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

Lecture-24
Processing Maps: Different Models

Hello Friends, continuing with our discussion on processing maps, today I will like to discuss some other different models. If you remember, we have already discussed dynamic materials model given by Y.V.R.K. Prasad, and co-workers so that we have seen in dηils. And today we will see some other models which some other researchers have proposed and kind of some comparison between different models.

So, some work people have done on comparing these models and trying to correlate it with the microstructure. So, you will see that a lot of different ideas people have come up to suggest certain equation. And in some cases these models are able to predict the stable or unstable region for deformation processing and which are like validated with microstructure. In some cases, some model for example, in some material, some model will be more convenient or will be able to more predict in better way.

In some other material maybe some other model will be able to predict in a better way. So, there is no final word on different models till now. People are still proposing new ways to plot the processing map or still proposing new models to understand the deformation behaviour. So, as already we have discussed in DM model, the stress is dependent on a strain rate and there is a power law relationship already we have seen relationship like this (refer to below figure).

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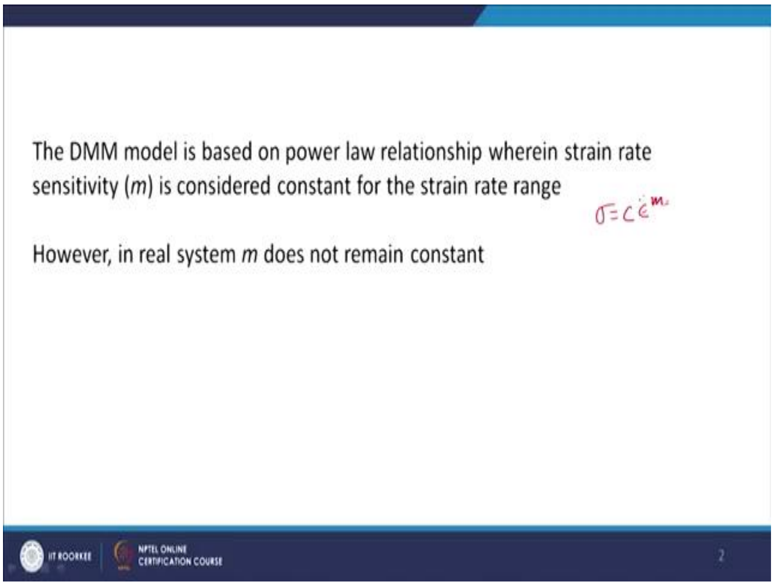

So, you can see that this power law relationship, the m is supposed to be a constant. So, strain rate sensitivity is at constant here. So, they have assumed that strain rate sensitivity will remain constant in the strain rate range where they are trying to develop the model and this kind of relationship is called power law behaviour or power law relationship. However, if you are considering a large strain rate range, then, you will see that m does not remain constant.

For a particular strain rate window, maybe you can take strain rate as constant but if you keep changing the strain rate over a large window, you will see that the strain rate does not remain constant and already I have told you that there is a power law breakdown also. That means the stress dependence on a strain rate sensitivity will be very low. So, there will be a power law breakdown also and m also keeps changing as a function of a strain rate.

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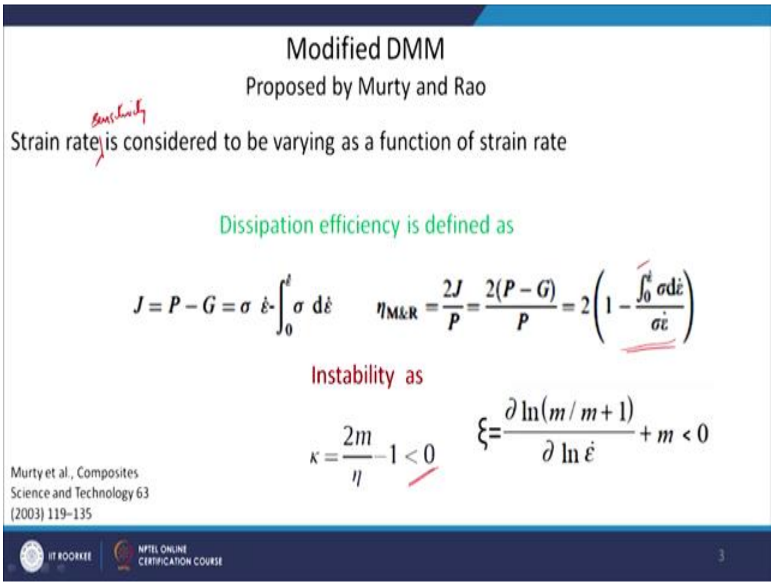

So, to take this into account the, another model proposed by which is called as Murthy and Rao. Narayana Murthy and Prasad Rao, they proposed another model which is usually called as modified DMM and they also proposed the both the parameter efficiency, dissipation efficiency that how efficiently material is able to dissipate the power through microstructural change rather than only through heat. That is what we want.

