Thermo-Mechanical and Thermo-Chemical Processes
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Lecture-09
Dynamic Recrystallization Critical Stress and Strain

Hello friends, we have already discussed about dynamic recrystallization the microstructural part. In today's lecture now, I want to discuss about the stress and strain behaviour as well as how I can find out the critical strain or stress required for dynamic recrystallization.

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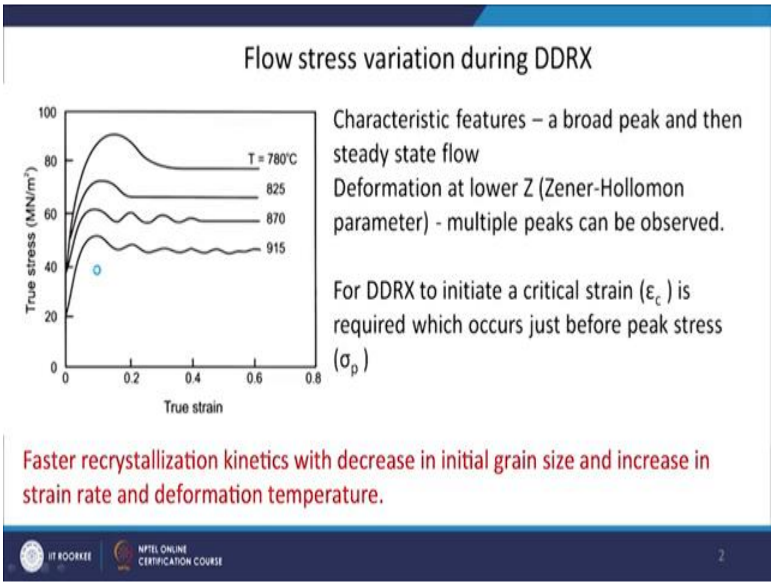

Now, we have already these (refer to above figure) flow stress curves. And you can see when you have discontinuous dynamic recrystallization, the stress strain curve or the flow stress curve has this kind of a peak and then it comes down and more or less is it becomes a steady state. And as a function of temperature if you see the temperature is increasing so, flow stress is reducing.

So, you can also see that this hump or this peak is of kind of lower magnitude and as you increase the temperature more now, you see something very interesting that now there are oscillation in the flow stress curves. So, a characteristic feature if you want to define it is basically a broad peak and then the steady state flow and deformation at lower Z (Zener-Hollomon) parameter we already know this.

You will be seeing the multiple peaks (refer above figure). So, the lower Z means either strain rate low or temperature high. The temperature effect you can see here, as temperature is increasing you started seeing these multiple peaks. Similar behaviour you may be able to see when you are reducing the strain rate. So with lower Z, always remember lower Z means strain rate is low temperature is high, you will start seeing instead of one single broad peak you will see multiple peaks.

You can also understand that for discontinuous dynamic recrystallization to initiate, it will require some critical strain. Now, I can just define a critical strain just before the peak stress. So, peak stress is where slope of this particular curve is zero (refer to above figure). So, let's say this is my peak stress and then the critical strain to initiate the dynamic recrystallization. You can understand that dynamic recrystallization is more or less completed here that is why the flow stress has started decreasing after that.

So, the dynamic recrystallization must have initiated somewhere at this (refer to above figure) point but we are not sure which this strain is right now, we will find out how I can find out that lets say that is some critical strain. So, one of the objectives of this particular lecture is to also find out this critical strain or critical stress. So, corresponding stress will be your critical stress to initiate the dynamic recrystallization, so, that we must know as an engineer that what kind of strain I have to impose in the material to start the dynamic recrystallization process.

So, recrystallization kinetics if you see kinetics means, how fast the recrystallization after start how fast it can complete. And usually it also follows the S shape curve is in phase transformation. So, if I kind of have the complete recrystallization here (refer to above figure), zero recrystallization here as a function of time it will have some behaviour like this S shape curve. So, kinetics means the time required to from start to finish will decrease with initial grain size.

So, at higher deformation temperature it will take lower time to complete the recrystallization process.

