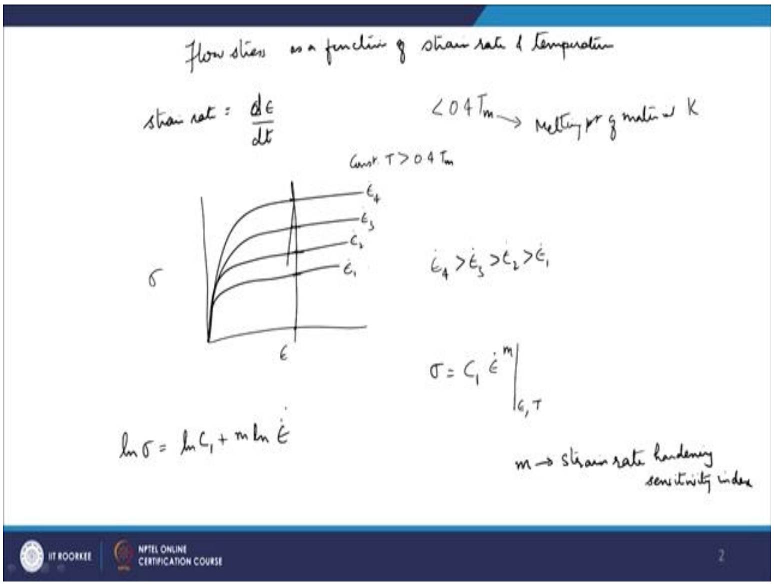
Thermo-Mechanical and Thermo-Chemical Processes
Prof. Vivek Pancholi
Department of Metallurgical and Materials Engineering
Indian Institute of Technology-Roorkee

Lecture-05
Effect of Strain Rate and Temperature

Hello friends, we will start with the new lecture, lecture 5 and that is going to cover two effect on the flow stress which we did not talk about in the previous lecture that is the effect of a strain rate and temperature. So, let me define the strain rate to you first. So basically, we will be talking in this lecture.

(Refer Slide Time: 00:47)



So, flow is stress as a function of strain rate and temperature. These two effects we did not discuss earlier. So, now, our new term has come here strain rate. Strain already we know what do we mean by a strain So, a strain rate is basically you can say $\frac{d\varepsilon}{dt}$.

That is at what rate I am putting the strain so, that is a very important parameter during the deformation process.

So, in rolling, forging, extrusion all these processes if you see whether I am deforming slowly or I am deforming at a very high rate some idea about this rate you must be having from the your basic courses that impact is one of the type of loading condition and one is where you do very slow deformation. So, a very slowly deformation and a very high deformation where you call it as impact ok.

So, the material behavior is very different in these two cases. So, a ductile material which is showing good amount of ductility in case of a slow strain rate test becomes a almost like a brittle material in a impact kind of condition and impact kind of conditions are very important in case of automobile application nowadays, where they want to know the crash worthiness that how much energy a material will take during a high speed collision.

So, strain rate is a very important parameter in industrial deformation also that at what rate I am deforming the material. So, if I want to show the effect of strain rate now, we will also bring the effect of temperature here. So, the earlier flow curve which I showed you in the previous lecture you can consider that all those type of the stresses flow curve you will see it in a material at a temperature which is less than $0.4T_m$.

So, what is T_m . T_m is the melting point of material so, for example melting point of material and of course, you have to take it in Kelvin. So, a melting point of material is suppose 1000 Kelvin then if you are deforming the material at lower than 400 Kelvin then you will see the flow stress curve which I showed you in the previous lecture, but if I am deforming at temperature which is more than 0.4 of its melting point.

So, let us have for more than 400 Kelvin then you will see now the effect of temperature also on the flow stress curve. So, first to define the effect of strain rate on flow stress again we can take the; lets now, because we will be always talking about true stress from this lecture let us I will remove this T part here. So, if I am writing σ simply it is true stress and ε is of course true strain and let's say I am taking a simple deformation condition which is basically a steady state condition.

So, after the yielding you have a steady state flow. So, usually you will see curves like this (refer above slide), like this. So, I have drawn different curves. Now, the temperature is constant here. So, these are all at constant temperature some temperature which is more than 0.4 T_m. So, let's say this constant temperature is more than 0.4 T_m. And now what is the difference between all these flows stress curve that they are at different strain rate. They are all at different strain rate.

