepsilon}_1} = \left(\frac{\sigma_2}{\sigma_1}\right)^{1/m} = (1.01)^{50} = 1.64$$

So the strain rate factor of only 1.64 can cause 1% difference in the flow stress for the case of titanium where m is higher. So what we learn is that as m increases, required ratio of strain rate decreases.

Meaning a strain rate ratio of only 1.64 is able to cause the same amount of flow stress difference when m is higher. So that is the take home message that we get over here. So now that is the example, which has which gives us a very good understanding about the effect of strain rate on flow stress that I mentioned earlier about super-plasticity.

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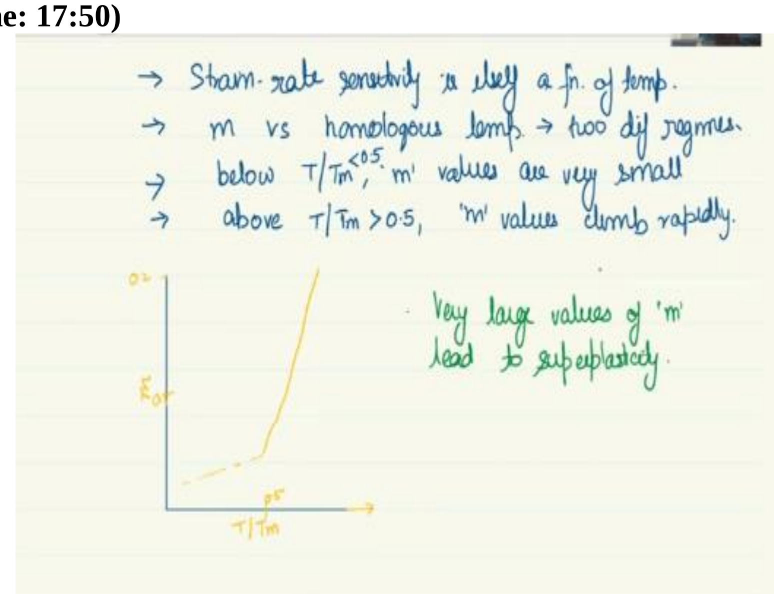

So we mentioned at one point that strain rate sensitivity is itself a function of temperature. If you plot m versus homologous temperature, then you can see two different regimes, will give you two different regimes. Below T over T_m you would see that m values are very small and not very temperature sensitive. However above, so T/T_m less than 0.5.

Above T/T_m greater than 0.5 m values are very large and climb rapidly. So if I were to schematically draw, this is how it would look like. So let us say here we have T/T_m. Somewhere over here you have 0.5. And here you have strain rate. Sorry this is m. So what you would see is that up to this close to 0.5 m values are very small, something of the order of 0.05.

So this is 0.1 and beyond 0.5 it climbs rapidly. So it reaches easily above 0.2 values. And what is the significance? The significance is that very large values of m lead to super-plasticity.

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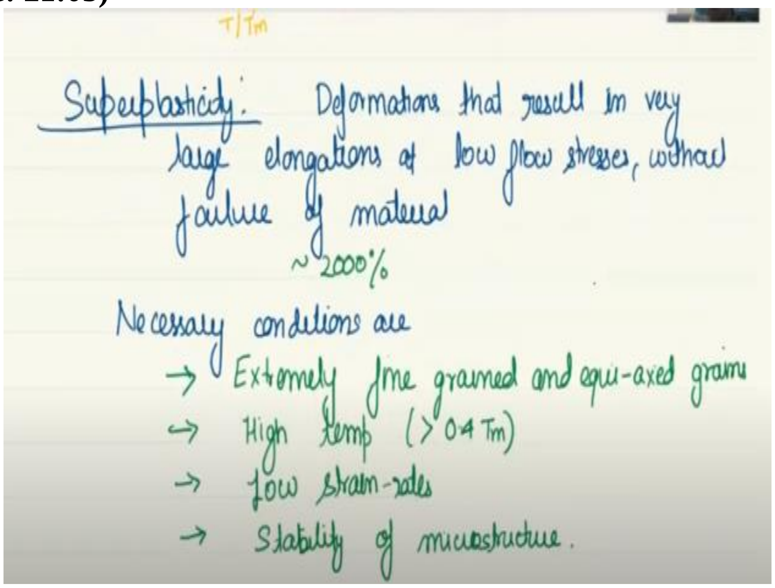

Now what is super-plasticity? Now, that we have invoked this term, let us quickly take a look at what is super-plasticity. So when you get very large elongations then you say that the material has super-plasticity. And that too would happen mostly at low flow stresses without failure of material. So that informal definition would be deformation which result in very large elongations at low flow stresses without failure of material.

