Thermo-Mechanical and Thermo-Chemical Processes
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Lecture-27
Friction Stir Processing (FSP)

Hello friends, so, continuing with our severe plastic deformation module. Today, I am going to cover another very important technique in severe plastic deformation. Again it is based on the shear deformation in the material and that is called friction stir processing (FSP)..

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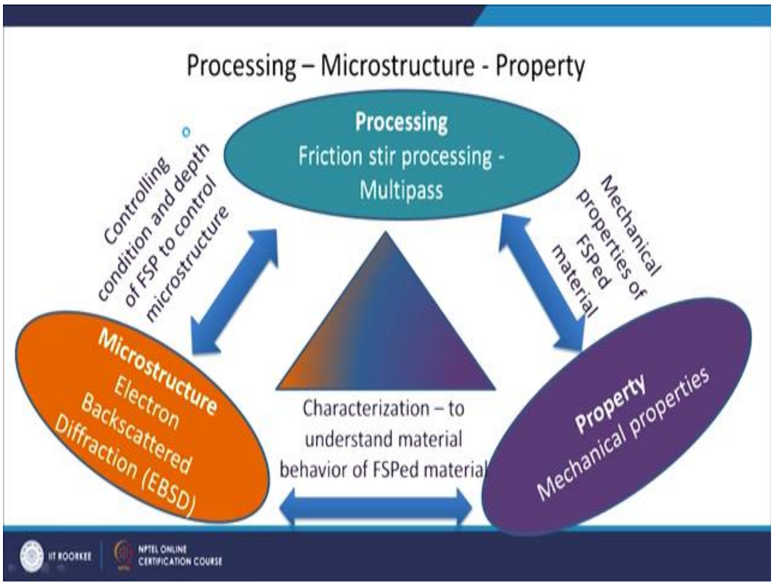

Just wanted to show you this particular kind of triangle (refer to above figure) where you can take any processing method here not only Friction Stir processing is connected with the microstructural change as we saw in ECAP or in the processing methods also. So, there will be a change in the microstructure. You can use certain techniques to characterize the microstructure. And the property which you are going to check is usually mechanical property because we are looking upon structural materials.

So, that will be there. So, processing then microstructure property that will be again give a feedback that we have not achieved the property which was which was required. You can look at the processing or you can look at the microstructure and try to change the processing condition and so on. So, this kind of interrelationship between processing, microstructure and property keeps taking place.

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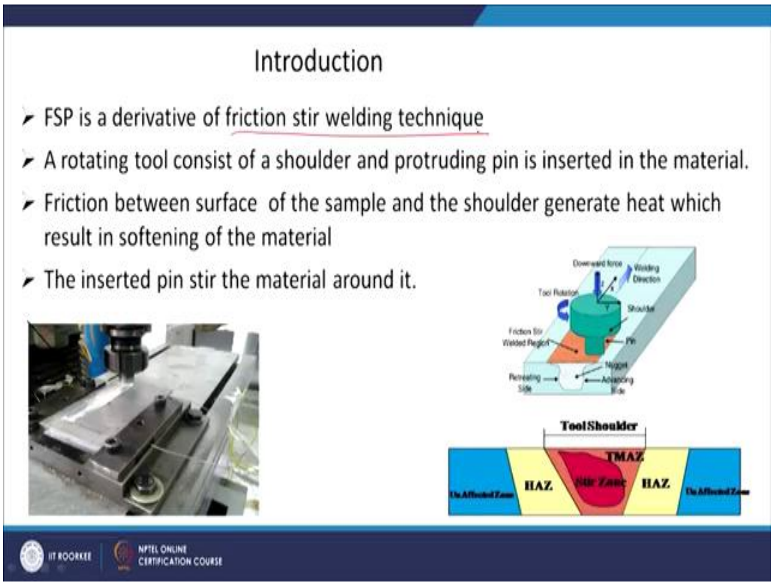

So, looking at the friction stir processing technique, again a very simple technique you can use if you have a milling machine in your lab or in your department you can use it very easily. Basically, you need a vertical milling machine. So, what it has is that you have a tool which contains a shoulder and a pin. So, shoulder is just touching the surface of the work piece with certain normal force.

There is a downward force and the pin is actually inside the material and this tool is now rotating at a good rpm. So, what will happen that this shoulder will rub against the surface of the work piece and will generate the heat through friction and this heat of course will dissipate around and when you go to higher temperature, we have already seen that the flow stress of the material keeps coming down.

So, basically materials become soft. So, then this rotating pin what it does is it stirs the material around it. So, this soft material will be continuously stirred around the pin. And now suppose you have started moving this particular tool at a certain traverses speed. Then what will happen the material from the front will be taken back where the cavity is created because of the movement when the tool is moving. So, this rotation will take the material from the front and will deposit at the back. Of course, this material flow is a very complex phenomena, lot of work is going on in understanding the material flow. So, but in kind of a layman's language it is like this that you are continuously bringing front material in the back and the tool is moving.

And because of this when the material is getting stirred around the pin, you impose lot of strain and strain rate is of course, related to the rpm. So, at very high strain rate and of course, there is a temperature involved. So, it is a very typical self-generated thermomechanical processing. So, in this case you are not heating material from outside the heating is also in-situ through the movement of the tool.

And the deformation is being carried out by this stirring process. So very elegant technique in that sense. Actually, this whole process started with the Friction Stir Welding technique, where you actually take two plates and you can join by doing this. So, there is a material movement from one side to another side. So, this material movement from one side to another side will ultimately join to two two plates, for example.

So, this is actually was proposed for as a welding technique initially and actually lot of work is there on friction stirring welding also. Later on by Mishra and co-workers they used this welding technique for processing. So, instead of having two plates joining plates if you have one single plate and in that you are doing moving this tool like this. What will happen? It will change the microstructure.

