Thermo-Mechanical and Thermo-Chemical Processes

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Lecture-22
Processing Maps: Dynamic Materials Model

Hi friends, today we will start with another lecture on processing maps. Already in the previous lecture we have seen about deformation mechanism maps and I told you that this idea of making map for different deformation processes was started with creep deformation. It was proposed by Ashby and then it was extended by Raj, so, you have Ashby maps and Raj maps.

Now we have also seen that there are few drawbacks of these maps that these maps are based on atomic processes. And you need to have intimate knowledge about these processes and you have to do a lot of microstructural analysis to understand the deformation taking place at different fields or regions i.e. different ranges of stress and temperature. To take care of these issues, there was another model proposed which is called dynamic materials model and which actually started making a map for doing hot processing. So, instead of calling it as deformation mechanism map, we are now calling it as processing map, by dynamic materials model, which is also called DMM. In the model it was proposed that these kinds of maps can be constructed to identify the processing region. So, how they are doing it?

The processing is modelled as a system, we are taking an example of forging here.

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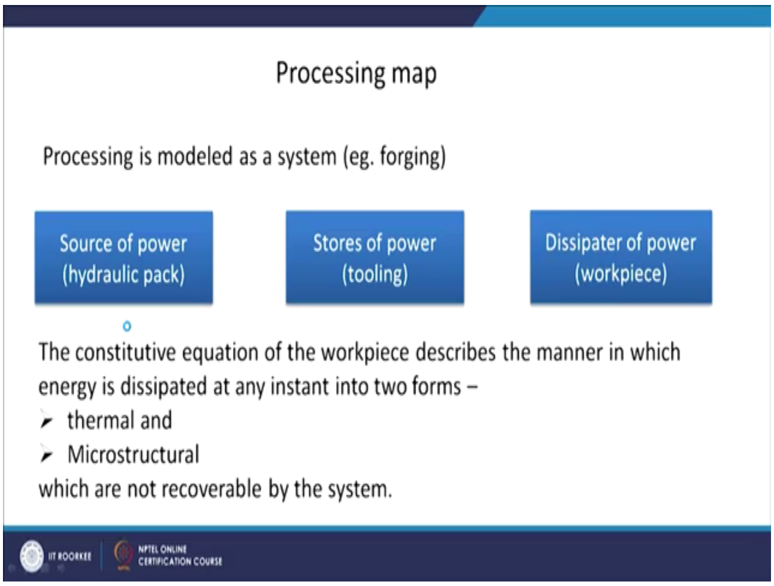

So, already we know how the forging process takes place. You have a hammer or movable ram and your work piece is there and you are having a compressive deformation. So, what is moving the ram? The movement is by power source which is moving that ram and that is the hydraulic system in this case.

So, hydraulic pack is the source of power and then this power is stored in the whole tooling, the movement of the ram and so on. And then when you are giving input of this power to the material, the material is acting as a dissipater of power. So, power is supplied by hydraulic, it is stored in the tooling arrangement and then the power is supplied to the workpiece and the workpiece is now acting as a dissipater of that power.

We already have seen constitutive equation. So, constitutive equation means how the material or workpiece is going to behave that decides how this energy will be dissipated and it will be dissipated in two forms. So, whatever power we are putting in, it will be distributed in two ways.

One is the change in the microstructure, which is a irreversible process. As we have already seen dynamic recrystallization and dynamic recovery and all those microstructural processes can take place like dislocations generation. So, some part of the energy which you are putting in will change the microstructure of the material.

And other part of this dissipation will be through thermal processes that means, generation of heat. So, already we have discussed that whenever we work on a material, whenever you are deforming a material, if you test the material after the deformation, there will be some temperature rise in the material. And that is due to the dissipation of whatever energy or power you are putting, in form of heat.