And from their flow stress values I can say that $\dot{\varepsilon}_4$ is more than $\dot{\varepsilon}_3$ more than $\dot{\varepsilon}_2$ more than $\dot{\varepsilon}_1$ ok. So, lower the strain rate the flow stress will be low, higher strain rate is high the flow stress will be high. So, if I want to give a relationship to this kind of effect of a strain rate on the stress. Very generalized relationship between the stress and the strain rate will be something like this. So, this is

$$\sigma = C_1 \dot{\varepsilon}^m \text{ at constant strain and temperature.}$$

So, already we have said that all the plots are at constant temperature and constant strain means, suppose I just take particular strain value here and find out that for $\dot{\varepsilon}$ what was the stress $\sigma_{1,}\ \sigma_2, \sigma_3, \sigma_4$ and so on. So, they will follow a relationship like this, where m is a strain rate you can call it as hardening also or sometime, we call it a sensitivity index that what is the sensitivity of stress to strain rate.

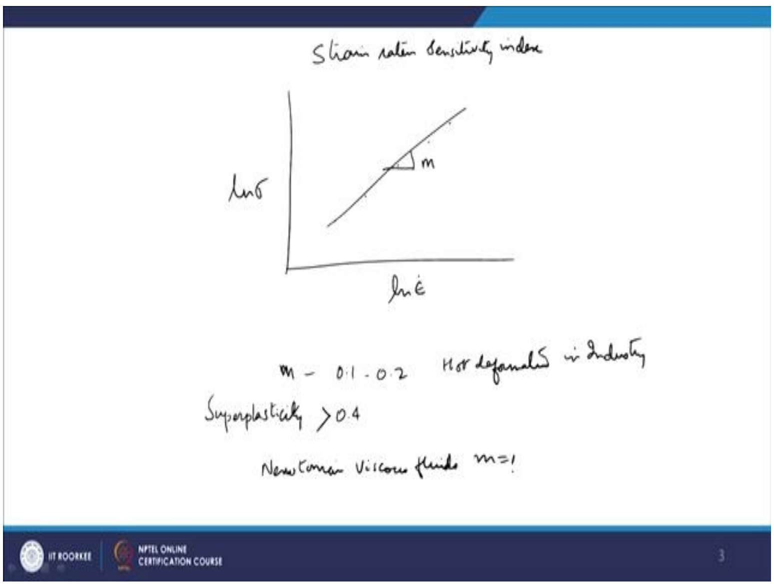
So, this m is defining that strain rate sensitivity index of the stress or you can also call it a strain rate hardening. So, it is similar to what we saw in the previous lecture where we talked about the strain hardening. So, at low temperature material experiences a strain hardening you can see in these curves the strain hardening part is very small. And in fact after a certain strain there is no effect of a strain on the stress so, there is no strain hardening at all.

So, at high temperature deformation the strain hardening is of the material is very low ok. So, the strain rate hardening is a very important parameter which stabilizes the deformation or which gives a uniform deformation ok. So, material experiences strain rate hardening and how to find out this a strain rate sensitive index again we can do similar thing what we did earlier if I take logarithmic on both the side it will become something like this

$$\ln \sigma = \ln C_1 + m \ln \dot{\varepsilon} \qquad C_1 \text{ is, your some material parameter.}$$

So, basically if I plot ln$\dot{\varepsilon}$ versus ln σ the slope should give me the strain rate sensitivity index.

(Refer Slide Time: 08:16)



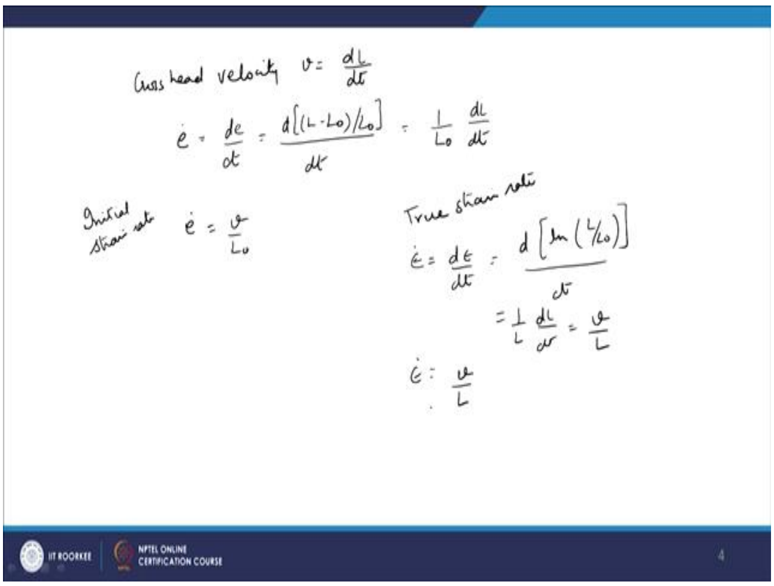
So, if I plot ln σ versus ln$\dot{\varepsilon}$ I should get some point like this by fit a linear curve here the slope should give me the strain rate sensitivity of the material. And the strain rate sensitivity is usually in hot deformation cases you will find for industrial hot deformation process like rolling, extrusion and all that the value may be somewhere between 0.1 to 0.2 for hot deformation in industry.