So, usually it will refine the microstructure because you are imposing very high strain at a very high strain rate at a higher temperature and if you see them this particular plane then, you will see a microstructural region like this (refer to above figure). So, this is what we call as a stir zone where the pin is stirring the material. Next to it is called a thermo-mechanically affected zone that means, the strain is not that in that much to refine the microstructure.

So, you here you can see elongated grains, which are partially kind of recrystallized or partially recovered. So, recovery is not complete or recrystallization is not complete, whereas, in the stir zone it will be very nice recrystallized microstructure can be observed. So, next to the stir zone you have thermo-mechanically affected zone. Next to that is because heat is there, so, it will dissipate. So, you will have a heat affected zone and then the base material.

So, these are the different microstructural zone you will observe in the friction stir processing. So, this is one micrograph for that you have nugget zone (refer to below figure).

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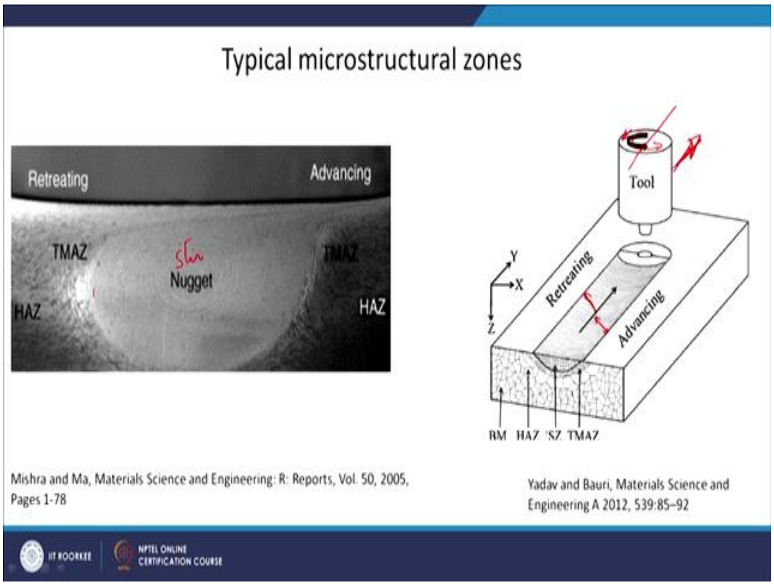

You can see as it is a macrostructure you cannot see very fine grain inside. So, you have a nugget zone or stir zone. It is also called as Stir zone or nugget zone. Then you have thermo-mechanically affected zone and then the heat affected zone. Then there are two sides shown here one is called retreating and another is called advancing. So, let us say what is advancing and what is retreating.

So, in this case for example, in this schematic you can see the tool is rotating like this. There is a rotation like this and the tool is also moving in this direction. So, when you have this kind of condition, you will obviously have two different set of material flow on this side of the tool. If you take this as centre line, my rotation direction and my traverse direction both are in the same direction. So, that side I will call as advancing side.

On the other side, my tool rotation is in this direction and my of course traversal speed will still remain in the same direction. So, these are in now opposite direction, the tool rotation and the and the traverse speed. So, this part of the processed zone I will call as retreating side. So, there is one called advancing side and another, what we call as retreating side. And another very nice schematic is shown here for different microstructural zones.

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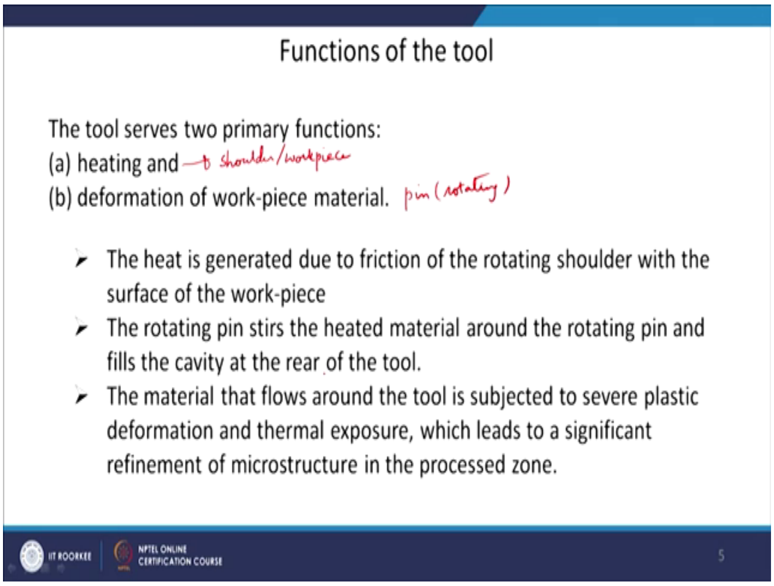

So, function of the tools already we have discussed. So it serves primarily two functions: heating and deformation. So heating is primarily through friction between shoulder and work piece. And deformation is primarily through the rotating pin, shoulder also contribute to some part of the deformation, but primarily it is the pin. So, heat is generated due to friction of the rotating shoulder with the surface of the work piece.

And the rotating pin stirs the heated material around the rotating pin and fills the cavity at the rear of the tool and the material that flows around the tool is subjected to severe plastic deformation and thermal exposure, which leads to significant refinement of microstructure in the process zone. So, already I have told you about this that all this stirring at high temperature will refine the microstructure.

Now, what are the process parameters, which is going to affect your microstructure and obviously, the properties also? So, there are you can categorise them in three variables here (refer to below figure).

