Thermo-Mechanical and Thermo-Chemical Processes
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Lecture-30
Severe Plastic Formation: Case Study

Hello friends, to continue with our discussion on severe plastic deformation in this last lecture of this particular module I am presenting a case study. And I am using friction stir processing again, as the technique for this particular case study. And we are looking at the one of the deformation methods or the one of the deformation processes which is called superplasticity. I have mentioned this particular word couple of times during previous lectures.

So I will introduce you what do we mean by superplasticity. So, basically superplasticity if you want to define it is the capability of very fine-grained polycrystalline material. So, one of the requirement is that you should have very fine grain materials, already we have a polycrystalline material usually in all engineering applications and they undergo very high tensile plastic deformation.

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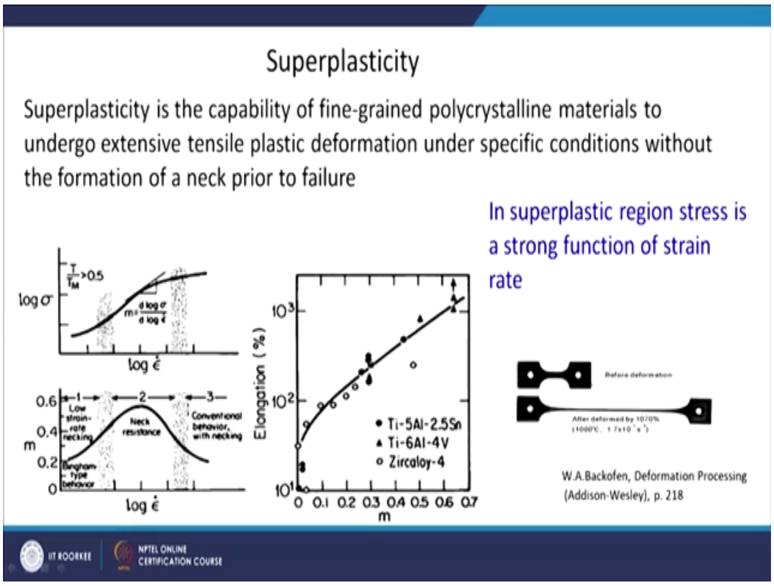

So, if you see (above figure) the sample which was initially of this size after deformation it has shown the deformation of around 1000% here, so very high elongation 1000% means in normal engineering alloys high ductility of 30-40%, if some alloys showing 30-40% elongation that is considered as very good ductility. Whereas in this particular condition you can see the elongation is around 1000%.

So, and the other unique thing which you can see here is that the deformation is uniform throughout the gauge length. So, it is a one single dimension you can see from very close to the other part of the shoulder. The deformation is uniform. There is no deformation localization, there is no neck formation. So, this kind of very uniform elongation you are able to get.

So, in this case, in this particular material you can get very high elongation and in superplastic region of course stress is a strong function of strain rate and that is what we call as strain rate sensibility. So, couple of graphs are shown here that when you plot a lnstrain rate vs lnσ in superplastic window you see that the slope is quite high where material show superplasticity and then m start decreasing that is where in this particular material we say power law breakdown is there.

And in lower strain rates you will start going towards the creep kind of deformation. So, there is a strain rate window in which the strain rate sensitivity is very high. So, if you see the m as a function of ln(strain rate), so m has been calculated from the slope of the top graph. So, you see that the m is very high where the superplasticity is expected. And m is usually more than 0.4. What is the effect of m? Already we have seen that when m of the material or strain rate sensitivity of the material increases your elongation is increasing.

So for example m of 0.6 is able to give you elongation of around 1000% and these are true for different set of materials. For example here titanium and zirconium alloys are plotted and when m is lower than 0.4 or around 0.3 you cannot even reach may be around 100% or so. And as you go towards the m of 0.1 let's say, the elongation is around 50%. So, the elongation is a strong function of strain rate sensitivity.