Another way important and deformation phenomenon in materials what we call the super-plasticity. I am not going to detail right now, just to give you an idea the value will be more than 0.4. So, it is highly strain rate sensitive condition and just to kind of connect it with your other understanding for example, fluid mechanics or fluid. Then Newtonian viscous fluids have m equal to 1. So, for Newtonian viscous fluid the strain rate sensitivity index is 1.

So, for other materials either it can be less than 1, in this case it is less than 1 in materials and usually it is in the range of for normal hot deformation 0.1 to 0.2 and super-plasticity more than 0.4 a very important parameter to have during the hot deformation process. Now, how to find out that what is the strain rate which you are imposing during a tensile test which you which we normally do in the labs.

So, just to give you an idea that if I want to find out that what is the strain rate at which I am deforming the material basically when you deform the material what you control or what your machine controls is the cross headed speed that is how fast or slow it is moving the cross head. It is not going to give you a strain or the strain rate that you have to or of course, there are software which you can do that, but just to have an understanding of that I am giving you an idea here.

(Refer Slide Time: 11:14)



So, basically cross head velocity if you see cross head velocity if I want to find out

$$v = \frac{dL}{dt}$$

So, what is the change moment of the cross head divided by the time it takes in that moment. So, if I in terms of simple engineering strain or strain rate if I want to find out then it will be

$$\dot{e} = \frac{de}{dt}$$

That will be equal to

$$\frac{d(L-L_0)/L_0}{dt}$$ all in differential

Since L_0 is your constant so; it comes out and this become

$$\frac{1}{L_0}\frac{dL}{dt}.$$

So, my $\dot{e}$ becomes

$$\dot{e} = \frac{V}{L_0}.$$

So, if I know my cross-head speed that ok moving cross head at this speed which I can easily find out from my machine and if I know my original length, I can easily get the engineering strain rate. So, engineering strain rate is the rate or it is the original strain rate which you are imposing you will be taking only the original length of the sample but again as we said that during the deformation your continuously length is changing.

So, whether you are imposing initial constant strain rate or you are imposing a true strain rate there it is also again kind of a debate you can have that whether I should impose a constant strain rate or I should impose a continuous or constant strain rate. So, this is my initial strain rate