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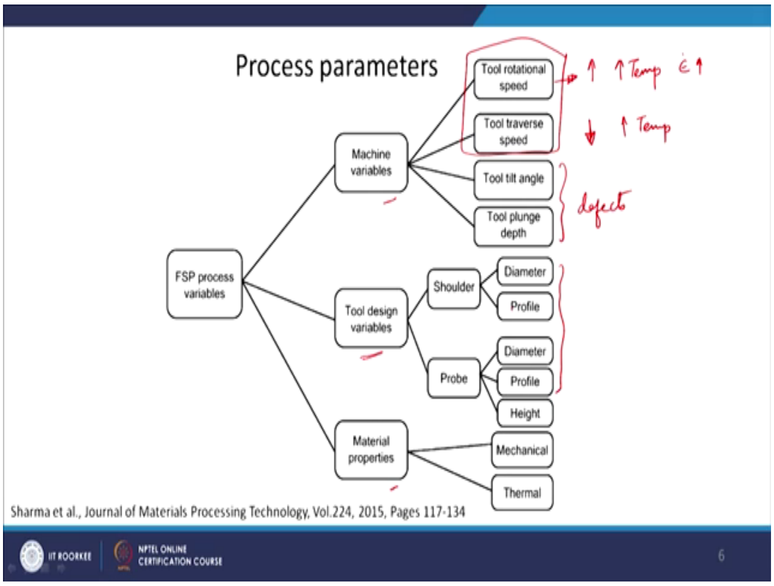

One is machine variable, which you can change on the machine, then you can have variable in tool design and of course material properties. So material property of course, once your material is, you cannot do anything. In machine variable, these two parameters are the most important parameters, tool rotation. So, as rpm is increasing, there will be more frictional heating because friction will be more between the shoulder and the surface of the work piece. So, high rotational speed will obviously affect the temperature.

So temperature attained will be higher. Of course, there is a self-limit, here you cannot have a monotonic increase in the temperature. After some time what will happen the temperature will be so, high that the material close to the pin surface will be in molten condition and there is no transfer of power from the tool to the material. So, if it localized heating takes place, you cannot have addition of heat to the material.

So, it is a self-limiting process so, you cannot keep increasing temperature continuously, but in general if you increase the rpm, temperature attained will be more and also because the stirring is more, the strain rate which you achieve will also be going to be more, as you increase the rotation is speed. Tool traverse speed if you have a slower speed, the temperature attained will be more.

When you have a very high speed, your tool is not giving enough time at a particular location. So, the rpm which is generating the heat does not get enough time to to raise the temperature. So, the temperature attained will be lower will be higher if you have a high traverse speed. So, these two are very important parameters.

Tool tilt angle and plunger depth will of course affect, will have an important bearing on the defects in this process. So, by manipulation of these two parameters people were able to achieve defect free processing in the material. Shoulder and in tool design, shoulder of course shoulder and the pin diameter and they are their profile is going to affect the heat generation.

So, when you have a higher shoulder diameter of course you will have more heat generation. Similarly, when you have a bigger pin diameter, you will have higher peripheral velocity. So, it will affect your strain rate. So, tool design also is very important. So, dimension as well as profile.

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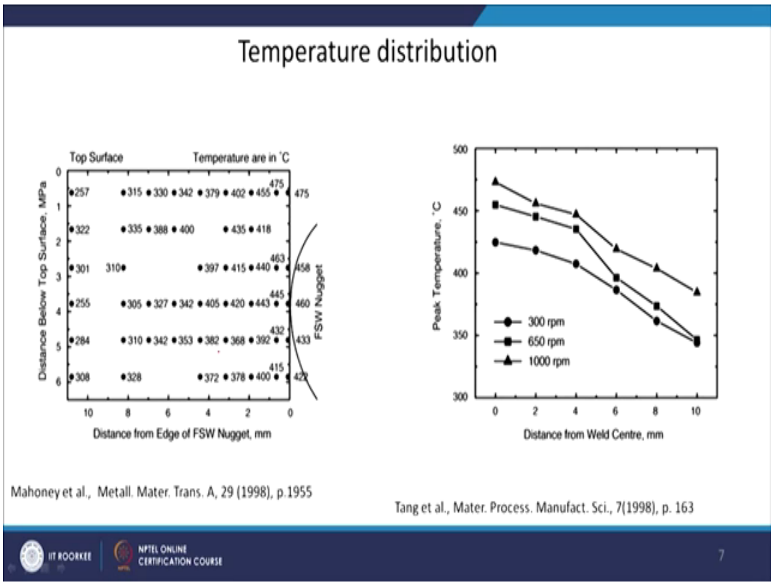

Now, let us say the temperature which you achieve usually in this kind of processes. So, a nice profile is given for the temperature (refer to above figure). So, this is your FSW nugget zone, where the nugget is there and of course, I cannot measure the temperature in the stir zone because if I put a thermocouple there due to stirring it will be destroyed. So, either I can predict the temperature through some modelling processes that what is the actual temperature of the stir zone.

Through experimental process I can only find out the temperature in the vicinity of the nugget zone. I cannot find out exactly in the in the nugget. In the nugget, you can only do some modelling exercise and find out the temperature. So, this is your top surface. And this is your distance from edge of FSW nugget is on the x-axis here. And this is distance below the top surface. So, this whole temperature profile is shown here (refer to above figure).

So, as you go towards the FSW, the nugget or the stir zone, the temperature is more so, this is for aluminium alloy. So, the temperature attained is around 400 to 500° around 473° and so on. So, temperature you can say it is around 0.7 of melting point, $0.7T_m$ of aluminium. So, in FSW/FSP the temperature attains are around that, of course, it will also depend on the rpm.

And as you go away from the nugget zone as well as if you come down from the top surface, the temperature is continuously changing. So, here the important thing is to understand that the temperature is going to be continuously changing as a function of distance from the top surface. So, how much distance you are away from the shoulder in the downward direction and as well as how much distance you are away from the stir zone.