The application of superplasticity is of course superplastic forming, the idea is that when you have superplastic deformation these are all high temperature deformation, the flow stresses are very low. So, you can deform a material just by using gas pressure.

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So, all these parts which you are seeing here (above figure), these are metallic part formed only using gas pressure which we do generally in case of glassblowing operation or making some plastic part i.e. these products are made by just applying a gas pressure. And whatever the die shape is there the material take that shape. So, this is what is when component is taken out from a furnace.

So, you keep it in furnace apply the gas pressure and whatever is the die shape on the other side you can get the shape of that die. So, you can form very complex shapes as you can see one shape here very complex shape, very complex geometry and this can be made only in one go means only in one cycle you can produce the whole thing. If you are going to do with this with conventional fabrication method all these parts will have to be made separately and then they will be joined using welding or some riveting techniques.

So, in one shot you can get a very complex shape like this in superplastic form through superplastic forming.

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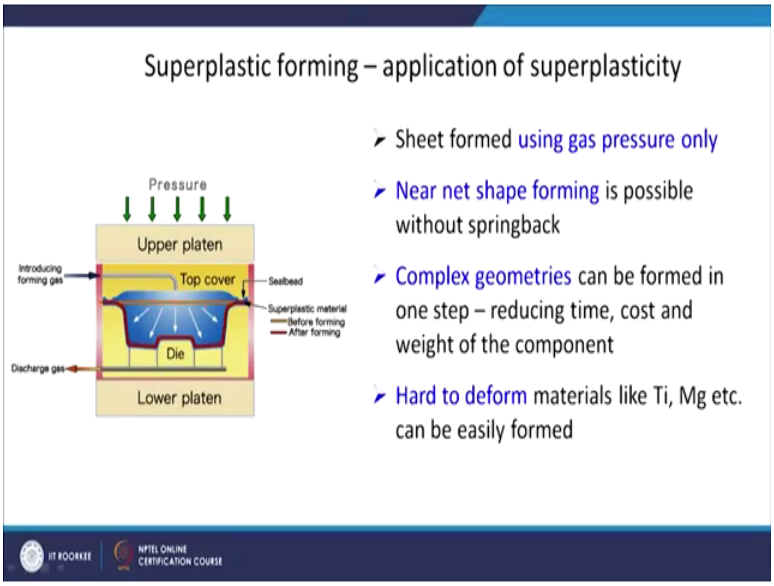

So, as I was telling you that for example this is your initial sheet which is shown by orange colour (refer to above figure) then you have applied the gas pressure and the shape of the die is shown here. So, when we are applying the gas pressure the sheet is deforming so this red one is the deformed sheet after forming and it is able to take the shape of the die by applying a constant pressure.

Other very good advantage of superplasticity and superplastic forming is that you can deform or you can form these complex geometries in materials like titanium and magnesium which are hard to deform because they have hexagonal closed pack structure HCP structure. So, they have very limited slip system. So, deformation at room temperature through dislocation movement is very difficult.

And they generally have very low ductility but with this technique because here the deformation is not through dislocation movement the deformation is through grain boundary sliding which is what we call as GBS. So, the crystal structure is not a factor here because deformation will be on the grain boundary. So, you can easily form material of titanium and magnesium alloys also through this process.

And the advantage of doing that with titanium and magnesium is that they have low density so these are lightweight. So, very important for aerospace application. So, this is what already we have discussed about the strain rate sensitivity.