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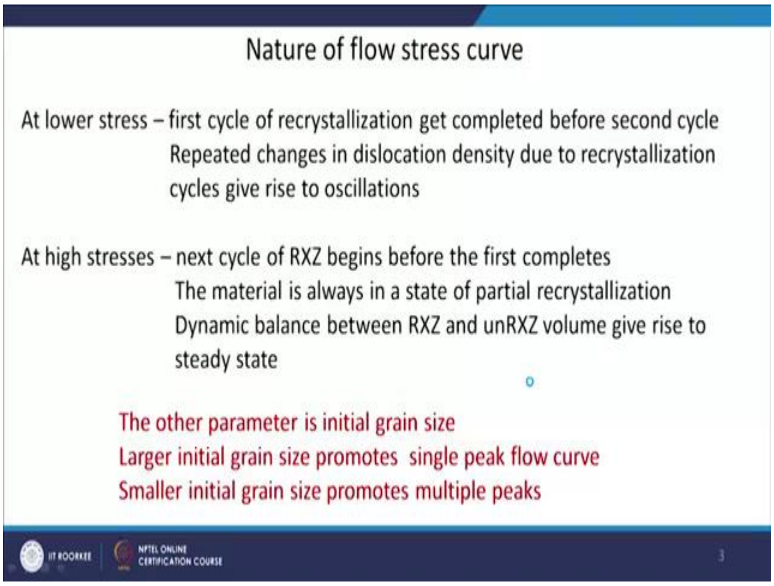

So, the nature of flow stress curve as we have just seen. At low stresses as you had these kind of multiple peaks that these will happen at lower stresses or lower Z values. So, the first how this multiple oscillation takes place there is what we want to explain. So, as you can understand that the flow stress increases as the dislocation density increases in the material.

So, dislocation density is increasing and flow stress is increasing because of that and when the recrystallization has happened, now the grain size has refined and grains are relatively strain free that means the flow stresses flow stress will come down. Then the next cycle of the recrystallization will take place and you will have again peak, again the recrystallization is completed, stress will come down and again the next cycle of recrystallization will take place.

So, this repeated change in dislocation due to density increase and after recrystallization it will decrease give rise to these oscillations (refer to above figure). Whereas, if you see the single one broad peak. So, in this case what happens is that after the first recrystallization cycle before it completes the next recrystallization cycle starts in the already recrystallized grains. So, you should understand that recrystallization from start to finish it has some finite amount of time or duration is there.

So, if after let us say 60% of material has already recrystallized 30-40% is still remaining, it is getting recrystallized. Suppose in these 60% recrystallized grains again the next cycle of recrystallization happens. So, then there is a continuous or the material will always be in the partially recrystallized condition. And because of that, you will see after the first recrystallization in the drop in the stress you see more or less a steady state condition because in some part of the material there is always some recrystallization cycle is going on, in some part it is coming to end, in some part already recrystallized grains are again starting to build up the dislocation density and getting into recrystallization mode, at some other end already the crystallization is about to complete and so on. So, it is a continuous recrystallization or dynamic balance between recrystallized and unrecrystallized volume give rise to a steady state.

Whereas, in oscillation after completion of one cycle, the whole material gets recrystallized, then the next cycle again the dislocation density increases and then the recrystallization happens again. So, at lower stresses oscillation will happen that means at lower stain rate and higher temperatures where the where you have sufficient amount of time to build up the dislocations. At higher stresses, that means higher strain rate and lower temperatures you will have this one single broad peak and there will be continuously some recrystallization must be happening at some part of the material.

The other parameter is initial grain size, larger initial grain size promotes single peak flow curve and smaller initial grain size promotes multiple peak. So, there are two effects, stress and initial grain size.