Both of these are going to affect your temperature profile. In the next graph, you can see the effect of distance from the weld centre on the x-axis, on the peak temperature which is attained, and at three different rpms so, from 300 rpm to 1000 rpm. So, in 300 rpm which is shown by these circles. The temperature attained is around 425° and as you, you are going away from the centre line so, in the nugget zone it is around 425° and at a distance of let us say 10 mm and the temperature is around 340 or 330°.

So, almost 100° difference is there, but if I increase the rpm from 300 rpm to 1000 rpm, the temperature attained here now is around 475° so, almost a change of 50° by changing the rpm and of course, if your peak temperatures are more, temperatures at other location is also going to be more. So, rpm has a direct effect on the temperature you can achieve during the Friction Stir processing or welding technique.

What is the effect of strain on strain rate? So, this is of course a computational work using some computational analysis.

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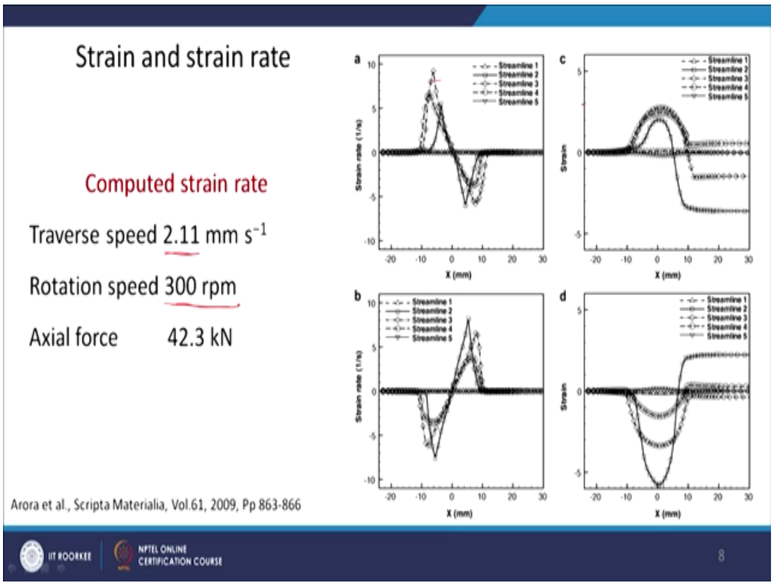

So strain rate if you see here (refer to above figure), the strain rate achieve is around 10 per second. These of the two conditions, I am not sure about the conditions right now. But the rotation speed was taken as 300 rpm and the traverses speed was 2.1 mm per second. So, to just get an idea about strain rate, the strain rate achieved is around 10 per second. And the strain achieved is around 3 in the in the stir zone.

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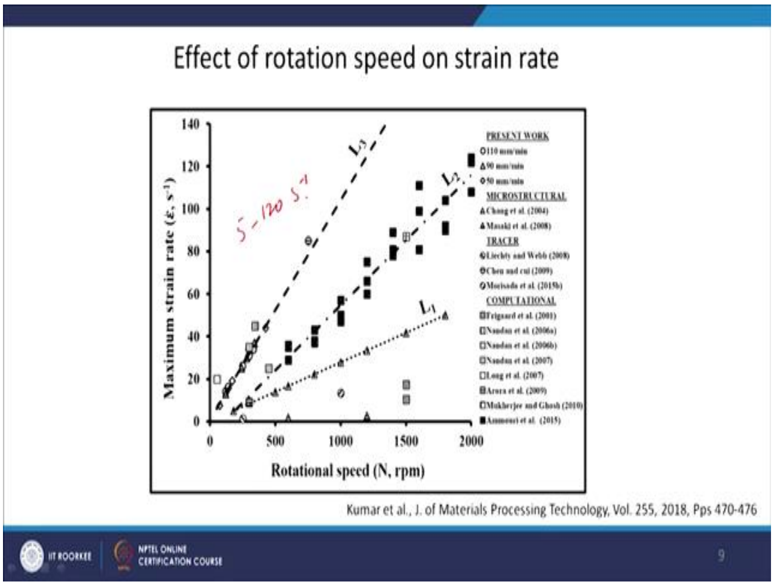

There is from another paper (above figure). We have actually found out the strain rate reported by different people using microstructural analysis and computational work. The strain rate you can see there is a wide variation in the strain rate reported in the literature. So, if you see the rotation speed is shown on the x-axis. So, as you as you are increasing the rpm of course, the strain rate is increasing.

So, that is clear in all the work that when you increase the rotation speed, your strain rate is going to increase. But which technique you use mostly the strain rate calculation depends on that. But again to just get a flavour of strain rate the strain rate reported is in a wide range, I would say maybe let us say from 5 to 120 per second, depending upon the method which is used to measure the strain rate or to predict the strain rate in the computational case.

So, one thing is clear. The temperature attained is around more than 0.5 T_m the strain rate attained is at least more than one per second; it can go up 100 per second also. The strain which you are achieving is also in the range of 5 to 10 for example. So, strain, strain rate achieved and the temperature all this contribute to the dynamic recrystallization in these materials. And if you remember in continuous dynamic recrystallization, we said that in a low stacking fault energy material also, you can achieve a continuous dynamic recrystallization if the amount of strain is sufficiently high.

So, in these SPD processes because you are able to put lot of strain in the material the refinement and the microstructure which you get has a very high fraction of high angle grain boundary and with considerable refinement in the microstructure and this is what you can see the effect on the microstructure.