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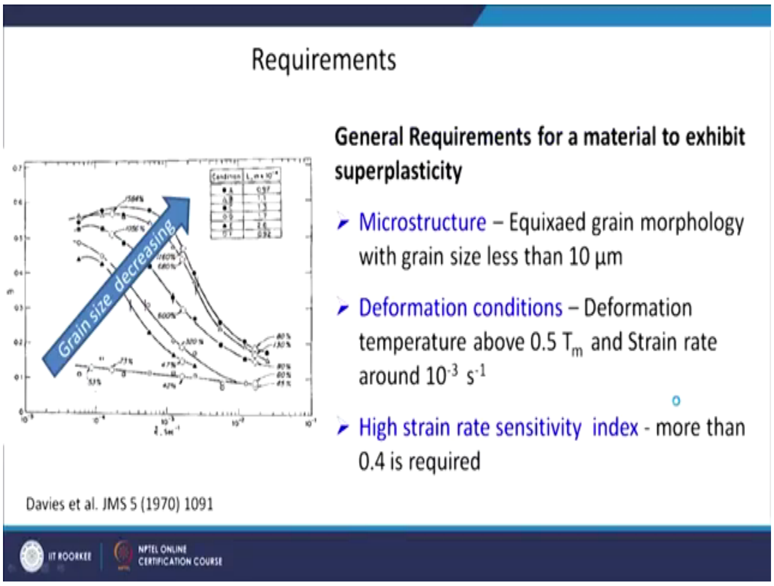

Now what is the effect of, what are the general requirements for a material to show superplasticity. There are three main condition for example that the microstructure should be equiaxed, we have equiaxed grain morphology that means in any direction if you measure the grain size it will be able to have same size. And the grain size in conventional superplasticity should be less than 10 microns or around 10 microns, it can be 15 microns also.

But the limiting condition is around 10 microns because when you have fine grain material then only you have more grain boundaries and then the deformation happens through grain boundary sliding. So, all these equiaxed grains, finer grain size helps in the grain boundary sliding process. The deformation condition the temperature has to be above 0.4 or 0.5 Tm. So, this is where you have high temperature deformation conditions.

And the strain rate is around 10^{-3} s^{-1}. So, strain rates are very low as compared to other forming processes or hot deformation processes so that is the only drawback of superplastic deformation. One is of course high temperature that you have to take material to high temperature. And the other is the very slow strain rate. So, when we are doing forming also one part will be produced in a very long time.

So, the productivity will be low if you are going for superplastic forming and of course strain rate sensitivity as already told should be more than 0.4. And what is the effect of grain size if you see the grain size how it affects the strain rate sensitivity m. So, these are strain rate values this 10^{-4}, this is 10^{-3}, and so on. And the m values are 0.1 here, 0.2 here and so on and the grain size is increasing in this direction (refer to above figure).

So, the effect of grain size is that as the grain size is decreasing for example, the strain rate sensitivity of the material is increasing and of course you have to look for the superplastic window here which is around 10^{-3} here.

So above that only you have strain rate sensitivity of more than 0.4. So, in this window and as the grain size is reducing my m is increasing and you can also see that as grain size is reducing my window for high strain rate sensitivity is going towards higher strain rates. So, for example in a very fine grain material I can have superplastic window extended up to 2×10^{-3}. So, if you can reduce grain size further you can still go to higher strain rates.

So, effect of grain size is very strong that by reduction of grain size the m increases and also the window for high strain rate sensitivity shifts towards the high strain rate that means I can deform at a higher strain rate that means my time for deformation will be smaller now.

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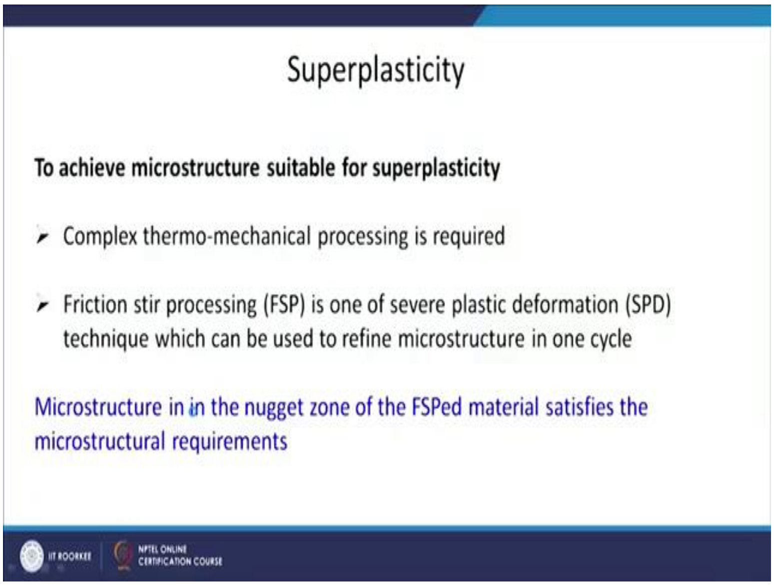