So, they have proposed dissipation efficiency as well as the instability criteria. So, they have considered that the strain rate is going to change as a function of strain rate sensitivity, sensitivity should come here varying as a function of strain rate (refer to above figure). So, that is why they have taken integral here as you can see here and this is $\eta_{M\&R}$,they proposed an equation like this.

I am not going into dηil of how they are coming up all these equations, because in these lectures we do not have time to go into dηil of each model. But there are lot of research papers are available. So, if you are interested you can go to these research papers and see the derivation of these models. Similarly, the instability criteria given by this model gives the instability like this

$$K = (2m/\eta) - 1 < 0$$

If you remember in case of Prasad and Rao, where they have shown this as ζ and in this case the stability criteria is slightly different. If it is less than zero then, it has a instability so, one another variation to the same parameters, but looking in a different way.

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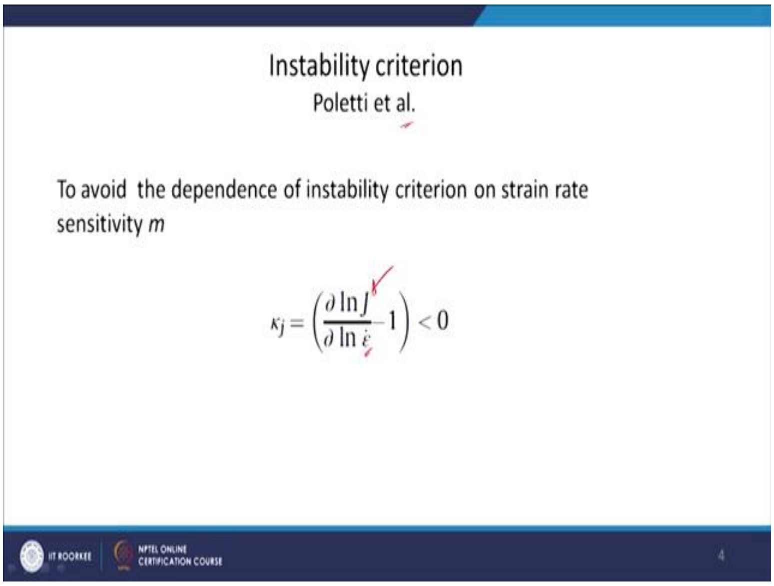

There is another instability criterion, this is proposed by Poletti and group (refer to above figure). And they said that not to consider the strain rate sensitivity in the calculation. So, they calculated directly from the J co-content, the variation of J co-content as a function of strain rate. And from there they calculated the instability parameter KJ. So, another variation now, looking in a different way to avoid strain rate sensitivity calculation there.

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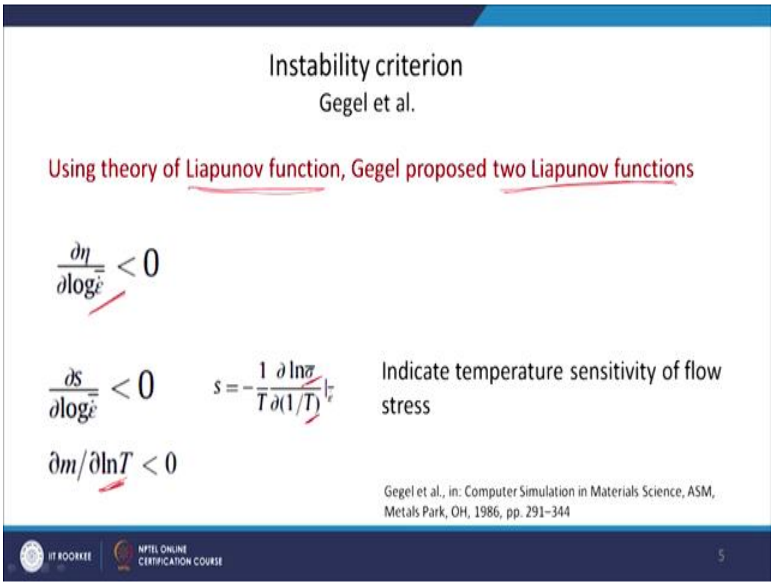

There is another model given by one more group, which is usually we call it as a Gegel model. And they use another some thermodynamic function which is called Liapunov-function and using that they propose two Liapunov-functions, where now they are using efficiency.

$$\frac{\partial\eta}{\partial log\dot{\varepsilon}} < 0$$

They introduce another parameter here, which is S parameter and what is the S parameter, it is the temperature sensitivity of flow stress that how the flow stress is going to change as a function of temperature. So, they have introduced another factor here which is temperature sensitivity of flow stress and if you do some more jugglery with the mathematics, you will come up with this particular parameter for instability. So, one parameter is this, another parameter is this based on the temperature sensitivity (refer to above figure).