$$\dot{e} = \frac{V}{L_0}.$$

And another can be my true strain rate

$$\dot{\varepsilon} = \frac{d\varepsilon}{dt}$$

that will be $$\frac{d\left[ln\frac{L}{L_0}\right]}{dt}.$$

that will be $$\frac{1}{L}\frac{dL}{dt}.$$

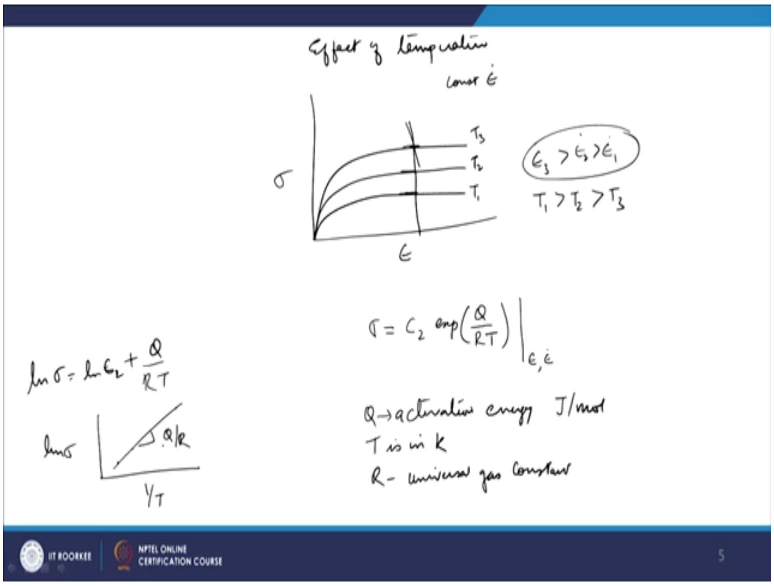
that is $$\frac{v}{L}.$$

So, continuously the length is now changing here it was a constant length it is a instantaneous length. So, now to have this kind of constant true strain rate, your machine has to have a closed loop hydraulic machine that means it is continuously feeding that what is the change in the length or change in the extension to the machine and you can see that to maintain the cross head speed to maintain the true strain rate constant.

And since my length is continuously changing my velocity also has to continuously change whereas in this case my velocity will remain constant to maintain because my L_0 is constant. So, I will have a constant engineering strain rate but here it has to continuously change the velocity as the deformation progresses. So, you have to have a closed loop type of machine which is continuously feeding that what is the, now the latest length and accordingly the velocity has to change ok. So, now you can see there is strain length is increasing the velocity has to continuously decrease.

So, this is actually nowadays all these are done by software. So, if you want a constant true strain you can give that kind of condition and it will be for the program will be following that using a loop.

(Refer Slide Time: 15:41)



Now, what will be the effect of temperature so, again I am drawing some flow stress here σ verses ε ok. So, again I am taking a simplified steady state type of flow and giving them some temperature to T_1, T_2, T_3 and these are all done at constant strain rate. So, when you want to change temperature, you have to fix the strain rate as constant and keep changing the temperature for different samples or you can do at a constant temperature and keep changing the strain rate for different samples.

And from the flow stress value I can tell you that my T_1 will be more than the T_2 it will be more than the T_3. So, it is exactly opposite of what we saw in case of strain rate. In a strain rate I said $\dot{\varepsilon}_3$ will be more than $\dot{\varepsilon}_2$ and then $\dot{\varepsilon}_1$ that was the case in case of but here for increasing flow stress the condition will be like this ok. And again, we can define this behavior using some relationship between stress and temperature.

And that will be something like this

$$\sigma = C_2 exp\left(\frac{Q}{RT}\right) \text{ at constant strain and strain rate.}$$

So, again I can take it a particular strain here at different temperature T_1 σ_1 is the flow stress T_2 σ_2 is the flow stress T_3 σ_3 is the flow stress and so on. So, you can see that it is in the denominator so as temperature is going to increase my stress is going to decrease.

This Q is the activation energy, energy for deformation and its value is joule per mole temperature is of course in Kelvin. The temperature is in Kelvin and R is your universal gas constant. So, C_2 is again some constant for material ok. So, again I can find out what will be the value of Q here if I again take logarithmic on both the side it will become something like this

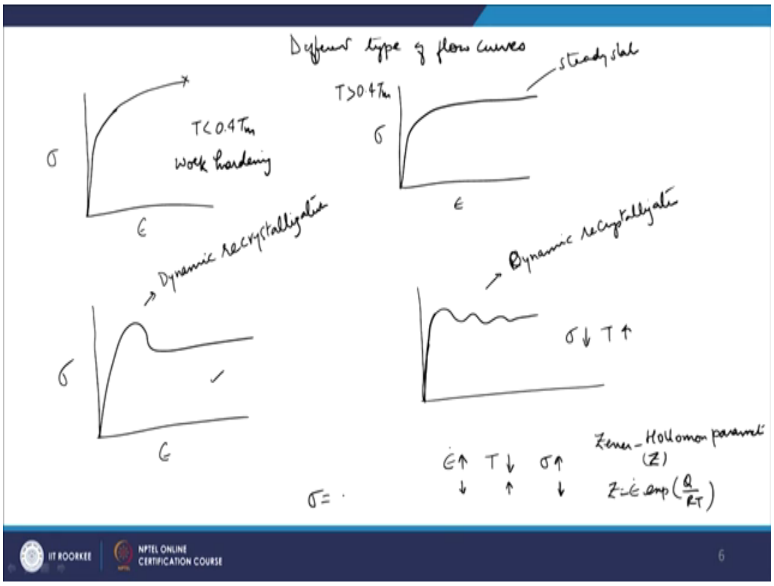
$$\ln \sigma = \ln C_2 + \frac{Q}{RT}.$$

So, if I plot curve between ln σ verses $\frac{1}{T}$.