Now for getting super-plastic deformation or material for which it can exhibit super-plasticity usual method is of course your normal thermomechanical processing to have recrystallization in the material to generate fine grain size material. So, normal thermomechanical processing like rolling, extrusion and all these processes are already there.

So, precipitation will be done and precipitation simulated nucleation of new finer recrystallized grains will be there. All those complex thermomechanical processes are there for production of material suitable for superplasticity. The problem with those methods is you have to have very intimate knowledge about materials to get material suitable for superplasticity. In this friction stir processing is a very promising technique which has been able to generate these fine grain size materials in one cycle.

So, just by traversing the tool through the material you are able to generate the fine grain size material in one shot. So, I do not have to do a very complex thermomechanical process to get the fine grain size material. And the microstructure which is there in the nugget zone or the stir zone, fine grain size microstructure that is able to satisfy the condition require for superplasticity.

Already whatever requirement in that we have seen so the microstructure which is in the stir zone or nugget zone is the one which is able to satisfy those conditions.

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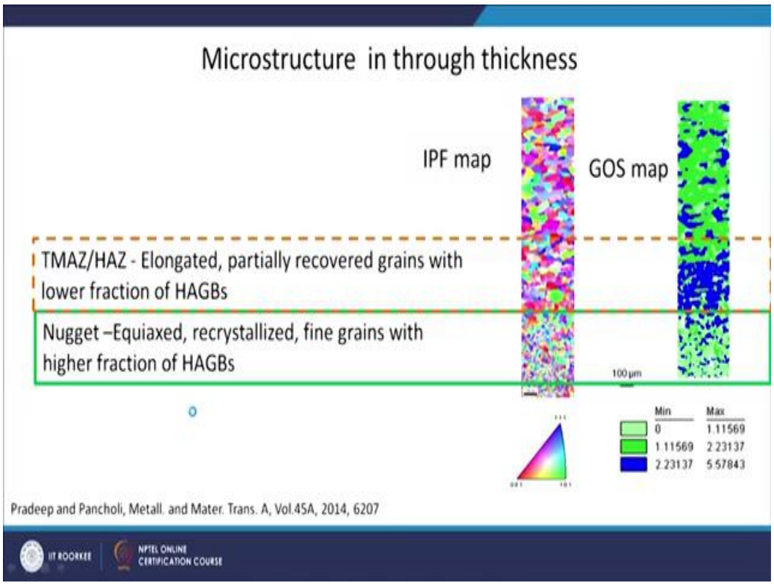

Now the problem with FSP is that which we have already seen that you have a microstructural gradient. So, only the microstructure will be refined depending upon the length of the pin. So, if my pin is up to here the refinement will takes place up to here, recrystallized grains will be there and above that it will be a thermo-mechanically affected zone means it is elongated grains not recovered grains which is not suitable for superplasticity.

So, this material is suitable for superplastic deformation as defined in our previous slide whereas this material and above this coarse grain also this you can say is non superplastic. They cannot exhibits superplasticity. So, now the idea here is that to understand this deformation behaviour of these fine grain and coarse grain materials separately. And then what is the effect of this combined microstructure on the superplastic deformation.

So, one should understand that is when only we will be able to use FSP as a technique for microstructure or for superplasticity. So, the idea is to understand individual deformation behaviour of fine-grained material, coarse grained material and the combination of this which we will be calling as composite material or composite microstructure.