So, basically how the strain rate sensitivity is going to change as a function of temperature and how, efficiency is going to change as a function of strain rate. So, both temperature and strain rate dependence is taken as a function of instability. So, when it is less than zero when efficiency change as a function of a strain rate is less than zero that means it has a low efficiency then it will be in instable region.

Or strain rate sensitivity as a function of temperature, if it is less than zero then again, you will have instability.

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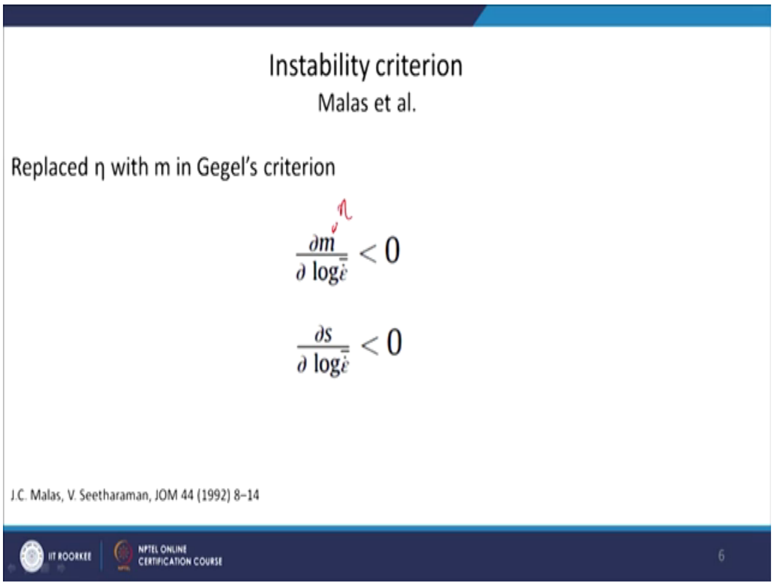

So, another model for instability, another model given by Malas and workers, they replace η with m in Gegel's criterion (refer to above figure). So, if you see here they have said η, so, in the next one now you can see that instead of η, they have replaced it by m. So, now it is strain rate sensitivity change as a function of a strain rate, it if it is negative. And also the one parameter which was introduced by Gegel which was the sensitivity of flow stress to temperature that is still there.

So, S parameter is still there and this is another parameter which is like a strain rate sensitivity as a function of strain rate. So, you can try to see that these are variations of the parameters in different way, they are looking at the problem in a different way and trying to come up with the instability criterion. So, Gegel if you see and Malas, if you see, more or less same, only the difference is that η is replaced by m here in the first equation.

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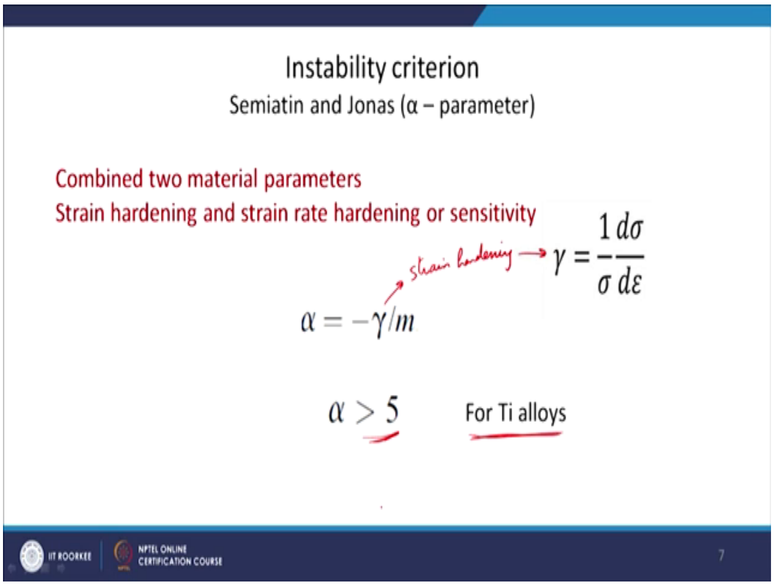

There is another now quite change from the calculations which we were doing. Another one which is a proposed by Semiatin and Jonas, they have done a lot of work on this. Now, they have combined two material parameters here. So, till now, we are only seeing the important material parameter is the strain rate sensitivity and only we are looking at the variation of strain rate sensitivity change as a function of different variables.