Then I will be getting some $\frac{1}{T}$ is increasing here means temperature is decreasing here. So, you can see my flow stress has to increase here different values coming from here I can plot a straight line here, fit a best fit line and the slope will give me the value of $\frac{Q}{R}$. So, from here I can find out that what is the activation energy for deformation. So, as we saw that when we were relating stress with the strain rate important parameter is the strain rate sensitivity index.

What is the sensitivity of the stress to strain rate when we are relating stress with the temperature the important parameter which relates temperature with the stress is the activation energy that what is the activation energy of deformation. Now, we can try to see some more type of curves I have shown you a very simple curve till now. Now, you can see that there are variety of flow curves which you can find out when you are doing a deformation at high temperature.

(Refer Slide Time: 20:03)



So, that I will show you to this different type of flow curves (refer to above slide). So, one we have already seen at low temperatures σ versus ε will have some elastic part, plastic part and then deformation and some fracture here. So, you can see that in this case the flow stress is continuously increase increasing as a function of a strain. So, this is what you will get usually a temperature lower than 0.4 T_m this kind of behavior you will always see where you will only get phenomena what we call as work hardening.

As you increase the temperature now, another type of curve again we have seen just now that you have elastic part and this and then steady state behavior. So, this is what we call it steady state behavior because there is no change in the stress value is a function of a strain. So, everything is in a steady state condition there are no changes in the material and this happens when how we get work hardening because of multiplication of dislocation your dislocation density keep increasing.

So, since we are not getting anything here that means the dislocation multiplication or dislocation generation is kind of nullified by some other mechanism. So, what is that mechanism because we are deforming at a temperature more than 0.4 T m here ok. Now, other micro structural processes will start and one of them is called dislocation recovery. And dislocation recovery is helped by the vacancy concentration in the material.

So, you must be knowing that equilibrium vacancy concentration of material increases exponentially with temperature. So, you may increase temperature linearly but vacancy concentration will increase exponentially and these vacancies help the dislocation in recovery process. The actual mechanism is dislocation climb. So, dislocation recovery takes place. So, the number of dislocations which are generating and the same number of dislocations are getting recovered.

So, you because of that you get a steady state deformation ok. Now, another type of curve which you will see I have not shown you till now which will be something like this it goes like this make a hump come down and become steady state. So, this is another type of curve and different micro structural process will take place here this is as I told you recovery will be there this is the type of curve which you will have when you are having dynamic recrystallization.

All these terms we will see later on another type of curve which you can see instead of this is like this you know like this goes up and something does something like this. So, instead of one hump you get multiple humps again this is a process where recrystallization is happening or dynamic recession is happening and multiple stage. And usually it happens at a lower stress and higher temperatures. So, when the stress is lower and temperature is higher, so against if you compare with this one this will be at lower stress higher temperature.

Now one interesting thing you can do is if you see earlier also I was showing that the effect of a strain rate and temperature is entirely different on the stress, if you remember if I increase the strain rate or decrease the temperature , my stress will increase And if I do other way around so, there is a almost opposite effect of strain rate and temperature on stress and we have given you two different equations for that.

You can in fact a smart thing was done, and done by two scientists and they are on their name the parameter is known and this parameter is called Zener-Hollomon parameter which we call it Z, this combines both this effect in one. So, Z can be written as $\dot{\varepsilon}$ $\exp\frac{Q}{RT}$. So, you can see $\dot{\varepsilon}$ and T both are now considered here and σ can be then just can be shown as some function of Z. Where both the effects are combined together and brought in a single equation.

So, when your temperature is low, strain rate is more means the Z will be more and the stress will be more when the strain rate is low, temperature is more your Z will be less so, your stress will be less. So now, for σ we will see what kind of functions can be there, but it can be some function of the Zener-Hollomon parameter. So, I think with this I have explained you different type of flow stresses which you will see in hot deformation.

And what is the effect of two very important parameters which you control during deformation, which is a strain rate and temperature. So, how fast you are deforming and what temperature you are deforming. So, flow stress will be dependent on that and flow stress will also be keep changing depending upon what is the condition of deformation. So, whether you are deforming at what temperature or what strain rate so, different conditions will give you a different type of flow stresses.

And of course, there will be change in the micro structure accordingly and that is what we want when we are doing any hard deformation process we want to change the micro structure and those microstructure will help us giving in the properties which we want, so, thank you