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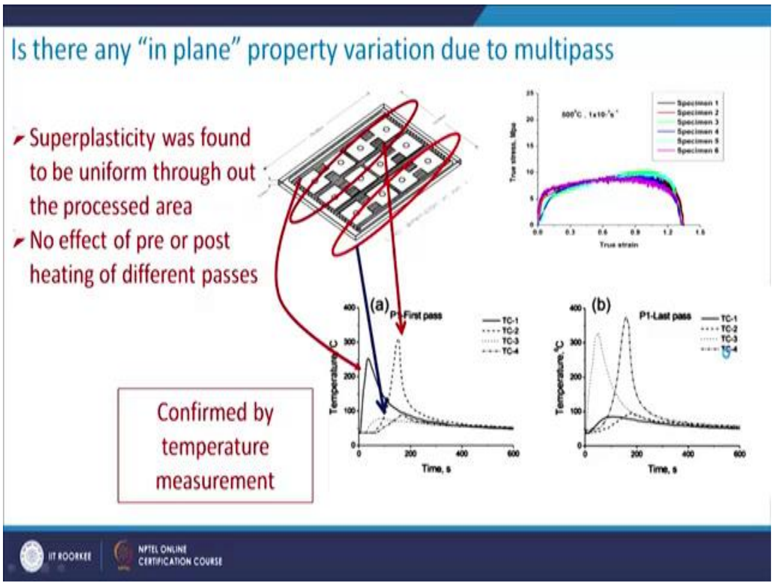

Before going to that we have discussed about multi pass, that I can use multi pass FSP to get a bulk microstructure or I can use it as a bulk processing. So, in that it will be an interesting thing to understand that what will be the effect of multiple processing on the material which is already processed. For example, if we are starting from here this is my first pass and this is my last pass so, what will be the effect of this first pass on the material which is still unprocessed that means I will call it as preheating.

Or what is the effect of last pass on the first pass then that means it will be a post heated material or post heating. So, what will be the effect of these individual passes on the microstructure of the material whether microstructure is changing or the properties are changing. To do that first we measure the temperature that what is the temperature rise when you are doing FSP. So, suppose the pass has started from here and going in this direction so thermocouple placed here measures the temperature.

So, the temperature goes up to around 250° of course we are measuring the temperature away from the stir zone. I cannot measure in the stir zone. So, there it is around 250° and then quickly coming down to room temperature in around 200 seconds. The next thermocouple measures the temperature which is placed somewhere here temperature rise of 300° and then coming down also again in a very short time.

What is the effect of this when the processing is being done here, what is the effect of that in the already process material that is shown with these two curves here (refer to above figure). That says that the temperature rise in the other part of the material is not very high, it is even lower than the 100°. So, effect of the first pass on the other part of the material is very small. Similarly when you see the last pass the temperature rise in the thermocouple which are placed here it is around 300 or 400°.

But the temperature rise in the thermocouple which are placed here is very small only up to less than even 100°. So, we can conclude that there is not much effect of individual passes on the microstructure. It should not be too much effect on the microstructure because the temperature rise or the temperature comes down to room temperature at a very in a very short time within 200 seconds or so means it is only an exposure of 3 or 4 minutes.

And there is not much effect of temperature on the other part of the sample. To confirm it more what we did is we took sample of a large process material from different locations and these are the deformed material samples specimen 1 2 3 4 5 6 and you can see (refer to below figure) in all the cases that deformation is very similar. There is not much effect of the thermal cycle on the microstructure as well as property of the material.