They said that for any instability when instability is there, it also affects the strain hardening exponent. So, that is already we have seen in the room temperature deformation that whenever the strain rate hardening is not there or material has lower strain rate hardening parameter then the instability can easily initiate and it can propagate, it can grow as a function of strain. So, strain hardening already we know this parameter strain hardening.

And strain rate hardening or you can say strain rate sensitivity both are same. So, γ is your strain hardening coefficient and m is coming as a strain rate sensitivity. So, they have introduced this parameter called α and whenever α is more than 5, you have a instability and this particular value five they have found out for titanium alloys. So, still it is not a universally applicable phenomena or criterion because you have to determine for each material class that what is the value of α parameter is valid for that particular material. So, this is another in stability criterion.

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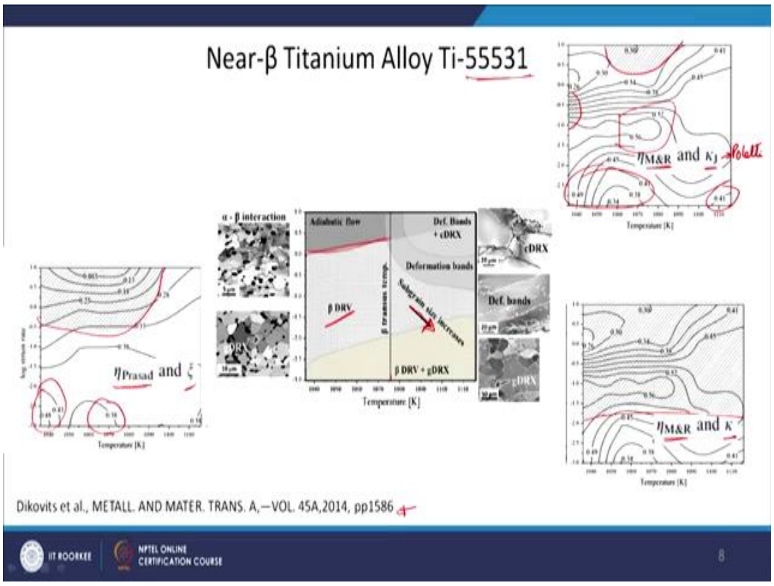

Now, we would like to compare these criteria with different materials. In different materials, I have taken the references and the references always shown in the bottom part here. So, this is a work on β-titanium alloy (Titanium 55531) and three processing maps you can see here. So η, the efficiency is calculated by an expression given by Murthy and Rao. And in this case, the instability is calculated by the parameter which is given by a Poletti.

This particular processing map η is calculated by Prasad's calculation the DMM model and of course, ζ is the instability parameter. And the third processing map, η is calculated again with Murthy and Rao and the stability is also calculated by the modified dynamic materials model.

So, these the maps with different instability criterion is shown here. So, you can try to see that where the maximum efficiency you are getting in case of DMM model you are getting somewhere here and one here and this area is the instable area that is the lower temperature higher strain rate. With instability criteria given by Poletti you can see the instable regions are here and the high efficiency regions are somewhere here (refer to above figure).

And somewhere here and one is given here also and in case of Murthy and Rao efficiency again Murthy and Rao, instability is also from their model. Again the of course, the efficiency will be same because in both cases the efficiency parameter is taken as same, but you can see the instability is over a very wide range in this case. Almost all the strain rates above 10^{-2}, it is showing instability (refer to above figure).

So, all the strain rate above this for all the temperatures whereas in this case you are looking at certain pockets and now, they have done of course, microstructural analysis by doing a microstructural analysis, they have also plotted a deformation mechanism map kind of. So, you can see lower strain lower temperature, higher strain rate. Higher strain rate already we know that there is a lot of chances of adiabatic heating.

So, you will see that there is a adiabatic flow that is the flow due to adiabatic heating , somewhere here you have deformation bends and CDRX also continuous dynamic recrystallization, this is the dynamic recovery in the β field, this is your β transit temperature and this is your dynamic recovery in the β field plus geometric dynamic recrystallization.

And the subgrain size they have shown to increase in this direction that means going towards higher temperature and lower strain rates. So, subgrain size is increasing because temperature is high and strain rates are low. So, more chances of subgrain size will tend to increase. And these are all done through this microstructural analysis here, where you have continuous dynamic recrystallization, deformation bands and so on (refer to above figure).

And looking at it if you compare, this DMM model is able to predict instability in this region, the top region here matching with that, some part of this also is matching somewhere here. Whereas, if you see the modified DMM that is showing instability for a large range here, which we are not able to see here (refer to above figure). So, from this you can say that this modified dynamic materials model is more conservative than other models.