So when I say very large elongations we are talking of the order of 2000% elongation meaning twenty times from its original size and the other necessary conditions are, of course one we have seen that very large values of m lead to super-plasticity which is of the order of greater than 0.5.

So when you have m greater than 0.5 that is when you see or observe super-plasticity, which is deformations that result in very large elongation at low flow stresses without failure of material and large elongation means of the order of 2000% meaning 20 times its original length. Other than m value being very high, what are the other conditions that we require?

The other conditions that we require are micro structurally it should be extremely fine grained material, fine grained and equi-axed because the theory is that this grains is small grains actually when you are doing very small slow small strain rate deformation, then these grains keep rotating and readjusting and that is why you are able to get such large elongations. Temperature should be relatively high. So that the flow can occur easily greater than $0.4\ T_m$.

And this is usually observed at very low strain rates and another condition that must be fulfilled now that we are talking about high temperature. So at that temperature it should not be that some kind of micro structural transformation is taking place. So stability of microstructure is also a required condition. Okay, so this is briefly about superplasticity which you would see when you have m of the order of 0.5 or higher.

And before that we saw the effect of strain rate on flow stress. Now one more topic just related to effect of strain rate is how would the relation equation look like, if both strain and strain rate are to be included into the equation.

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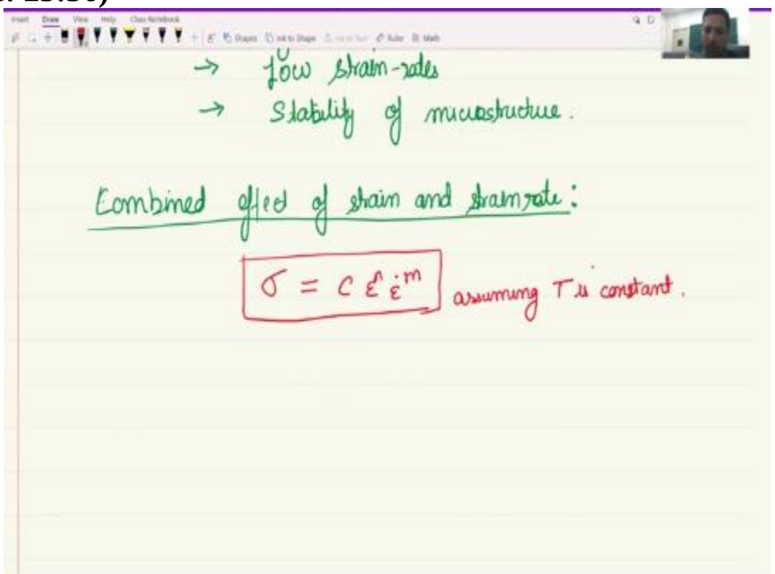

So let us say combined effect of strain and strain rate. And this is not very difficult. It is not a very difficult equation. This equation is simply

$$\sigma = c\varepsilon^n \dot{\varepsilon}^m$$

assuming that temperature is constant. So the flow stress can be given as a function of strain as well as strain rate.

And this equation is able to combine strain and strain rate which are two of the important parameters of deformation. The third one which is the temperature is kept constant. So we will now look at effect of temperature on flow stress. So again we will start with the question of if you increase the temperature what would happen to the flow stress? Would it increase, decrease or remain same?

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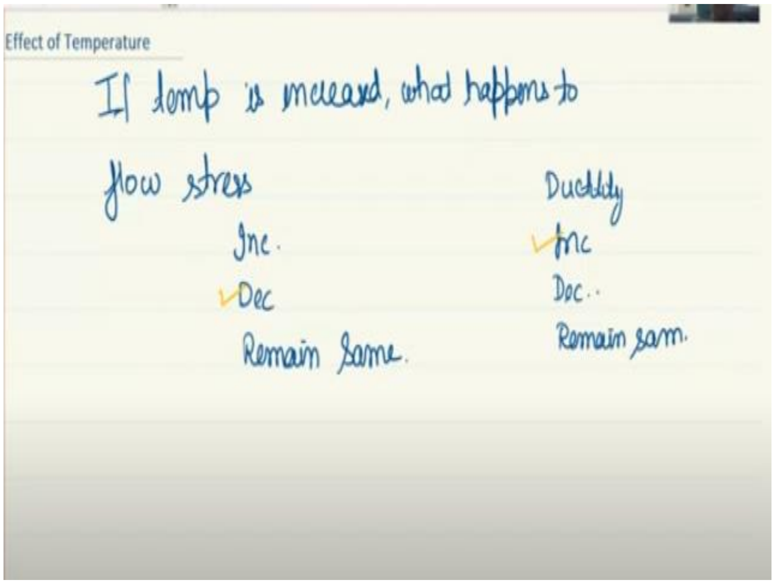