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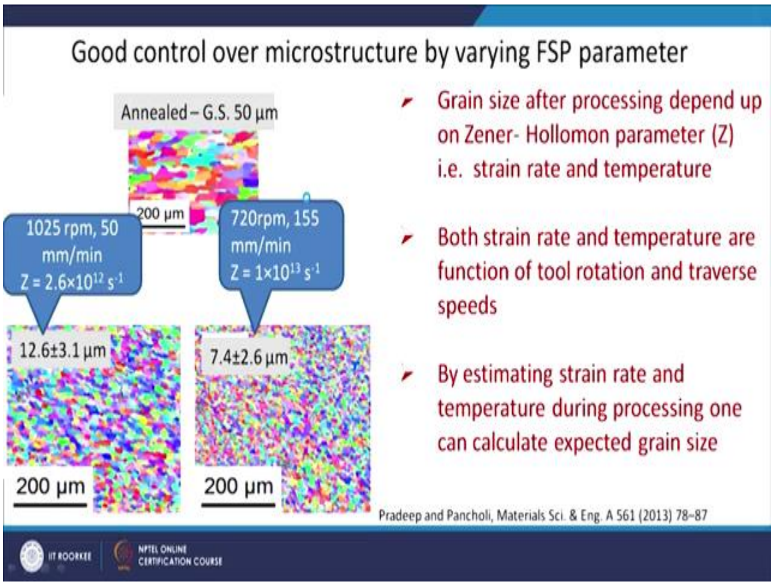

So, this is another work taken from one paper of ours (above figure). So, this is an aluminium 5086 alloy. This is the initial grain size, which is in annealed condition. Grain size is around 50 micron. So, two set of processing conditions are used 1025 rpm at 50 mm per minute and 720 rpm at 155 mm per minute. What will be the effect on the Zener-Hollomon parameter is also shown here. So, from at high rpm, low traverse speed I am able to get lower Z and at lower rpm, high traverse speed I have, higher Z.

So, as Z is increasing I should have finer grain size material. So, you can see here from 12.6 to 7.4 grain size I am able to achieve from 50 micron. So, just by changing the rpm and traverse speed you can do a very nice control on the microstructures or the grain size. This is the effect of the starting material.

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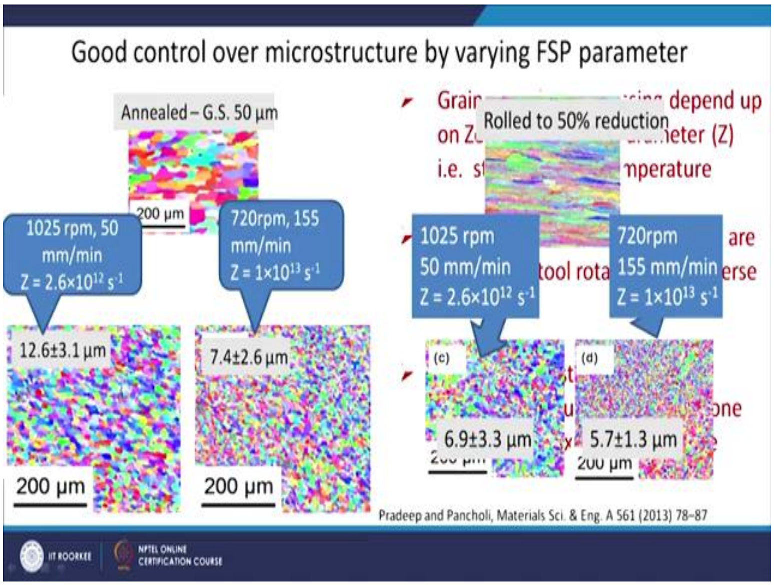

So, this instead of taking annealed material if you would have taken a rolled material. This is a rolled material and rolling was done up to 50% reduction. So, already some amount of cold rolling was done, some amount of dislocations were already introduced in the material and when if you do a processing of this material at the same condition, which we did for the annealed material, the grain size refinement is even better.

So, now, what we could achieve 12.6 in the annealed material that got reduced to 6.9 micron in case of rolled starting material and similarly, 5.74 higher Z parameter. So, this is the effect of both the rpm and the traverse speed on the microstructure. And as I told you, that when you increase the rpm, actually the temperature attained will be more. So, you can see the effect of that on the grain size.

The grain size achieved in case of higher temperature, deformation is more whereas in a lower temperature, the grain size is fine.

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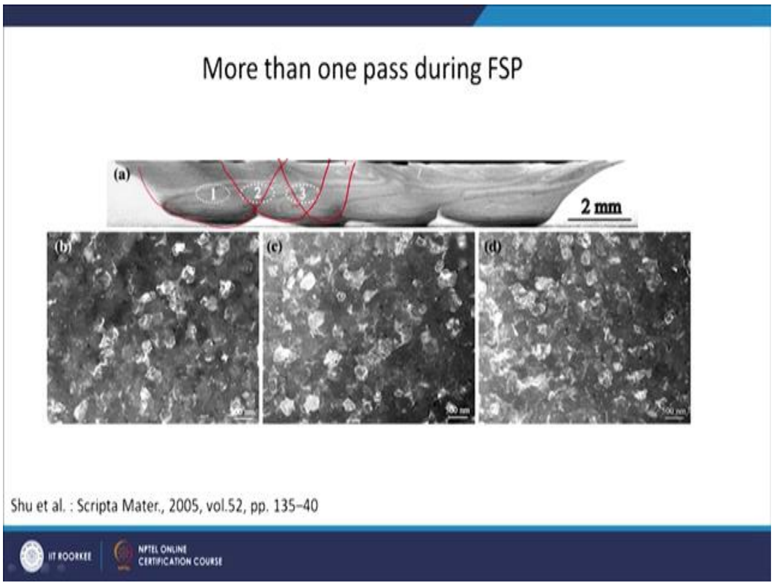

Now, another advantage of FSP is that you can do it by doing multiple passes. I can extend the amount the area of deformation. So, in one pass I can only affect maybe the area around pin size. If my pin size is around lets say 6 mm so, the area affected will be around in that range only 6 mm or so, but if I want to have larger volume or larger area to be processed, what I can do is I can do multiple passes.