And if you see higher efficiency of course, we are able to see dynamic recrystallization in this area where you have higher efficiency in all the cases. So, efficiency wise more or less both maps whether we are creating with DMM or modified DMM they are able to predict those areas where you are seeing dynamic recovery and dynamic recrystallization.

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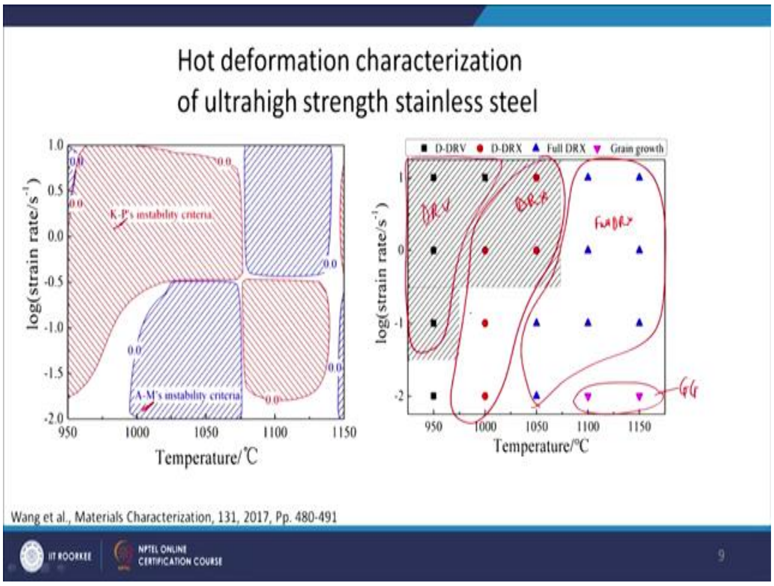

Another work, another comparison, in ultrahigh strength stainless steels (refer to above figure). The models which are used are Prasad's, it is also called as Kumar and Prasad's and one is by Malas, already we have discussed that. They have taken it as Alexander and Malas, different groups have proposed this. So, they are showing instability criteria from Prasad's DMM model which is shown with red hatching here and the Malas's instability criteria, which is shown with blue hatching (refer to above figure).

And again then they must have done microstructural analysis at different conditions. And those conditions are shown on the in the right one, this particular micrograph. So, these areas are the square black field, are the ones which are showing the dynamic recovery. So, this is the area where you have dynamic recovery. Then, you have dynamic recrystallization. So, one area here you can show as dynamic recrystallization.

Then, you have these areas full DRX. And then this one you see as grain growth. So, if you compare with the instability criterion, both they are not able to show the same instability criteria here. On instability conditions here, because you are seeing either dynamic recrystallization or dynamic recovery in this case. And of course, at higher temperature you are also seeing the grain growth which we saw in case of work by Poletti also that the earlier work that the grains subgrain size is increasing as you are going to lower strain rate, higher temperature. So, again here we are at lower strain rate higher temperature. So, here you see grain growth. But more or less in in this case the instability regions are not at least whatever they are reporting and whatever they are showing. It is not being related with the microstructural analysis.

Because both dynamic recovery and dynamic recrystallization, we consider it as a safe deformation region. So, we do not see kind of that kind of instability here.

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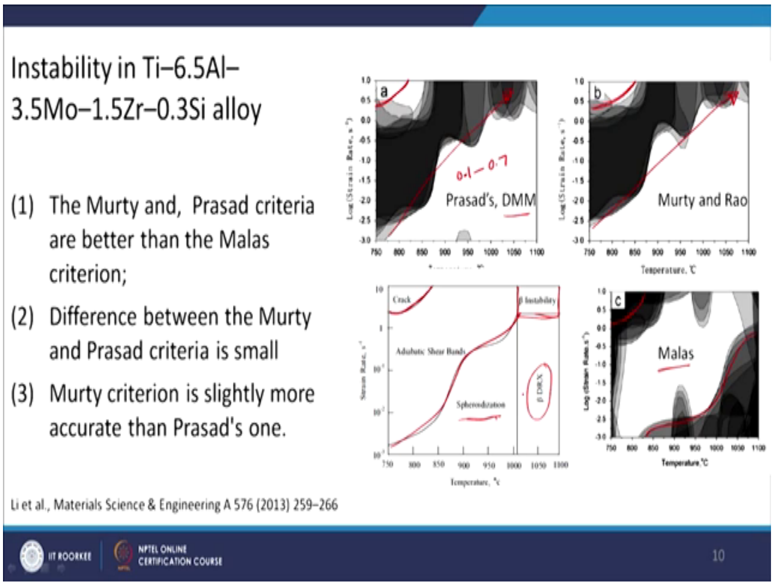

Another work on titanium alloy again and they have compared Murthy and Rao's model, DMM model of course, Prasad's model, Malas model. And what they have also done here that all these instability regions were plotted at different strain levels. So, the strain levels are from 0.1 to 0.7 at the interval of 0.1. So, the you can see lot of overlapping maps are there. And as the overlapping is increasing, it is becoming darker and darker.