And same question also about ductility. What will happen to ductility if you increase temperature? So we know that if we increase the temperature for the flow stress we know that it decreases and ductility increases. So strength and flow stress decreases as thermally activated processes like climb, dislocation climb, we have not talked about dislocation, but again just understand that there are structural elements called dislocation, which are able to climb.

And this climb is assisted only at high temperature. So when the temperature is increased this climb process is facilitated and hence the deformation becomes easier and therefore strength decreases and which also implies that ductility increases. Ductility also increases because simultaneously there is recovery and recrystallization taking place in the material. And one of the simplest relations that describes the flow stress with temperature is given by this.

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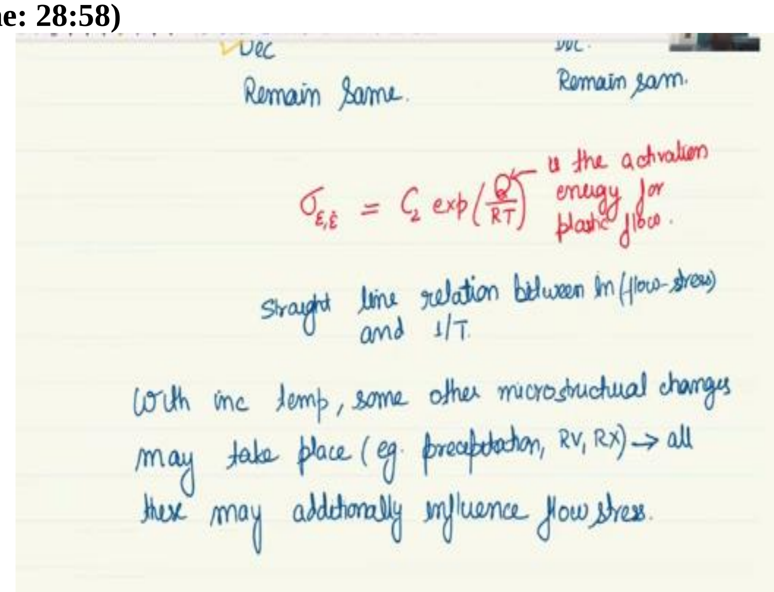

Assuming that strain and strain rate are constant. And I am using C. So let me put a C_2 just to make sure that this is not the same C as we have used earlier. So this term exponential (Q/RT) shows that this is a thermally activated process. And here Q is the activation energy for plastic flow. This relation predicts a straight line relation. So C_2 is a constant. So this relation predicts a straight line relation between log of flow stress and 1/T.

So you can take a log on both side and then you would see that this is a y=mx+c type of relation. Therefore what we have is that straight log of and 1/T. So this is capturing only the changes which are taking place because of the plastic flow. But with temperature some other changes may also take place. For example some other micro structural changes, for example precipitation, recovery crystallization.

So all these may influence flow stress. Additionally, may additionally. So next we will look at the combined effect of strain rate and temperature. So this is just a simple relation and as we have said that this is only assuming the plastic deformation being a thermally activated process and based on that this is the relation.

And other than that there may also be some other changes taking place with increase in temperature like recovery recrystallization, precipitation and other micro structural transformation. So all of these would also affect the flow stress.