So, second pass is kind of an overlapping on the first pass. So, you can see this was supposed to be first pass and then there is a second pass overlapped on that and then, there is a third pass and so on. So, by doing this multiple passes, I am able to do a processing of a volume. So, I can easily extend the FSP as a bulk processing technique. But the important thing is to understand that what will be the effect on the microstructure because you are continuously deforming, continuously exposing your material to high temperature.

So, what will be the effect of let us say second pass on the first pass or third pass on the first pass and so on. So, microstructure is taken from three locations where the first pass was there, then the second one and the third one. And you can see that from the microstructure, we do not see much difference in the microstructure. So, microstructure is more or less uniform, whether you are in first or second or third pass.

So, that is a very outcome of this processing that the microstructure is not getting affected too much by multiple passes. So, you can easily extend the friction stir processing as the bulk processing technique.

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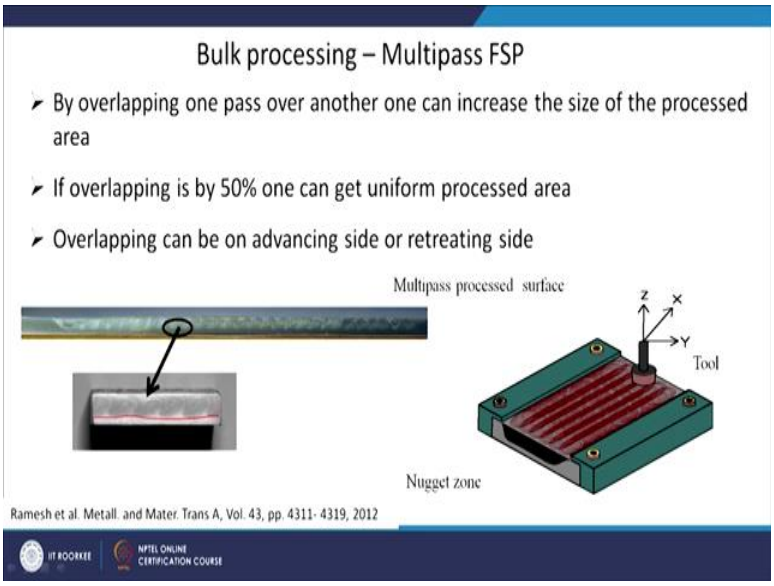

So, basically this is a macrostructure of the same multi pass technique. And in this work the overlapping was done by 50% on the retreating side. You can do overlapping on the advancing side as well as on retreating side. So, you can see that very a big sheet is kind of processed. And if you see in a smaller sheet, effect of individual passes can be seen on the microstructure.

And you can see that a bigger cross-sectional or volume is processed using the bulk processing technique here. So, you can easily extend the FSP technique as a bulk processing technique by doing multiple passes. Now, what is the effect of this processing on the microstructure? So, as we have seen that the material will be affected only equal to the pin length.

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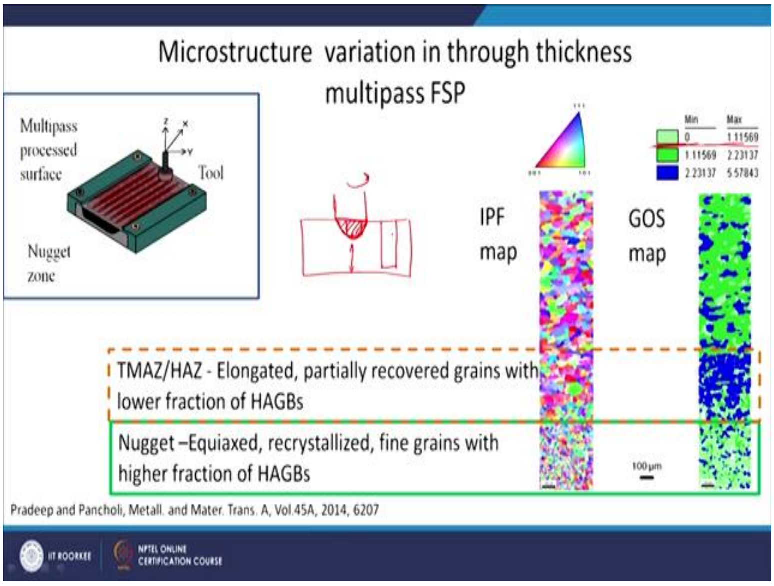

So, suppose this (refer to above figure) is my sheet, this is the thickness of the sheet in which this is your pin and this is my shoulder and which is rotating. So, you can see that only if I see the microstructure will show some basin like this. So, only this part of the microstructure will be affected. The rest of the microstructure in the thickness direction will not be affected that much. So, that is what is characterized here.

So, where the nugget zone, upto the pin length, these are very long scans. You can see that the scale is 100 micron. So, in this direction, it must be the default the thickness must be around 700-800 micron or so, so, up to maybe 1mm length. So, if you see up to where the pin is going, the grain size is refined. And also we have discussed about the grain orientation spread map. So, I told you that wherever you have recrystallization, the the GOS grain orientation spread value will be low.

So, this light green is the GOS value is up to one. So, that is what is defined as recrystallised grain. So, you can see here that as the recrystallization is happening the GOS values are lower there. So, all this light green and at few places dark green also is there. But if you see, this is where we say that you have a thermo-mechanically affected zone. That means the material is not fully recrystallised or fully recovered.

That means dislocation must be there, low angle grain boundary must be there. So, there you can see that the grain orientation spread is much higher and here are also I can see coarse grains here and the grain orientation spread value is much higher more than 2.2 here. So, this is my area which is I would say is a thermo-mechanically affected zone. And beyond that it is either heat affected zone or the base material.

So, very nicely you can see that how the different microstructural regions will be there in the material because of the processing. So, if you want to have process for the whole sheet of course, I will extend the pin. Of course, there is a limit to that also, but for example 5 mm 6 mm plate you can easily do a friction stir processing using a pin of 5mm or 6mm. Now, what is the effect of this on the mechanical property for example, Hardness?