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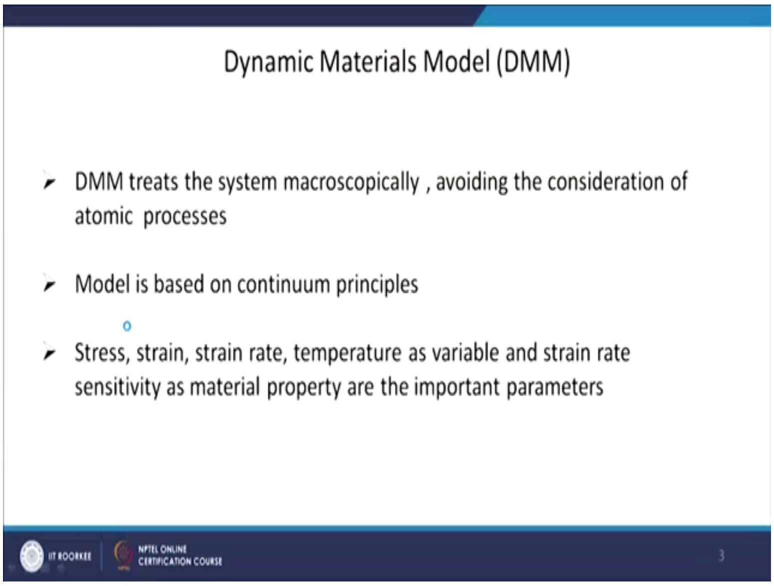

So, this created the argument for generation of processing map. So, dynamic materials model propose that it treats the system microscopically. So, earlier deformation mechanism map, we are going into the actual atomic processes and from there we were trying to delineate different regions for different processes. But now, DMM treats this microscopically and atomic processes are not taken into consideration and so material is treated as a continuum.

So, we are not worried about what is going inside. We are only looking at the variable or the input we give to the material in form of strain, strain rate and temperature, response of the material in form of stress. And using these values we are trying to find out that how we can construct a map. So, stress, strain, strain rate, temperature are variable and strain rate sensitivity is one of the material property (already we discussed) are used use to construct the model.

So, we are using now continuum principle not worried about what atomic processes are taking place and coming with a macroscopic model. Now, for a processing map what should be the requirements.

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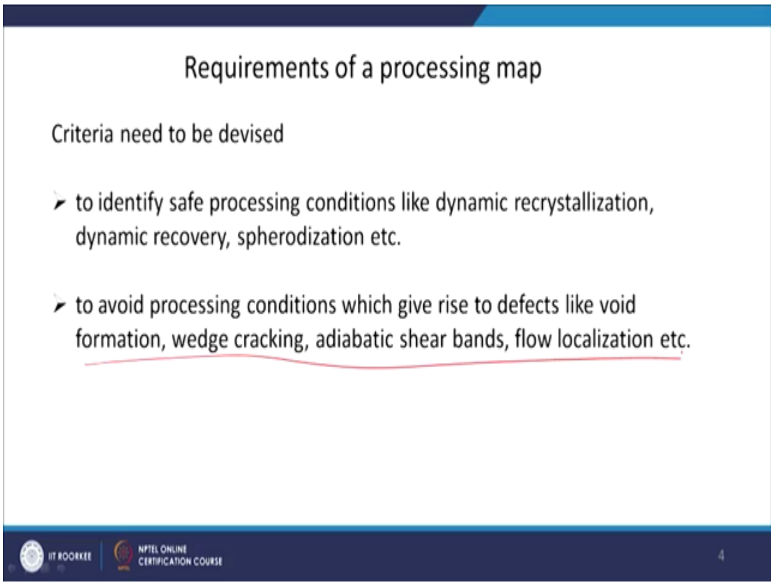

So, the processing map or the model which we are proposing should fulfil some criteria which, tells us or which identifies safe processing conditions. So, my model for example, in this case now DMM, the criteria for DMM model should be such that it should be able to identify the safe processing regions, like dynamic recrystallization, dynamic recovery and so on.

And how I can avoid the processing condition, which give rise to defects like void formation wedge cracking, adiabatic shear bands, flow localization. So, this is the requirement of a model or a processing map that it should be able to identify these two important considerations for me, safe processing condition and unsafe processing conditions.

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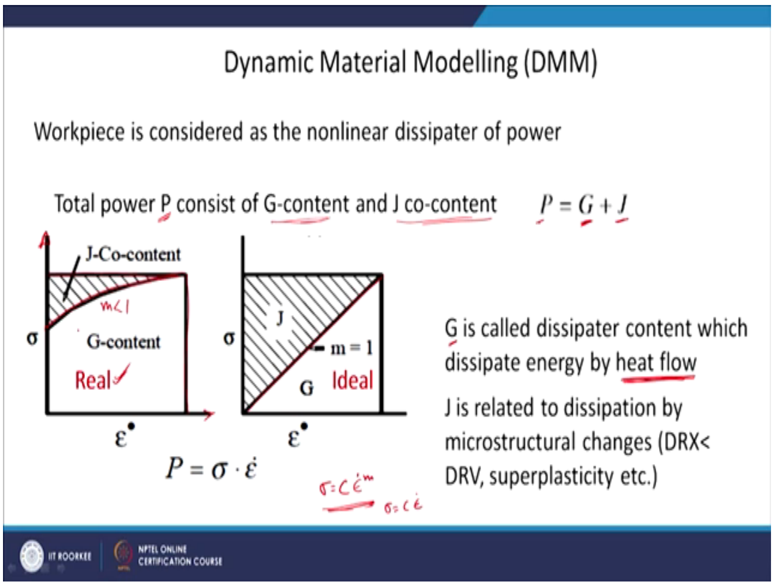