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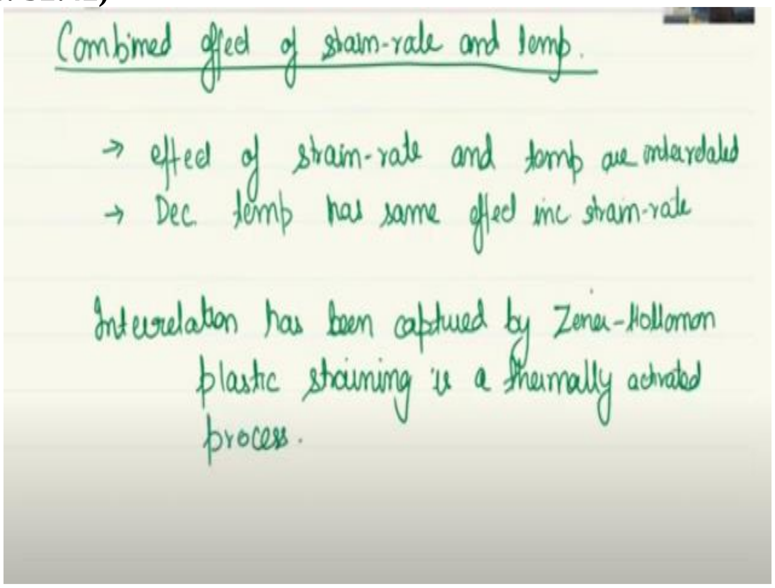

Now assuming all those changes are not taking place and then we have, then we may want to have a combined effect of strain rate and temperature. So the effect of temperature and strain rate are interrelated. It has been observed it was observed long ago that the effect of strain rate and temperature are interrelated. Decreasing temperature has same effect as increasing strain rate.

So this is also something we just observed that when you increase the strain rate, flow stress increases, when you decrease the temperature flow stress increases. So decreasing temperature has same effect as increased strain rate and all of these are related to the dislocations, the movement of the dislocations. So there has to be a correlation between strain rate and temperature and this has been captured by Zener-Hollomon.

And what they have done is they have proposed that plastics straining is a thermally activated process.

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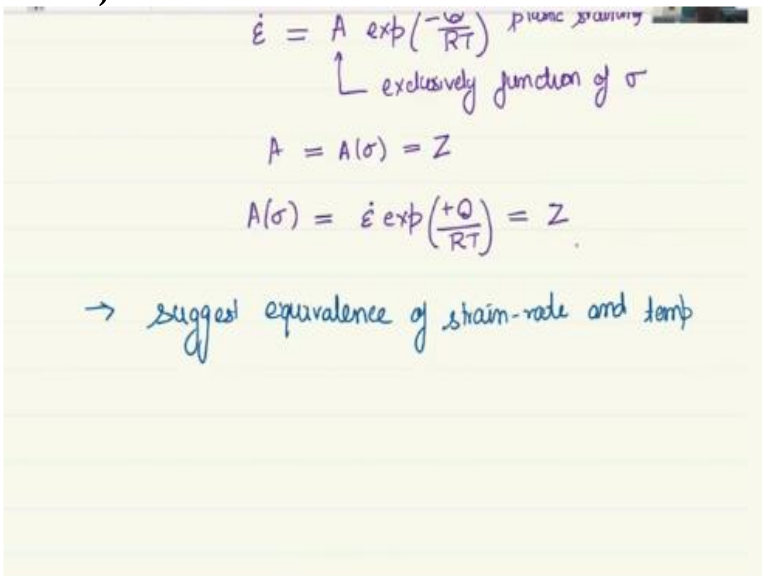

And based on this he derived the relation that

$$\dot{\varepsilon} = Aexp\left(-\frac{Q}{RT}\right)$$

where R is the gas constant, T is the temperature, and Q is the activation energy for the thermal activation, for the plastics straining, thermal activation energy for whatever process is causing this plastics straining. T is the temperature strain, $\dot{\varepsilon}$ is the strain rate.

And here A is exclusively function of flow stress. Therefore, we can write A= A(σ) and this is also denoted by the Zener-Hollomon parameter z. And therefore, we can write

$$A(\sigma) = \dot{\varepsilon}\exp\left(\frac{Q}{RT}\right) = Z$$

So let us say that one particular flow stress we are talking about. So that particular one flow stress can be obtained by different combinations of strain rate and temperature.

So this remains constant and this you can have different combinations. And therefore what we will see, we will see that it will give us some relations between the strain rate and temperature. So one thing is that it suggests equivalence of strain rate and temperature. So this relation as we had already hypothesized, now this relation concretizes that there is equivalence of strain rate and temperature.

And this was not done out of thin air. They have done some experiment which as they show are result from which and therefore based on that they have been able to establish this relation.