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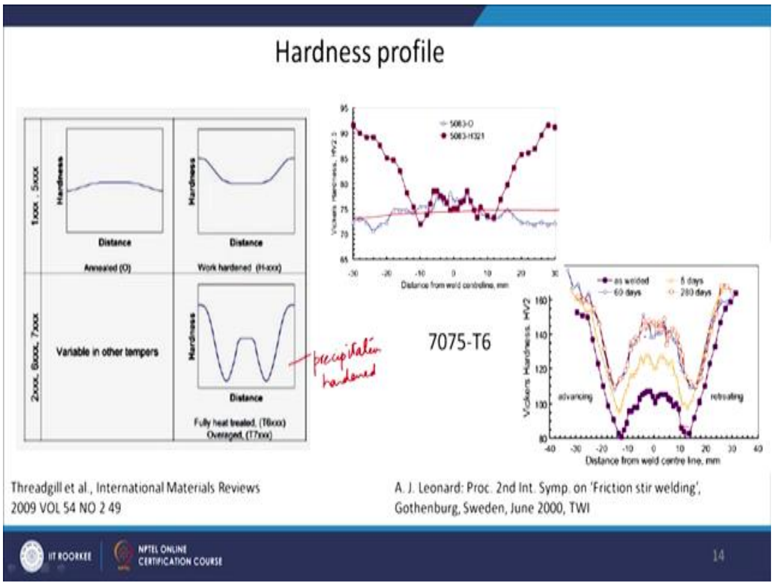

So, if you see in this schematic, there are three conditions are shown for aluminium alloy. Basically, you have annealed condition and in aluminium alloy, there are two different set of alloys, one which are precipitation harden and another which are non-precipitation hardenable. So, in those materials you can have work hardening. So, in precipitation hardenable material if you see the the hardness profile, the profile will be something like this (refer to above figure).

In the nugget zone actually the hardness comes down. In the base material the hardness is more. So, in that sense you can say that the actually mechanical properties are reducing in the process zone. You are refining the grain size, but in the material which is precipitation hardened because the precipitate are being exposed to high temperatures, what will happen? these precipitate either will dissolve in the material or there will be coarsening of the precipitate.

Both these things actually bring down the hardness or the strength of the material. There will be contribution from the grain size refinement, but it will not be able to compensate the reduction in the hardness or strength because of the reduction in or dissolution or coarsening of the precipitates. So, in the precipitation hardened materials, these are precipitation hardened materials, the reduction in hardness is quite significant because of the processing. In work hardened materials, which does not get hardened by precipitation. So, only method to increase the strength or give a hardening to the material is through introduction of dislocation through cold deformation or cold working. So, you increase the number of dislocation or dislocation density that will add the give the hardness.

So, this is what we call as work hardening. So, if you have work hardened material, there also the strength or hardness of the material will come down in the processed zone because of the recovery and recrystallization or removal of this dislocation through recovery recrystallization processes. So, again hardness is coming down. If you take a well annealed material which does not have precipitate, does not have dislocations. Only in this case may be you will be able to see slight increase in the hardness due to grain refinement. So, there are three classes of material and the actual results are shown here (refer to above figure) in the graphs. So, in the 5083 fully annealed condition you can see the hardness is more or less and maybe there is a slight increase in the hardness in the process zone, for a work hardened material 5083 which is cold worked before doing processing first one was only the annealed one. So, for the annealed one if you have done some work hardening in that you can see a large reduction in the hardness because of the removal of dislocation through recovery and recrystallization processes. This is a 7075, a very hard very high strength aluminium alloy containing magnesium and zinc, 7000 series alloys. Here you can see a very large reduction in the hardness because of the precipitate dissolution or precipitate coarsening.

Whereas if you do a simple natural ageing also the the hardness will start increasing obviously, because the precipitates will start nucleating and there will be increase in the hardness because of the ageing process. So, this is the effect on the hardness of the material due to friction stir processing. Now, there is another very important application of fiction stir processing that you can produce surface composites.

So, basically by some method like drilling hole and putting silicon carbide in the hole or alumina or whatever ceramic you are interested in. You put that and do the stirring process all these silicon carbide particles will be distributed through the matrix. And that will give you a hard surface and maybe a ductile or tough inner inner material.

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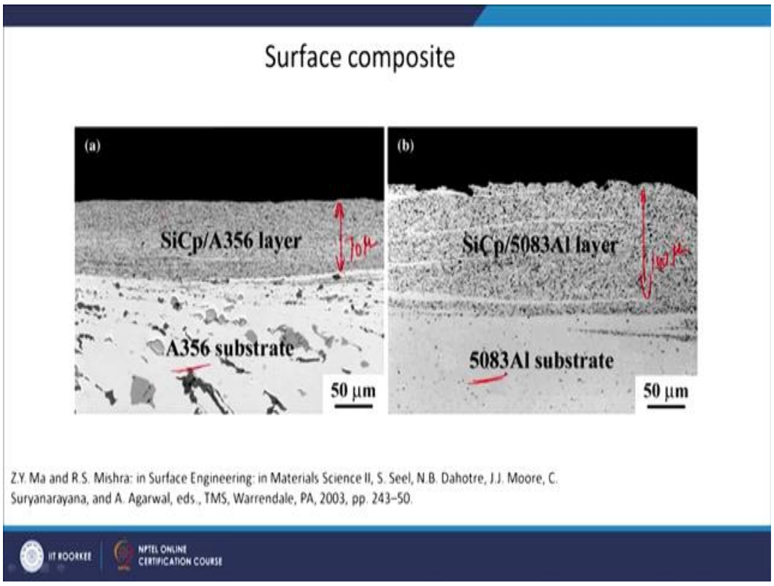

So, for example, this is a A356 silicon aluminium alloy in which silicon carbide particles are introduced on the surface. So, 50 micron is the scale so, this may be around let us say 70 micron thickness of the layer of the material. You have introduced a silicon carbide particle, the, another graph is for 5083 aluminium alloy where again around maybe let us say 100 micron thickness they have introduced the silicon carbide particles.