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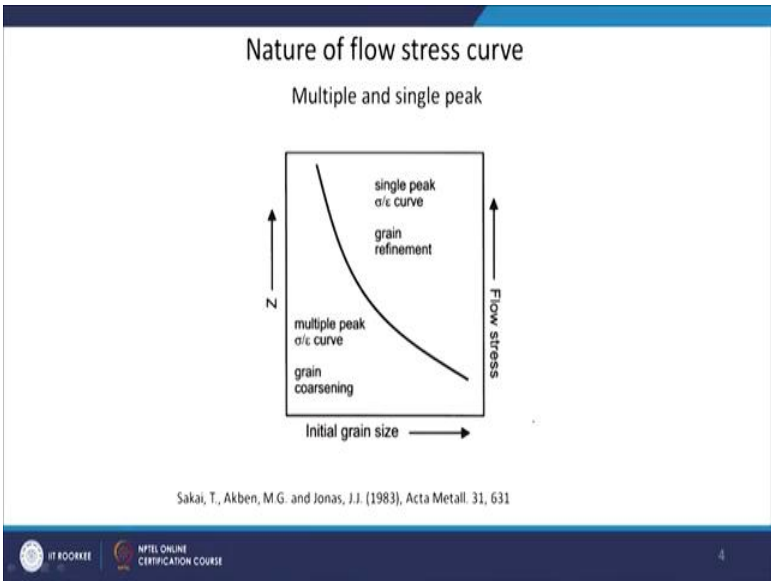

So, if you combine both in fact you can divide them into two regimes here (refer to above figure). So, on y-axis you can see the Z parameter or you can also say in terms of flow stress as already we have discussed many times that my stress is a function of Z and on the x-axis you have initial grain size. So, if initial grain size is more flow stress is low you will have single peak. If the initial grain size is small and my stresses are low or high you will have multiple peaks.

So, you can divide these two-deformation behaviours into two regimes using the idea of flow stress and grain size and this (refer to above figure) is your demarcation line above this you will have single peak curve below this you will have multi peak curve.

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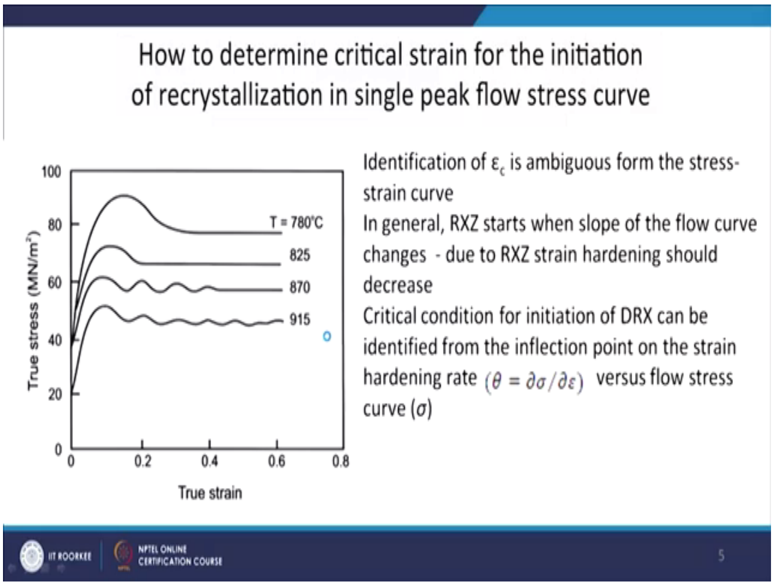

Now how to determine the critical strain for recrystallization in single peak flow stress curves. So, this is what we want to know that at what point which is that critical strain where the recrystallization has started and because you have to corroborate all these ideas with microstructure. Actually we will usually say that at least like 4 or 5% of material is recrystallized so that in a microstructure I should be able to identify that yes some few grains have recrystallized. If the nuclei is very small, if you are not able to see through normal optical microscope or SEM then it does not make any sense.

So, usually it is like around 5% or more recrystallizations, when it has happened then we say that it is initiated but we want to know this from the flow stress curves also. So, basically we want to know that what is the critical strain because right now, whatever way I am telling is ambiguous way that from the slope change I am trying to figure out that this point somewhere the critical strain is reached and the recrystallization will take place.

So, in general recrystallization starts when slope of the flow curve changes. Due to recrystallization strain hardening should decrease. So, when recrystallization happen you have a strain free grains that means the strain hardening should decrease. So, critical condition for initiation of DRX can be identified from the inflection point on the strain hardening rate. So, if I see a sharp change in my strain hardening rate and how I am defining the strain hardening rate, I am defining by the slope of this particular curve (refer to above figure).