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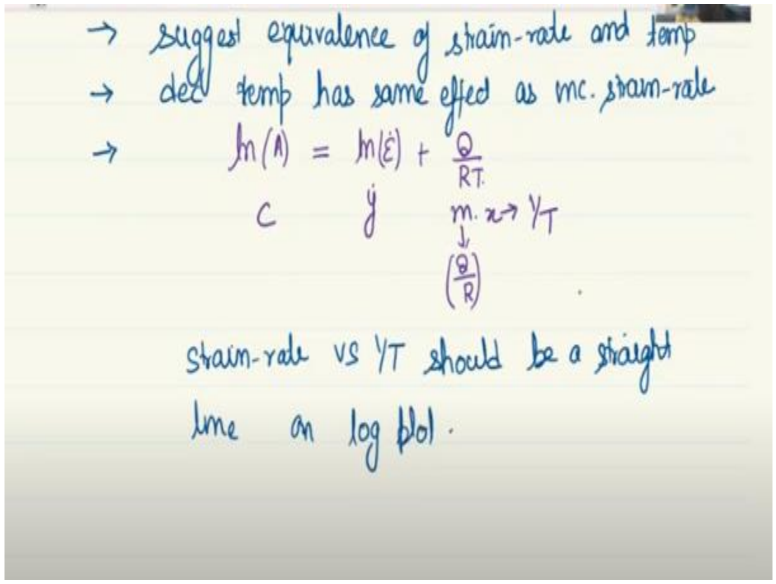

And now we can clearly see that decreasing temperature has same effect as, so what we were observing is now again put into the form of equation, it has same effect as increasing strain rate. Equation predicts a strain rate versus 1 over T should be a straight line. So if you take log on both sides what we get is

$$\ln A = \ln \dot{\varepsilon} + \frac{Q}{RT}$$

So here we have, this is y, this is c, this is m times x, where x is equal to 1/T.

This is y is $\ln \dot{\varepsilon}$ and m is Q/R. So this is a straight line relation. So what this is telling us this equation is that strain rate versus 1/T should be a straight line. And since the experiment of Zener-Hollomon on a log plot, okay that is to be made clear. So since the experiments of Zener-Hollomon, several other researchers have experimented and they have found that indeed you get a straight line relation.

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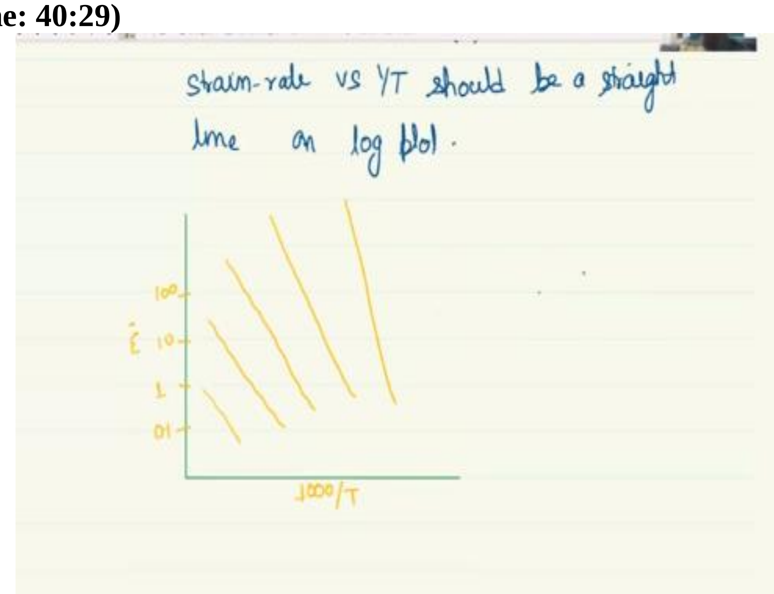

So you get something like this. So 0.1, 1, 10, 100 and here we can have 1000 by T, T is in Kelvin and you get approximately linear relation. So this is a very well established relation and we find that there is indeed a straight line relation between strain rate and 1/T.

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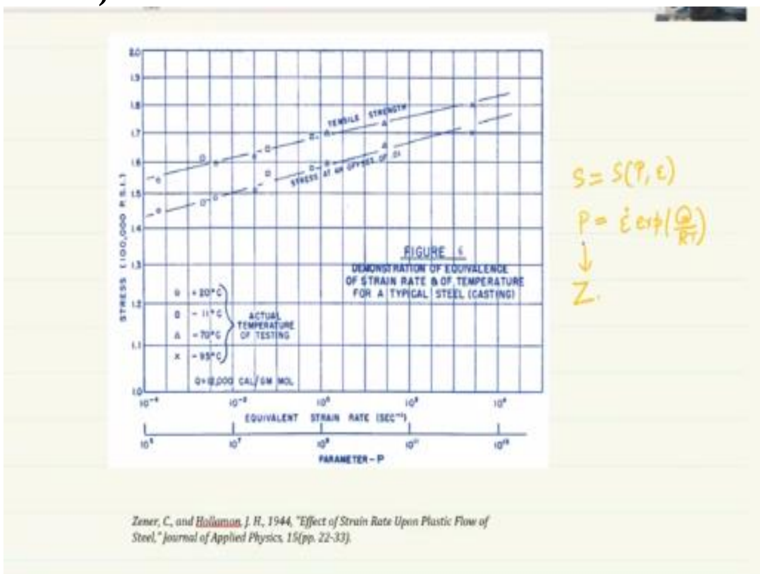