That means the instability is either reducing or increasing as a function of strain. So, that is what they are trying to show. So, if you see the the DMM model, the instability is starting from a lower strain rate and then going like some kind of diagonally to towards the higher strain rate as a function of temperature. So, at lower temperature at lower strain rate also you have instability. And then, it is going towards as you are going toward higher temperature, the instability shifting towards higher strain rates.

If you see the Murthy and Rao model also, again the behaviour is more or less same. Maybe because both are based on strain rate sensitivity calculation. So, you can see that again the behaviour is like this whereas for model given by Malas, who considered also the effect of temperature on flow stress, their model more or less all the boundaries are kind of covered with instable region. And the central part is shown as the safe region.

And of course, again they have also done a microstructural analysis where they are showing different zones. So, here low temperature, high strain rates, you will have crack initiation or cracking in the material. Again low temperature high strain rate you have adiabatic shear band formation area. Then, you have at lower strain rate as you go towards higher temperature you have spheroidization.

So, already we have discussed that spheroidization is also a safe region to operate, it should be related to the high efficiency region. And basically your acicular type of structure gets spheroidized,becomes globular so like a dynamic recrystallization. And as you go I think this must be the β transit temperature. So, you have dynamic recrystallization in the β-phase.

And in this particular zone you have β instability. So, if you see more or less both DMM and modified DMM model of Murthy and Rao, they both are able to predict this instability very nicely. Of course, they are not able to predict the instability in the upper region that is the lower temperature and highest strain rate , where in the microstructure it is showing cracking.

If you see the Malas's model of course, it is not able to predict the instability correctly because it is showing of course, the cracking where the crack formation is taking place and which could not be predicted by both DMM and MDMM that one was could be predicted by the Malas's model. But the high instability in this region is not corroborated with microstructural analysis.

So, you can see that different models sometime are able to predict some features may not be other features. In some cases they are conservative in some other cases they may not be conservative. And it all depends on the how the material behaviour is there, how the strain rate sensitivity is there, how the flow sensitivity is there to the temperature, to the strain rate.

So, all these parameter the material parameter kind of affects how the generation of the processing map and every time any processing map when we generate it has to be validated by microstructural analysis to confirm whether we are able to get the same efficiency instability in the microstructure also.

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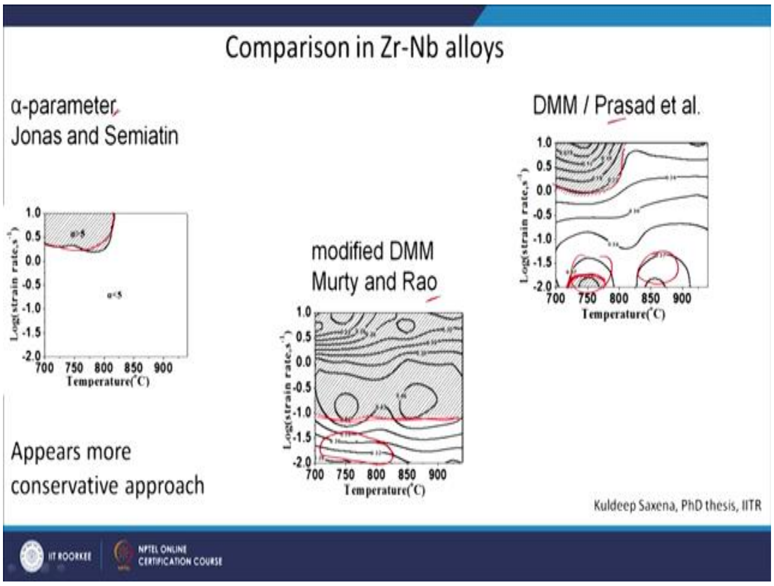

This is some of our work, this is again PhD thesis of one of the student Kuldeep Saxena. So, in in our work, we have compared in the Zirconium Niobium alloys. So, the α parameter given by Jonas and Semiatin, and of course modified DMM by Murthy and Rao and DMM model by Prasad et al. That is what we have taken. And you can also see as we have seen in case of earlier work also that the modified DMM is more conservative here.

Again showing very high instability in the all the strain rate above 10^{-1}. If you compare the DMM model with the α parameter, both are able to predict instability in the lower temperature region and higher strain rate. So, that is that is clear in both. However in DMM model, there is another one instability region is shown at lower strain rate and also lower temperature and more or less the high efficiency regions are these and these.