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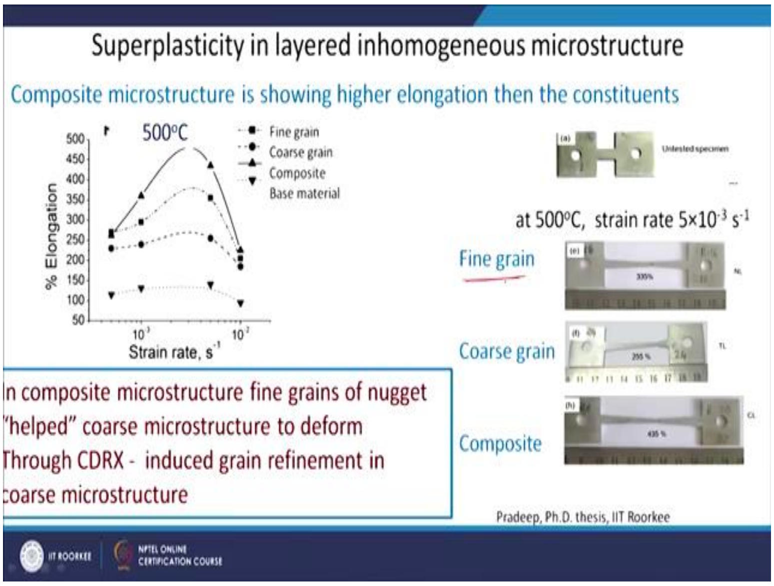

So, now taking material sample from different part of the microstructure so this is a fine grain microstructure sample, this is for coarse grain and this is for the composite one. So, in the coarse grain one you can see that there is a large reduction in the in the cross-sectional area that means there is a flow localization here whereas in fine grain one and the composite one more or less the deformation is uniform.

Of course, we have gone up to failure that is why you see necking in the last part of the deformation but more or less the deformation is quite uniform and the effect of that you can see on the elongation also. So, at different strain rate deformations were done. The interesting part here is that the fine grain which is shown by this square box is showing maximum elongation of around 350% whereas the composite microstructure which contains both the fine and coarse grain which is shown by this upright triangle the elongation is shown around 450% or so.

That means the material which has both fine and coarse grains are showing a higher ductility, higher elongation. So, somehow it looks like that the fine grain which is there in the nugget zone or stir zone is helping this coarse grain microstructure and in the process you are having continuous dynamic recrystallization and this addition of fine grain in the material is helping the composite microstructure to show higher elongation. So, to confirm this, what we are proposing we did microstructural analysis.

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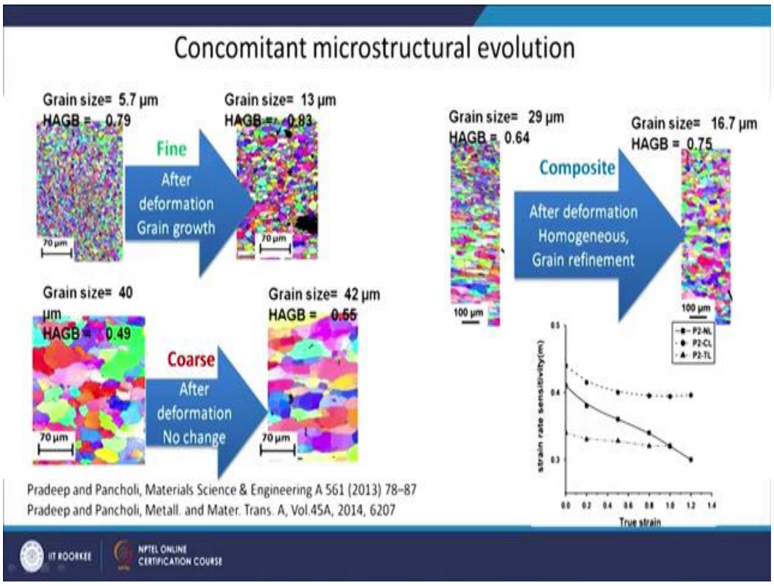

So, this is the initial fine grain microstructure, when we have taken the fine grain microstructure. After deformation it is showing dynamic grain growth. So, the grain size is increasing as you can see this is the initial grain size, this is the final grain size. From 5.7 we have come to 13 micron during the deformation. If you see the coarse grain part of the FSP material after deformation also it remains coarse.