Now let us take a look at the original work done by Zener-Hollomon. So this is the original work done by them and here they have defined S which is flow stress equal to as a function of T and epsilon, where P is something you can say also it is the equivalent strain rate. So which is defined, which can be defined as. So just the equivalent strain rate and this one is the strain rate.

And therefore, you have this parameter P which is nothing but our same as the Zener-Hollomon parameter. And therefore, what you see is that as you keep changing, if you keep the strain constant, then it is only a function of strain rate. And amongst the strain rate, if you assume that there is equivalence between strain rate and temperature, so if you keep having the combination of strain rate and temperature, then you would have the same effect as if you were just changing strain rate.

And this is the flow stress and for a particular strain which is 0.01. So this is a linear hardening behavior or linear behavior basically as you would expect in a c equal to epsilon dot to the power m. That kind of relation is what we observe over here. So this is for the yield stress, this is for the tensile strength. So both of them show this behavior.

So they did indeed, they did this experiment, demonstrated equivalence of strain rate and temperature for a typical steel casting. And it is based on this that they proposed this relation between that Zener-Hollomon parameter and the equivalence between strain rate and temperature. So this brings us to the overall understanding of the combined effect of strain rate and temperature.

So now let us take a look at some example to get a better understanding of what is happening here.

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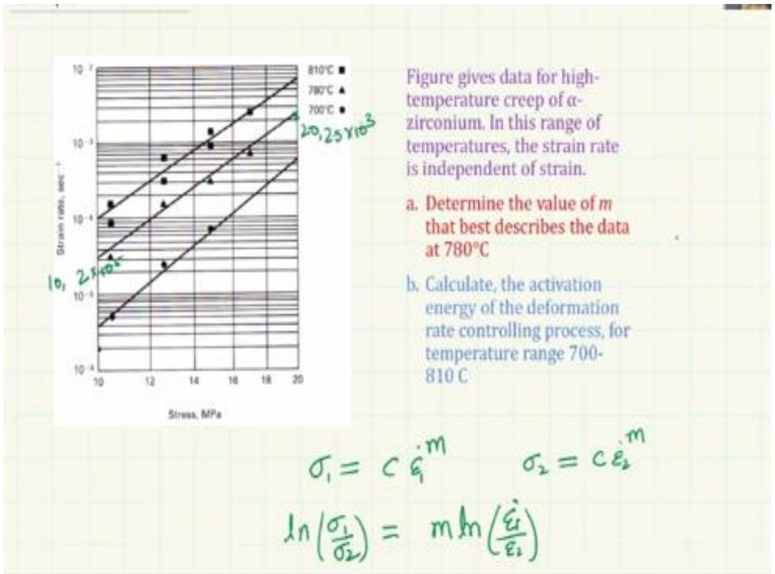

So here in this particular example, you are given data for high temperature creep of alpha zirconium. In this range of temperature the strain rate is independent of strain. So you can assume that strain rate is not dependent on strain. And you have to determine the value of m that best describes the data at 70 degrees Celsius. So you have given data for 700 degree, 780 degree and 810 degrees Celsius.

So here you can see that the flows, as the flow stress is increasing the strain rates are increasing and as the temperature is increasing again the strain rates are increasing. So based on this you have to calculate the value of m first for the 780 degree Celsius condition. Okay, so now let us begin with our relation.