So, now, what is Dynamic Material Model? As already we have discussed that work piece or the material is considered as a dissipater of power, of course, we are not considering it as a linear dissipater of power, it is a nonlinear dissipater of power. So, if total power we want to see in terms of strain rate and stress here now, so, the total power is simply stress × strain rate.

So, total strain rate × total stress, this whole area is the total power, this particular area, kind of a rectangle (refer to above figure). So, this is a rectangle, that is the total power I am putting in the system. And this total power, the model suggests that it can consist of two parameters, it is called G content and J co-content. And it means that power is composed of these G content and J co-content.

Now, what are these G and J co-content? G is called dissipater content which dissipate energy by heat flow. So, as we have already discussed that when you are putting power in, so, the work piece act as a dissipater of power and dissipation is through two means. One is microstructural change and another one is heat. So, the G takes care of the heat flow or heat generation and J is related to dissipation by microstructural changes. So, J is the one which takes care of the microstructural changes and as we have already seen that stress varies by some exponential function, if you remember stress is always expressed as $\dot{\varepsilon}^{m}$ that means the stress is a non-linear function of a strain rate. So strain rate is on x-axis and stress is on y-axis.

So, you can see that the deformation behaviour of material is such that stress is a nonlinear function of strain rate (refer to figure). That is why we are considering it as a nonlinear dissipater of power. So, it is a typical curve which you get whenever you are looking at stress and strain rate. And of course, as you can see in this particular case, the DMM model consider power law relationship between stress and strain rate.

So, it assumes a power law relationship between the stress and strain rate. So, which may not be true in some other processing condition, but the processing condition which they were looking at they consider it as a power law relationship and that is why you can see a curve like this and nonlinear variation of stress as a function of strain rate. So, now, this total power is divided into two areas now, because of this nonlinear curve. G content is the lower part, J co-content is this upper part (refer to above figure). So, above the curve is the J co-content below the curve G content. So, any real system will behave like this, of course, *m* must be lower than one, so, in this case *m* is lower than one. If m=1, then, it will be a linear relationship obviously. So, σ will be directly related to $\dot{\varepsilon}$ and there is no constant so, it will start from zero and it will be just a straight line that means it is dividing this rectangle now into two equal parts. So, J and G are equally divided. So, equal amount of power is going into microstructural changes and heat generation and this is the maximum you can reach.

You cannot go beyond m=1, that is the maximum I can reach, a strain rate sensitivity of one. So, this is the maximum you can achieve. So, this is my maximum energy I can put in for microstructural change which is the half of this rectangle. So, $\frac{\dot{\varepsilon}}{2}$ and now I can very nicely define that how much energy is going for microstructural change in a real system.

So, for an ideal system maximum I can get - half of the rectangle and what is the actual energy in any real system is going. So, if I have this kind of understanding, I should be able to say that whether my system is working at good efficiency or not, in terms of microstructural change, that is the idea of the DMM model.

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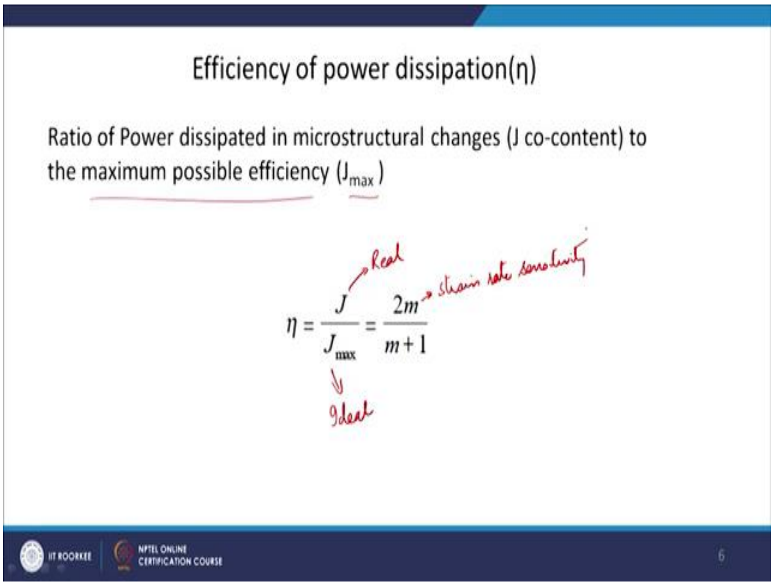