There is no dynamic recrystallization is happening. Coarse microstructure remains coarse. Grain size is 40 microns and still it is 40 microns in the after deformation. So, there is not much change in the microstructure and of course ductility is also very low. Whereas if you see the composite microstructure, this is the gradient you can see in the microstructure fine grain coarse grain. So, this is my fine grain, this is my coarse grain material.

And after deformation if you see the microstructure is now uniform throughout the cross-section. So, this coarse grain microstructure has undergone dynamic recrystallization which is what we call as continuous dynamic recrystallization and refinement is taking place. Whereas in a single coarse grain material or uniform coarse grain material you do not see any CDRX. So, these fine grains are somehow helping this coarse grain to undergo CDRX process.

And you can see effect on grain size also it is from 29 microns it is going to 16.7 microns. The very important effect of this microstructural change you can see on the strain rate sensitivity. So, if you plot strain rate sensitivity as a function of true strain that means after different deformation stages what is the strain rate sensitivity, the strain rate sensitivity of the fine grain this is my fine grain layer though it is initially very high more than 0.4 but it is continuously coming down with the deformation process.

And that is due to coarsening of the microstructure as we saw for fine grain material or fine grain size material the m was higher, for coarse grain m was coming down we saw one graph like that. So, because of this dynamic grain growth which is taking place my m is continuously reducing. In the coarse grain material of course, the m was low from the beginning and it remains low throughout the deformation process there is no change in the microstructure.

Whereas in composite if you see the strain rate sensitivity is remain continuously high more than 0.4 and the reason for this continuously high m is because you are feeding the material with fine grain size microstructure or you are continuously refining the microstructure through CDRX process. And that is what is helping m to remain higher during the whole deformation process. So, this is what is helping to achieve higher ductility in the composite microstructure.

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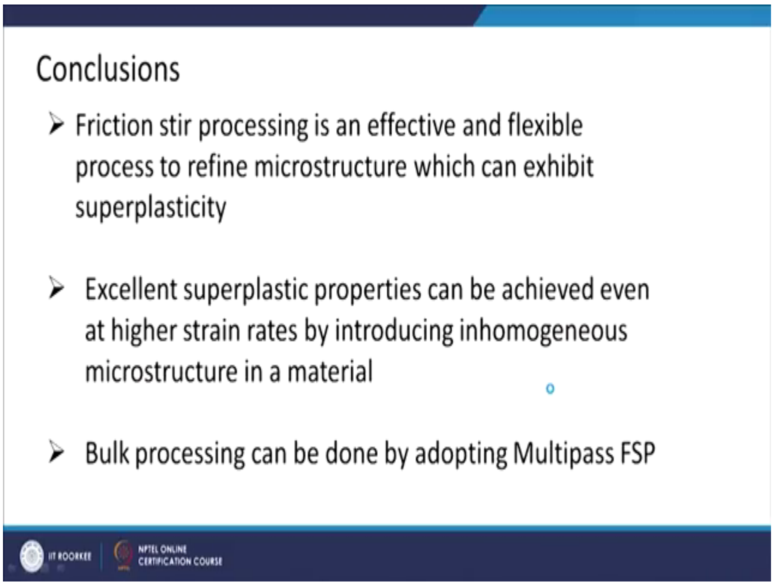

So, to conclude friction stir processing is an effective and flexible process to refine microstructure which can exhibit superplasticity. And you can achieve very good superplastic properties at relatively higher strain rates by introducing this inhomogeneous structure composite structure. And you can easily adopt FSP as a bulk processing technique by doing multiple passes.

So, this is the one case study on friction stir processing using severe plastic deformation method which is this FSP and where you can get superplasticity in the material. Thank you.

Keywords- case study, friction stir processing, superplasticity, composite microstructure.