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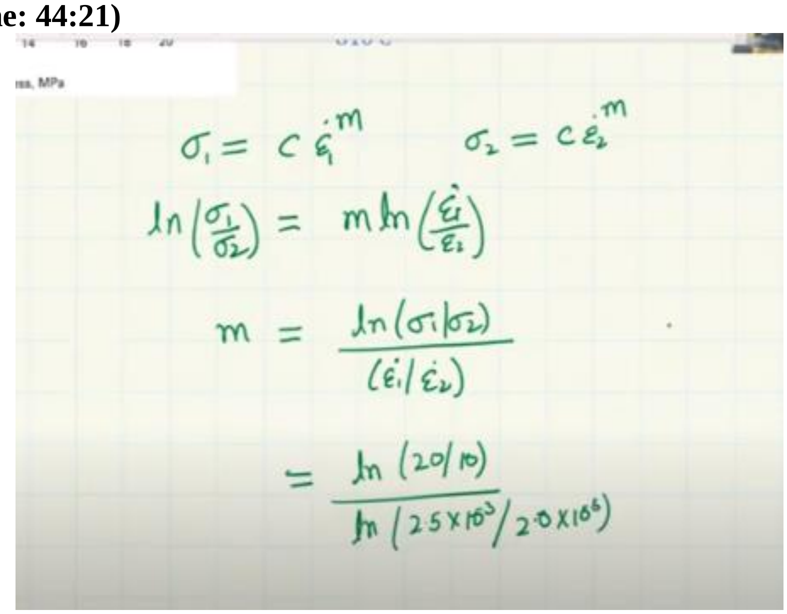

We know that the relation that we have to use is

$$\sigma = c\dot{\varepsilon}^m$$

So based on that we can get for two different stress conditions, sigma 1 sigma 2 equal to and if we take the ratio. So after taking log and would be on the outside and then it will. So what we are doing here is we will take $\sigma_1, and\ \sigma_2$. We will take a ratio, so c gets cancelled, and we have $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ and we take the ratio and then take the log.

So what we have here is m because m is constant on both the cases, m $\ln(\dot{\varepsilon}_1/\dot{\varepsilon}_2)$. And from here, we know that we can get m value if we have log of $\sigma_1\ and\ \sigma_2$, and $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$. So let us go back and for this is to be done for 780 degree Celsius, which is this one. So let us take values at this one and over here. So over here, stress is equal to 10 and the strain rate is equal to approximately 2.5 into 10^{-5}.

And here the stress is equal to 20. So this is actually 2.5. And here it is actually 2.5. So we are taking a little approximate values and because of that there will be a little variation, but then that is allowed. I mean, you will, if you are doing such calculation, there will be a range of acceptable answers. And here it will be 2.5 into 10^{-3}. So now we will put in this over here.

So we will assume this is σ_1, this is σ_2. Therefore, this becomes 20 /10. And this becomes $2.5\times10^{-3}/2.0\times10^{-5}$.

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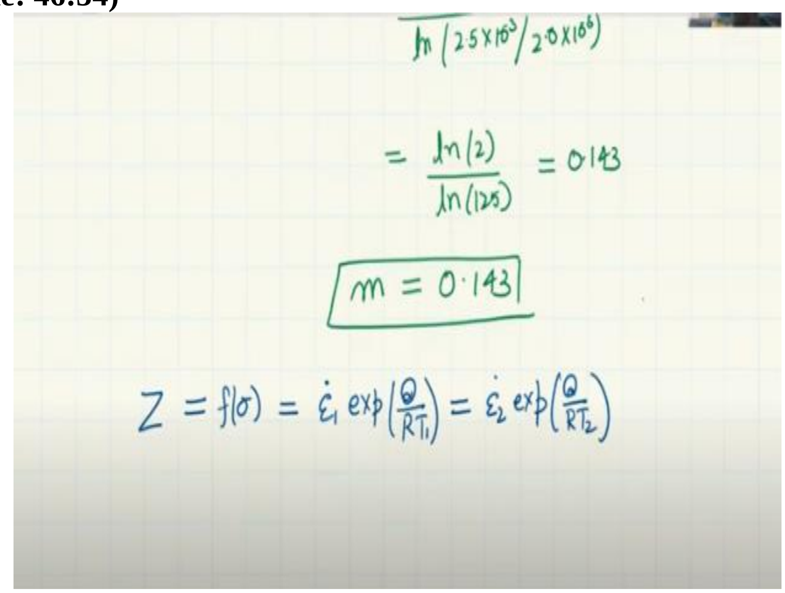

Which is ln 2 by you will see that the denominator becomes ln 125, which is equal to 0.143. So the answer is for this particular condition m is equal to 0.143. For 780 degrees Celsius, we get a m value of 0.143. Next, the question asked, calculate the activation energy of the deformation rate controlling process for temperature range 700 to 800. So first, let us frame the equation.