So, that is also can be seen in the modified DMM model. So, again different approaches, different ways of plotting the processing map.

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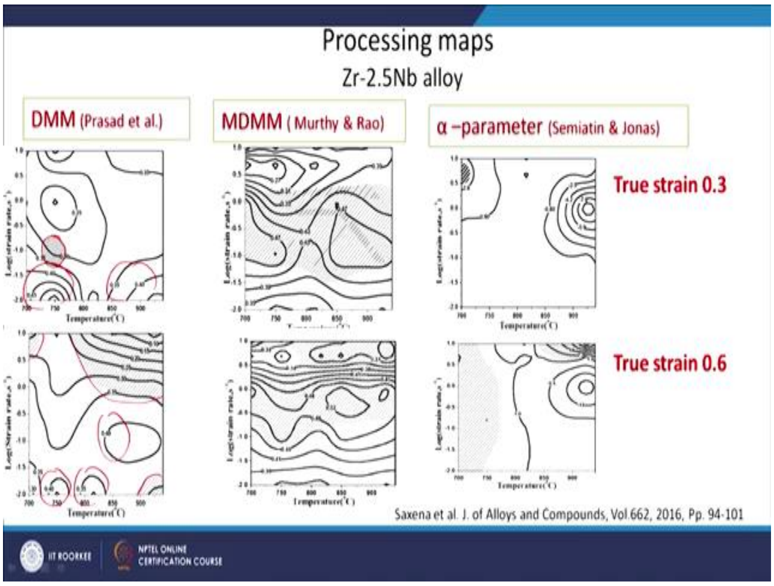

Again we can also try to do the microstructural analysis I will show you that. For example, this is another work on Zirconium 2.5 Niobium. Again the comparison is there between the DMM model, modified DMM model and α parameter at two different strain ever again it is plotted as we have seen in previous works also. As you go from 0.3 to 0.6, you can see there are some changes in the instability regions as well as the efficiency region, as you can see at lower strain only instability is here, but as you go to higher strain, the stability is coming in these regions.

Efficiency if you see you are getting high efficiency in these regions. And similarly at low strain also the efficiency is high in these regions. Again if we compare with the modified dynamic materials model given by Murthy and Rao, the instability is shown in the middle part and as you go to higher strain, all the strain rates above 10-1, you can see the instability.

In α parameter, the instability is extending at low strain, it is a in a small window, but at high strain it is extending for the all the strain rate range. Now, if you compare with the microstructures, we are taking this DMM model here.

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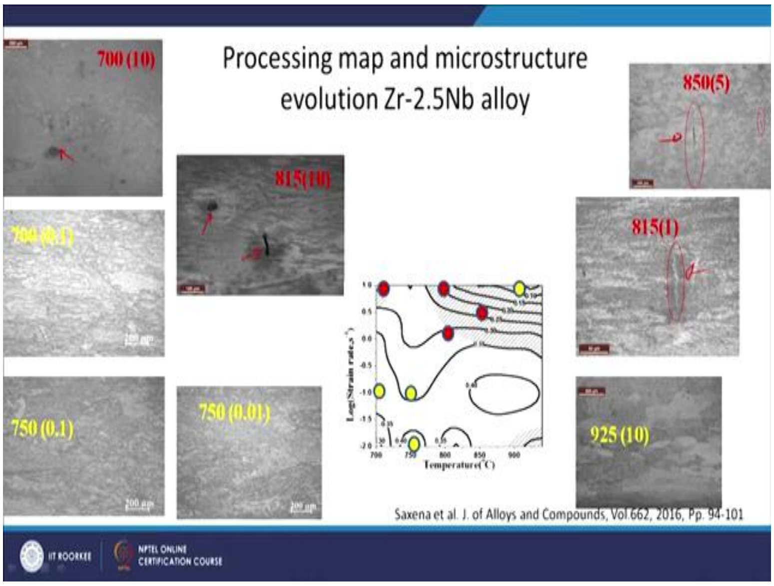

And from there we are taking the sample where we have high efficiency, where we have instability. So, the red dots are showing you the instability also observed in the microstructure whereas, the yellow dots are showing you that there are no instability in the microstructures. So, for example, from the model it says that it there should be instability at 900°C and strain rate of 10^{-1}.

But we do not see any instability at that condition, but other condition we are able to get instability as predicted by the processing map. And those are, you can see the processing conditions are also shown here. So, for example, you have voids formation here. Also some type of cracking at higher strain rates. At higher strain rate I can see cracking here also whereas, you can see adiabatic shear band formation at strain rate of one.