So, basically they have defined the efficiency of microstructural change by efficiency of power dissipation which is a factor we call as η. So, what it says that ratio of power dissipated in microstructural change, J co-content divided by maximum possible efficiency which is J_{max} which is $\frac{\dot{\varepsilon}}{2}$ as I just told you. So, if you do a little bit mathematics here so, J which is coming from the real system and J_{max} which is coming from an ideal system so, of course, if I take this ratio I should be able to say that what is the efficiency of my material under the certain processing condition to dissipate energy for microstructural change.

So, I should have more efficiency of that means η should be more so that I should have more energy going for microstructural change because all this high efficiency region are the region where actually all this good microstructural changes take place for example, dynamic recrystallization, dynamic recovery and so on . So, all these desirable microstructural changes takes place where you have higher efficiency.

So, that is what we are looking for here and it is simply dependent on the strain rate sensitivity. So, only one material parameter i.e strain rate sensitivity of the material. So, if strain rate sensitivity is going to be high then obviously, I will have higher efficiency. So, this is how now you can use the data of stress as a function of strain rate at different temperatures to construct a contour map. So, a three dimensional contour map is shown here (refer to below figure).

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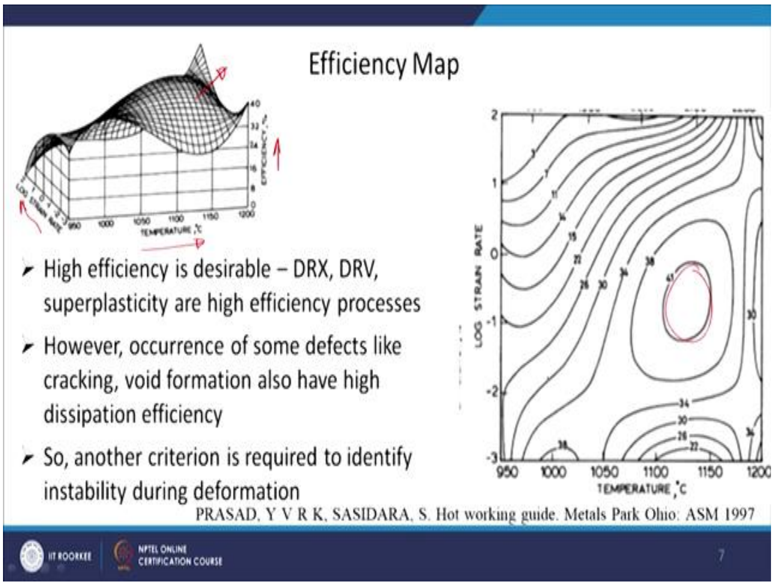

So, you have log strain rate on y-axis, temperature on x-axis and efficiency on the z-axis and there is some three dimensional envelope is there. If I take a section out of it, at any particular efficiency, I should see something like contours (refer to above figure). So, you have contours, which are coming from three dimensional envelope and now it is a two dimensional contours which are giving you the efficiency at different places.

So, 41 means 41% efficiency that means 0.41 η or in terms of percentage, you can say 41% and then 34%, 38%, 34% and so on. So, these are what we call as efficiency map. So, high efficiency is desirable, because I told you DRX, DRV, super-plasticity are all high efficiency processes. However, occurrences of some defects like cracking, void formation also have high dissipation efficiency.

So, this is another interesting thing that some defects also gives you a very high efficiency for power dissipation because lot of power goes in creation and propagation of these defects. So, not all energy will go in microstructural change, some energy may also go in creation of these defects and which are also high efficiency. So, just simply looking at a efficiency map and saying that this is my high efficiency that means, all the good processes may be taking place may not be true sometimes, because other defects which are produced in the material also have high efficiency.