So we know that Z which will be a function of stress, if we keep stress constant, then we will have $\dot{\varepsilon}\exp\left(\frac{Q}{RT1}\right)$ and if the stress remains constant and the Z also remains constant, so for the same stress, we can also find another combination of strain rate and temperature, it will be (Q/RT_2).

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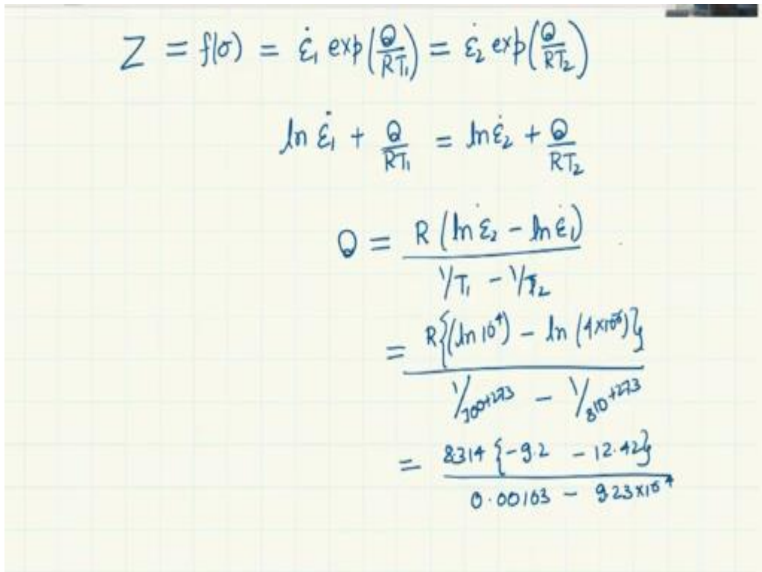

Now we will take log on both sides. And from here, you would see that Q is equal to R ln epsilon 2 dot minus ln epsilon 1 dot by 1 over T 1 minus 1 over T 2. So what do we do, where do we get these values? So we will look at this condition and this condition. So over here, okay let me delete this so that we can clearly see what is written here the values over here.

And so this stress is constant as you can see, and only the strain rate and temperature are changing. So the temperature for this one in 700 and for this it is 810 degree Celsius. And the strain rate here is 4×10^{-6}. And here it is 10^{-4}. Therefore, we can insert these values over here, is equal to $R(\ln 10^{-4} - \ln 4\times10^{-6})/(1/973 - 1/1083)$.

R would be 8.314 joules and you when you do this, you would see that this comes out to approximately 249 KJ/mole

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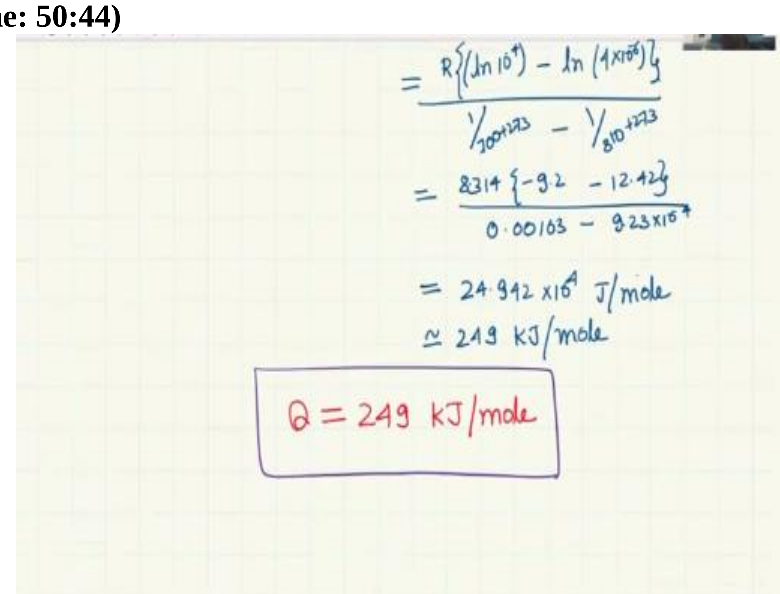

So our Q value comes out to, for this particular process this is the energy barrier, activation energy for this particular process of plastic deformation, okay.

So this gives us a very good idea this two examples that we have solved on the effect of strain rate and temperature, the combined effect of strain rate and temperature and the individual effects of strain rate and individual effects of temperature. So with that, we come to end for the effect of strain rate and temperature on flow stress. Thank you.