And at lower strain rates, you can see the microstructures are not very clear. The reason is that in Zirconium-Niobium alloy, there is a martensitic transformation when you quench the material. So, because these are deformed higher temperatures, in some cases it has gone into β phase. So, when you quench from β phase there will be a martensitic transformation and that kind of covers the actual microstructure which might have been there during the deformation process.

But at least I cannot see instabilities in these microstructure whereas, the microstructure from the instable region of the processing map I can see that there are few instabilities are there.

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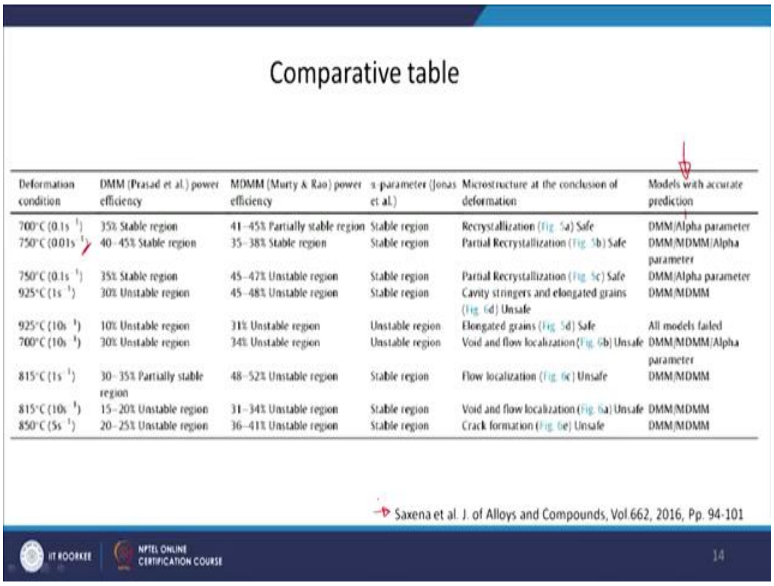

Comparative table

Deformation condition	DMM (Prasad et al.) power efficiency	MDMM (Murty & Rao) power efficiency	s-parameter (Jonas et al.)	Microstructure at the conclusion of deformation	Models with accurate prediction
700°C ($0.1s^{-1}$)	35% Stable region	41–45% Partially stable region	Stable region	Recrystallization (Fig. 5a) Safe	DMM/Alpha parameter
750°C ($0.01s^{-1}$)	40–45% Stable region	35–38% Stable region	Stable region	Partial Recrystallization (Fig. 5b) Safe	DMM/MDMM/Alpha parameter
750°C ($0.1s^{-1}$)	35% Stable region	45–47% Unstable region	Stable region	Partial Recrystallization (Fig. 5c) Safe	DMM/Alpha parameter
925°C ($1s^{-1}$)	30% Unstable region	45–48% Unstable region	Stable region	Cavity stringers and elongated grains (Fig. 6d) Unsafe	DMM/MDMM
925°C ($10s^{-1}$)	10% Unstable region	31% Unstable region	Unstable region	Elongated grains (Fig. 5d) Safe	All models failed
700°C ($10s^{-1}$)	30% Unstable region	34% Unstable region	Unstable region	Void and flow localization (Fig. 6b) Unsafe	DMM/MDMM/Alpha parameter
815°C ($1s^{-1}$)	30–35% Partially stable region	48–52% Unstable region	Stable region	Flow localization (Fig. 6c) Unsafe	DMM/MDMM
815°C ($10s^{-1}$)	15–20% Unstable region	31–34% Unstable region	Stable region	Void and flow localization (Fig. 6a) Unsafe	DMM/MDMM
850°C ($5s^{-1}$)	20–25% Unstable region	36–41% Unstable region	Stable region	Crack formation (Fig. 6e) Unsafe	DMM/MDMM

This is the comparative table for previous slide that where you can have instable region and so on. And which particular model is able to predict correctly so that is shown in the last column here. Whether DMM is the one which is able to predict this particular region, in another region DMM, all the three parameters or models are able to predict the partial recrystallization at this particular processing condition.

So, like that it is all kind of summarised in a table. And the work is taken from the from a paper our own work is there. So, if you want some details, you can go to these papers also and for other models and other work also I have shown you the source, from by which I have taken it. And if you actually see the work which is being carried out in high temperature deformation or thermo-mechanical deformation, huge amount of work on processing map constitutive equation development for each class of materials, and comparison of different models, comparison of different constitutive equations, there is a huge amount of work which is there. So, I cannot take all this in a small lecture like this. So I would encourage if you are interested to go and look for these publications, and this lecture can serve as an introductory lecture for you. So with that, thank you for your attention.

Keywords- modified DMM, Gegel model, Malas model, instability map, strain rate, temperature.