So, it may be possible that the defects are occurring at high efficiency region. So, we have to also have another criterion which is required to identify instability during deformation. So, one is high efficiency I want to know that what is the high efficiency regions. And you can understand that I am doing that just by knowing the stress as a function of a strain rate, strain and temperature.

So, you have temperature on x-axis here and strain rate on y-axis, of course, it is taken as logarithmic because we are changing strain rate by order of magnitude 10^{-3}, 10^{-2} then, 10^{-1} and so on . So, I have to have a log scale. Temperature, I am more or less varying in linear fashion. So, x-axis is linear here and on that we are plotting this high efficiency maps (refer to above figure).

Now, as I told you because of the defects, some defects are also having higher efficiency, I have to have another criterion which can tell me that where the instability is taking place.

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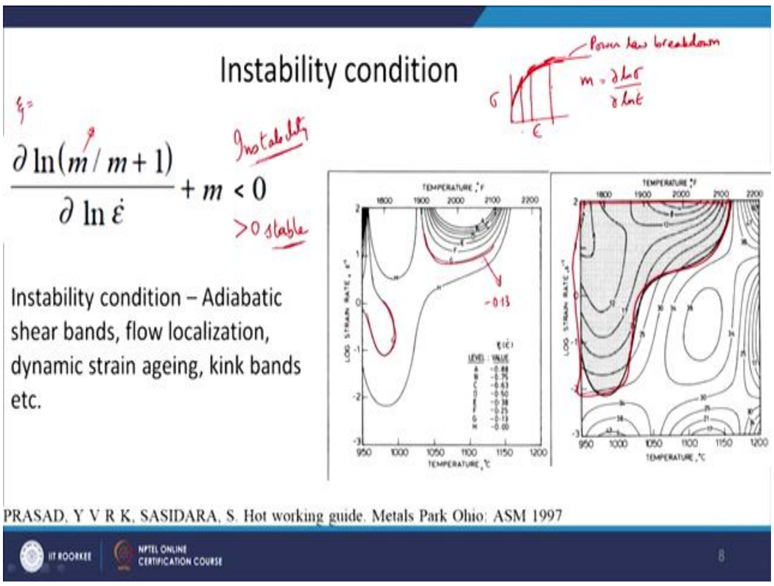

And that is again this DMM model suggest that what should be the instability criterion and that is also again dependent on the strain rate sensitivity. So

$$\frac{\partial\, ln(\mathrm{m}/(\mathrm{m}+1)}{\partial \ln \dot{\varepsilon}} + \mathrm{m} \;\; < 0$$

And this particular value should be less than zero then there is an instability. So, this is an instability criteria. If it is more than zero then I am in the stable region. So, sometime in books you will see the it is written as greater than zero, do not get confused. Greater than zero means they are trying to tell you that which are the stable processing conditions or stable regions in processing map and if it is less than zero means they are trying to tell you which are the regions where the instability can occur.

So, instability conditions are like adiabatic shear bands, flow localization, dynamic strain ageing, kink bands etc. So, lots of defects are there which can occur during the hot deformation process. So, this particular criterion can be used to identify the instable region. For example, here it is shown, in this figure here (refer to above figure), some contours are shown A, B, C, D up to H and if you see the ζ value, these are all negative, -0.88, -0.7, -0.63 and so on. H is zero basically and G is -0.13. So, basically here we are not concerned too much about what is the value of ζ as long as it is less than zero, that is enough for me to identify that this is an unstable region. I don't want to kind of find out whether it is more unstable or less unstable if it is less than zero that is sufficient for me.

So I will not be plotting these controls for instability when I am going to put it on a processing map. So, now you can see here two things are combined. So, you have efficiency contours 38%, 34% and so on and on top of that, there is a shaded region, which is taken from this final contour H here, where the instability parameter ζ have value of zero and below within that everything is now negative.

So, they have identified this particular region as the instable region. So, if efficiency is high, it may be possible that you have a high efficiency contour here, but we should not do any processing in this shaded region because that high efficiency may be occurring because of the presence of some defects or presence of some instability in the material .

So, already we have seen when we were developing constitutive equation that how you can get these parameters so, I hope you will be able to do these kind of calculations without any problem.

For example, m if I want to know, this is $\dot{\varepsilon}$, this is σ and you have some variation like this (refer to above figure), as we have just seen. So, if I want to calculate now strain rate sensitivity m, we know that it is dependent on this. So, one way is to take if the m is constant, one way is to take the ln of this thing and find out the slope of the straight line, which I have already told you.