So, this is a very good technique to make surface composites by only embedding the ceramic particle on the surface to give the surface hardness which will result in the wear resistance if the material is going to be used in some condition where wear resistance is required. So, the surface will get hard so, it will provide you the required wear resistance whereas, the core will give you the sufficient structural strength.

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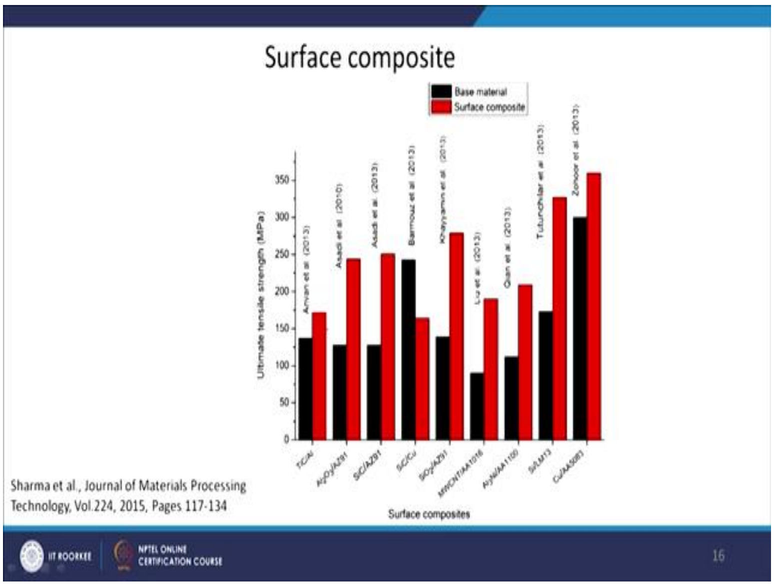

From a review paper, different set of materials, combination of matrix material and the ceramic particle that what kind of strength you will be able to achieve (refer to above figure). So, the black one is showing the base material and the red one is showing you the surface composite. So, there is a very good increase in the strength of the material when you introduce the surface or when you make a surface composite.

And there are different set of materials AZ91 is a magnesium alloy in which alumina and silicon carbide is added. In aluminium titanium carbide or in copper silicon carbide there you can see the reduction in the strength. We have to see the exact reason for that, but in general you can see the effect is that the strength increases as you are adding some or when you are making some surface composites.

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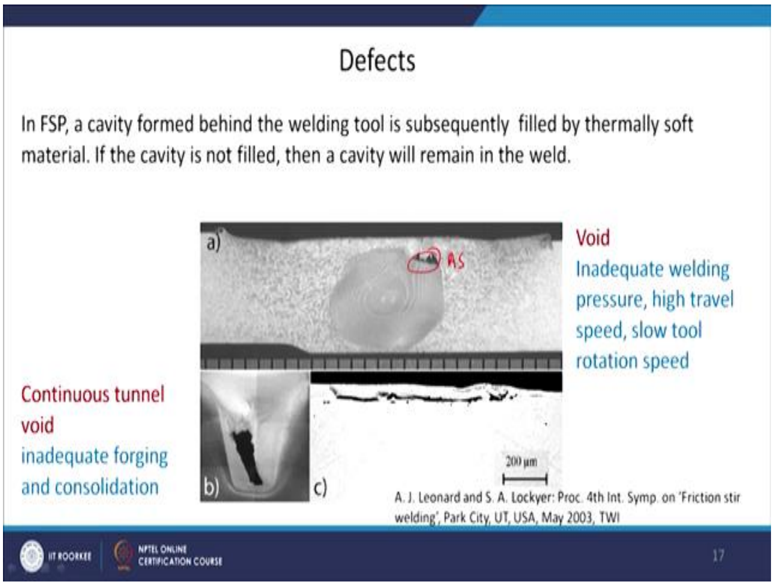

Now what will be the defects which you can encounter during the processing, few defects are shown here (above figure). And people have kind of now worked out that how we can remove these defects. So, one defect which is called void which can occur in the advancing side on the just below the shoulder. So, this is be, usually because of inadequate, you are not able to apply a sufficient normal force to the tool.

So, when you apply normal force what the tool shoulder is doing is actually creating a compression on the sample. So, when the material is stirring, it is stirring in the confined space between the shoulder and the cold environment of the work piece. So, if it is an inadequate pressure, the normal force or higher travel speed or slow tool rotation, so, all these contributes to this kind of defect.

High travel speed and low rotation speed means you are not heating the materials or softening of the material is not sufficient. Sometime you can have this kind of tunnel. So, this tunnel will go throughout the processed region from start to finish, there will be a kind of a channel. And that is also due to insufficient heating and insufficient normal force. So, when you increase the rpm or if you increase the normal force, you will be able to remove these kind of defects.

And some defects can come on the surface, you can see a long cavity is there just below the shoulder. So, these kinds of defects are there but more or less with the sufficient amount of work people have found out that how we can remove these defects. So, these defects can be easily worked out and you can remove that. So, with that we have covered a very important technique nowadays which is called friction stir processing to refine the microstructure, what will be the effect on the mechanical properties.

You can do some other things like surface composites and all that. That also adds to the strength of the material. And, few defects which can occur, people have worked out that and are now no more problems. You can easily take care of these defects. One of more cases study I will take on friction stir processing in the last lecture of SPD, in this particular module. So, that will clarify more or bring more ideas to the friction stir processing. Thank you for your attention.

Keywords- Friction Stir Processing, severe plastic deformation, strain, fine grain structure, mechanical property