So, at any point I can take the slope. So, if I take slope here (refer to above figure), you can see that strain hardening is more, if I take slope at this point you can see the slope is coming down that mean strain hardening rate is coming down, and that is given by θ. So

$$\theta = \delta\sigma/\delta\varepsilon$$

So, if I plot something like this, between the flow stress and this strain hardening rate, I should be able to see from the inflexion point that where there is a change in the hardening rate, the recrystallization must have started. And from there we should be able to tell this is my critical strain or critical stress to initiate the recrystallization process in the material.

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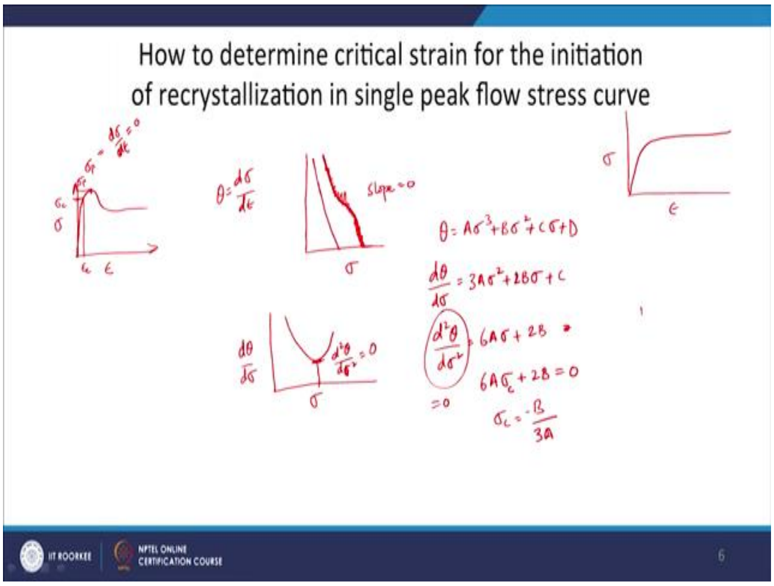

So, I will explain it on the monitor itself now (refer to above figure). So, basically you have this single peak curve. This is my ε, this is my σ. So, this is my σ_p. And how can I can find out the σ_p very simple where the slope is zero. So, σ_p should be associated with where

$$d\sigma/d\varepsilon = 0$$

The stress associated with that will be equal to σ_p.. So, somewhere here is my σ_p and somewhere here is my ε_c and stress associated with this is σ_c. So, first I will plot the flow curve in another form. Now I will take the differentiation dσ/dε which is θ. So, I want to now plot θ versus σ. And if I plot that it will give you a rough estimate of that the flow curve should be something like this (refer to above figure). And you can see that there is some inflection point at somewhere here where the slope is changing from one type of slope to another type of slope.

So, at that somewhere my slope should be zero because it is changing the direction from one side to another side. Is it is going like this and then it is changing the direction (refer to above figure). Another interesting thing is that if I want to plot the same curve for a DRV curve it will be a simple curve like this. There would not be any inflection point. Because if you remember the for dynamic recovery, we showed curves like this (refer to above figure) some strain hardening and then the steady state condition. So, this type of curve θ vs σ, it will be just one straight line whereas in recrystallization, you will see an inflection point like this.

Now, actually, if you see the data which you are getting from the machine and that you are plotting, large variation will be there. You can find out the slope and just plot it. So, basically you fit a smooth curve on this kind of varied data.

And to plot this kind of slop usually we take some polynomial equation. So, for example, in this case (refer to above figure), for plotting this particular curve, we have taken a polynomial equation of third order. So, cubic equation basically. So, it will have some relationship like this

$$\Theta = A\sigma^3 + B\sigma^2 + C\sigma + D$$

A, B, C, D are constants of material.

And now, to find out this inflection point that where the slope is changing, let us again differentiate with respect to σ, this particular equation.

$$d\theta/d\sigma = 3A\sigma^2 + 2B\sigma + C$$

So, it will be now $3A\sigma^2 + 2B\sigma + C$ and D is a constant it will become zero and I can again differentiate it

$$d^2\theta/d\sigma^2 = 6A\sigma + 2B$$

to get $6A\sigma + 2B$ and again C is a constant it becomes zero.