But suppose if the m does not remain constant during the deformation or at different strain rates, then, what you can do is, you can fit a polynomial equation to this curve here (refer to above figure) and then you differentiate it. So, that will be able to give you the m at different locations. So wherever you want you can put $\dot{\varepsilon}$ of that value . So, at different $\dot{\varepsilon}$ you will be able to get the slope if the slope is changing.

And suppose at some point maybe it will become straight then that is where you have power law breakdown, there is no power law dependence of stress on strain rate. So, it may be possible only in a certain strain rate window that your stress is dependent on strain rate with an exponent of m. Similarly, I think you should be able to calculate this ζ also because only m is there and $\dot{\varepsilon}$ is there.

So, you have to take ln of these and then differentiate it. And if the value is less than zero, you know that these are instable regions.

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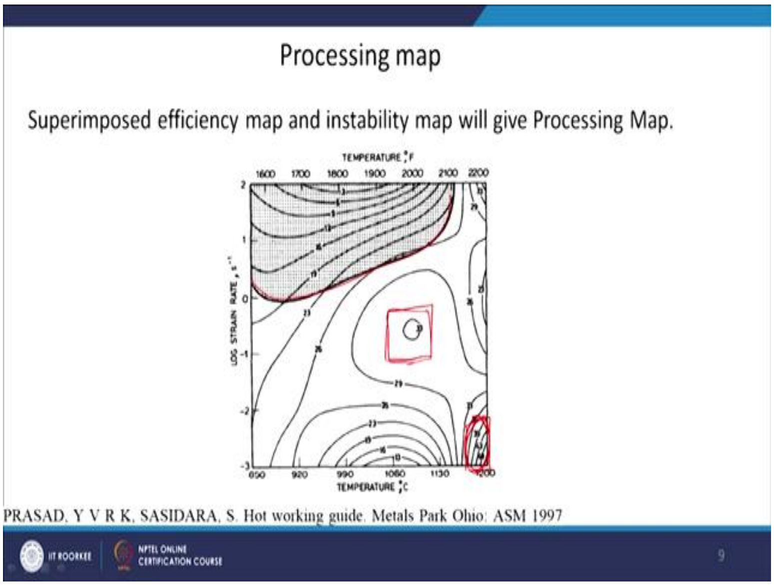

So, basically processing map is the one, where the efficiency map and instability maps are superimposed on each other. So, that combined give you some processing condition and that is why these are called processing maps. So, idea here is that you have to identify where you have higher efficiency. For example, you have higher efficient at this point (refer to above figure) then you have higher efficiency somewhere here and you have instability here.

So, now the remaining areas are safe areas. I can do processing there, but I would like to do processing where the efficiency is high. Generally, we would like to avoid higher temperature region because if there recrystallization is taking place, then subsequent grain growth will also be a possibility. Of course, in any industrial processes, if you want to increase the temperature you also have to consider the cost of heating or cost of raising the temperature to a high level i.e. electrical cost.

So, you can always have a kind of a give and take here. So, maybe you can choose a lower efficiency region, here it is 48% but here is only 33% , but the temperatures are lower. And of course, strain rates are slightly higher. So, that is also good that you can do the processing at a higher strain rate. So, it will take much less time. So, the productivity will be more. So, all these things have to be considered by an engineer who is designing the process.

Of course, you have to avoid the instable region. Now, how to interpret and validate whatever you are developing? Till now, we have not talked about microstructure at all, we have just used the material response in terms of flow stress as a function of the strain, strain rate and temperature and use that to develop this processing map. We have not talked anything about the microstructure right now.

We have said that the high efficiency regions are the one where you will have dynamic recrystallization, dynamic recovery and maybe some defect formation and the unstable regions are where you have adiabatic shear bands or flow localizations. So, but we have not come to the processing map from the atomistic processes, we have come it from the continuum mechanics.

So, once we developed that I want to know whether what I am trying to say or predict from the processing map is what was also being followed by the material so, you have to do a microstructural analysis, but, the advantage here is that you have to do very selected sample for microstructural analysis, so, wherever you have high efficiency.

So, two three samples from there then maybe couple of sample from instable region to identify that in these regions some defect is occurring. So, that will be able to validate your processing map that it has been generated properly.

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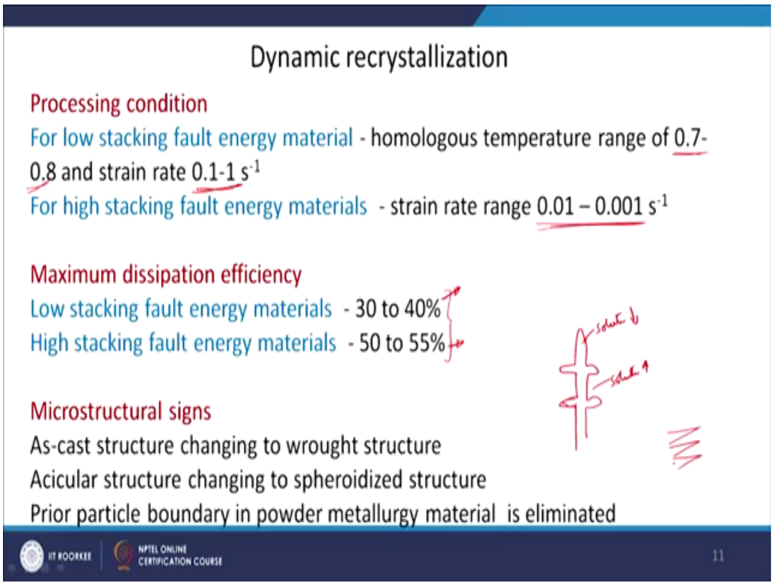

So, as we told that dynamic recrystallization is one of the our primary objective to select processing condition. So, in general from different materials, when people have done work on this (refer to above figure) , they are able to identify a few ranges, in terms of processing condition for low stacking fault energy materials, the temperature range is around 0.7 to 0.8 of melting point and the strain rate range is around $0.1\text{-}1s^{-1}$, for low stacking fault energy, this is where you should be able to get a dynamic recrystallization. Whereas, for high stacking fault energy material, the strain rate range is lower as compared to the low stacking fault energy materials, the temperature range will be more or less same. If you want to talk in terms of dissipation efficiency just to know that what efficiency we should aim for. So, for low stacking fault energy materials 30 to 40% efficiency if you are getting you should be in the dynamic recrystallization domain. And if you have a high stacking fault energy material like aluminium and so on, so, the efficiency should be in the range of 50-55%. So, if you are able to get that kind of efficiency in a particular processing domain then you can be in that dynamic recrystallization region.

So, this is what you should be looking for. Of course microstructure size, we have already discussed about dynamic recrystallized microstructure that how they look. Few more things you can add there that if you have a as-cast structure, as-cast structure already I have explained that you have dendrites, there is primary dendrite and then you have secondary dendrite and so on.

These are the dendrites which have lower solute content and in between the two dendrites there will be inter dendritic region where the solute content will be high. So, if this type of microstructure is changing into a wrought structure then, it is a good sign that, your processing condition is able to generate this kind of wrought structure.

Acicular means, which contains kind of blade like kind of features (refer to above figure), is changing into spherodized or globalized microstructure then, again, you are in the good processing window. And prior particle boundary in powder metallurgy alloy material should be eliminated. So, you should not be able to see that what were the particle boundaries in the powder metallurgy material. So, if you are able to see all these features you are in that dynamic recrystallization region.

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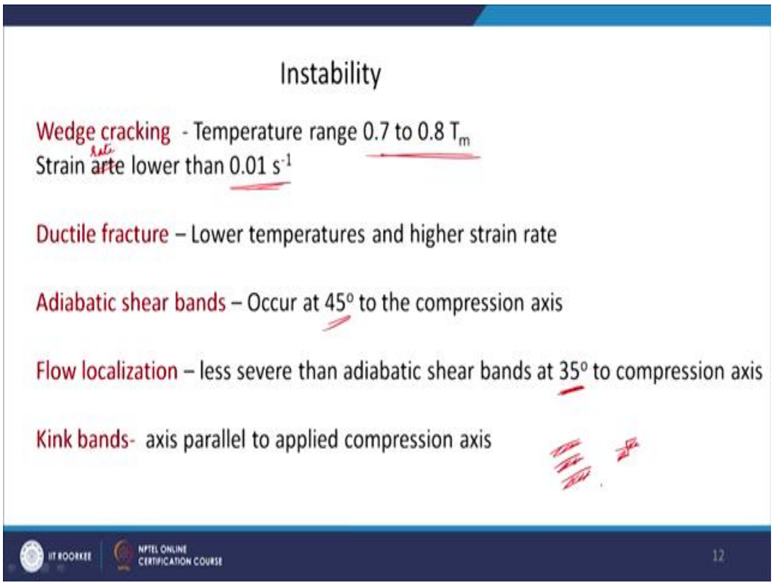