So, if I plot this, the curves for example dθ/dσ it will be comes something like this (refer to above figure). So, it has some minima here. And this minima will have the slope equal to zero. This is also plotted as a function of σ. So, the slope of this particular curve between dθ/dσ and σ where it is giving you zero that is the point where it has changed the slope and that is my inflection point. So, this is actually now I can put

$$d^2\theta/d\sigma^2 = 0$$

$$6A\sigma + 2B = 0$$

Now changing σ to σ_c

$$\sigma_c = -B/3A$$

So, from these constant I will be able to find out that what is the critical stress for initiation of recrystallization and correspondingly I can find out what will be the critical strain for initiation of recrystallization. Another interesting thing is if I plot σ_c as a function of Z you will get a straight line that means at different Zener Hollomon parameter or if I increase the Zener Hollomon parameter, critical stress to initiate the recrystallization also goes up.

As you can understand as increasing the Z that means I am increasing the strain rate and I am reducing the temperature. So, obviously, critical stress to initiate recrystallization will keep going up. Now, same thing we can do for strain also. Some interesting type of curves are there for the strain.

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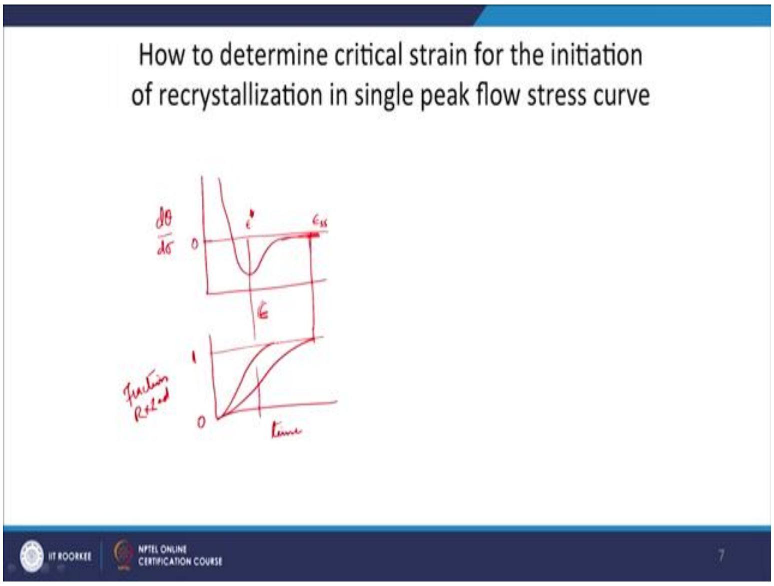

So, if I plot the same dθ/dσ, but now as a function of a strain I will see some curve like this (refer to above slide). This is the steady state strain. And this also gives me about the kinetics of the deformation if I plot (refer to above figure). So, where it is reaching the steady state of strain at that point I will be completing my recrystallization process, so, this is 1, this is 0 and this will be fraction recrystallized and this is my time. And somewhere here it will be able to complete 50% of strain. It will start something like this and complete something like this. So, this is a typical S shaped curve for the kinetics. So, I will be also able to find out that what is the kinetics of the recrystallization process. So, this is what I have already discussed with you. So, with this we are able to see that what is the critical strain and critical stress for recrystallization process by doing some simple mathematics here I am able to find out that what parameters will be able to give me the critical stress and correspondingly there will be a critical strain.

And if I want to do find out the kinetics of the process then I have to plot again the same $d\theta/d\sigma$ as a function of a strain and that will give me that what will be the kinetics of the deformation process and as you can understand that as I am going to increase our temperature the kinetics will be faster. So, it will go towards the lower timescale. So, this kind of analysis will be able to give us that what will be the critical conditions of deformation to get a recrystallized microstructure and what amount of a strain I have to impose in the material to get this kind of recrystallization.

And if you are designing the process, you always have to keep an eye on the flow stress part. So, suppose we know that at lower temperature it will be the kinetics will be faster but we also know that the stresses will be higher. So when you are designing a process OK. So the stresses are higher your rolling mill every all the parts which are used in the deformation process have to be designed for that kind of stress.

So, there is always a kind of a balancing act here to find out the proper condition of deformation to get a recrystallized microstructure in the material. So, thank you. With this I am ending this lecture.