Instability regions, wedge cracking already we have seen that in the Raj map that what do we mean by wedge cracking. Temperature range is of course high here, the strain rate range is low. It is basically very high temperature and very low strain rate where you have superplastic kind of deformation usually there you can see wedge cracking. Ductile fracture of course, will occur at even lower temperature and higher strain rates.

So, usually that should not be our concern in hot deformation, adiabatic shear bands you will observe at 45° to the compression axis usually. Flow localization are usually less severe than adiabatic shear bands and this occur at around 35° to the compression axis. And there are Kink bands. So, if you know the pearlitic structure where you have alternate bands of ferrite and cementite and when you deform this kind of structure there are kinks which developed in this lamellar structure. So, it becomes something like this, there will be a kink like this (refer to above figure), it has kinked. So, this is another kind of defect because later on you can have a crack initiation at these points. So, this type of different instability condition can arise and these are the microstructural features for that.

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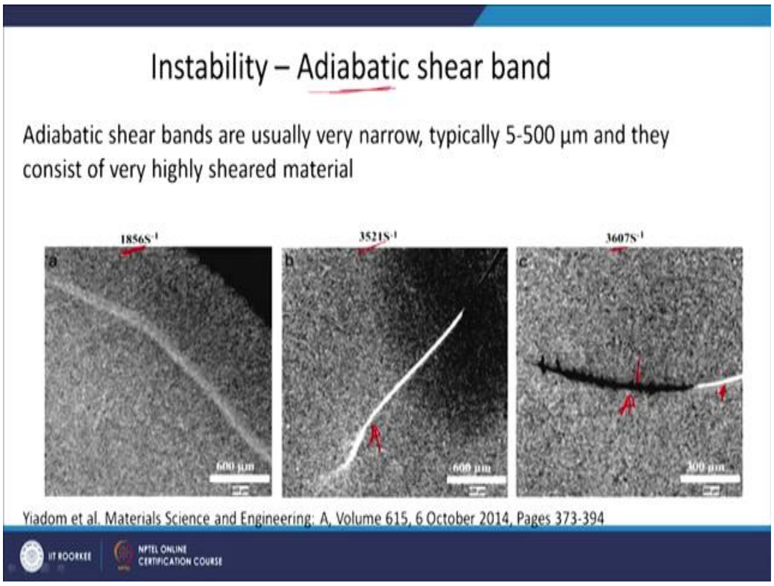

For example, few images are given here. This is an image for adiabatic shear bands (refer to above figure). These are very narrow typically 5 to 500 micron and they consist of very highly sheared material. So, this happen as the name suggests because of adiabatic heating. So, we know that when you are deforming at very high strain rate you can also see the strain rate is mentioned here, 1×10^3 and s^{-1} 3×10^3 s^{-1}.

So, you are not giving enough time for heat to dissipate. So, locally temperature will rise and the material will become very soft. And when you are deforming progressively that deformation will be concentrated in that narrow region. You can see that these are very long. So, they will usually cover large number of grains. For example, here it is 600 micron is the scale and it is almost covering the whole figure.

So, it must be around 1000 to 1500 micron shear band. So, it should at least cover 50 grains or so, of course, depending upon the grain size. Similarly, you can see here very big shear band is there. Here also you can see a shear band formation with the crack formation also. It looks like there is a crack here and the shear band is somewhere here (refer to above figure).

So, if you see in the shear band, you will see that very fine microstructure were highly deformed material will be there because the deformation has localised there because of adiabatic heating. That is why these are called adiabatic shear bands. So, this is the one kind of microstructural feature I wanted to show you when we are talking about defects.

So, after deformation mechanism map we have seen processing map and the model which is used is called dynamic materials model to develop this processing map, we have discussed that and it contains two important maps. One is efficiency map and another is instability map and combined that you should be able to identify the processing condition for your material.

So, in the next lecture, we will see these aspects of processing map in more detail to understand that how we can see a processing map with more details. Thank you.

Keywords- Dynamic materials model, efficiency map, instability map, microstructure.