Thermo-Mechanical and Thermo-Chemical Processes
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Lecture-29
Multi Axial Forging (MAF)

Hello friends, we are continuing with severe plastic deformation and the next process which we are going to discuss today is called Multi Axial Forging (MAF). So, as I was mentioning earlier also in accumulated roll bonding that you can use easily use your existing equipment to do these processes and easily can be modified to to this SPD processes. So, multi axial forging is also based on forging.

So, if you have a forging press, it can be easily used to do this kind of deformation. So, basically in this what we do is again the idea for all SPD process is that there should not be change in the dimension of the of the sample or of the work piece when you are doing the deformation. So, whether you take ECAP or you take ARB or you take Friction stir processing the overall dimension of the material should not change when you are deforming the material.

Whereas in our conventional processes, there used to be a change in the dimension of the material. So, if you are doing rolling your thickness will reduce, if you are doing extrusion your cross sectional area will reduce and forging again your lengths and the thickness of the billet will reduce. So, there is always a change in the dimensions of the work piece.

Whereas in case of a SPD processes, the process is designed such that after may not be in first pass but may after doing multiple passes or doing a one cycle of pass, you should be able to get back to the starting condition. And there should not be any geometrical change in the sample and in the work piece and that is how you actually you are able to introduce so much deformation or strain in the material because you are coming back to the original dimension. So, in that series again this is a multi-axial forging.

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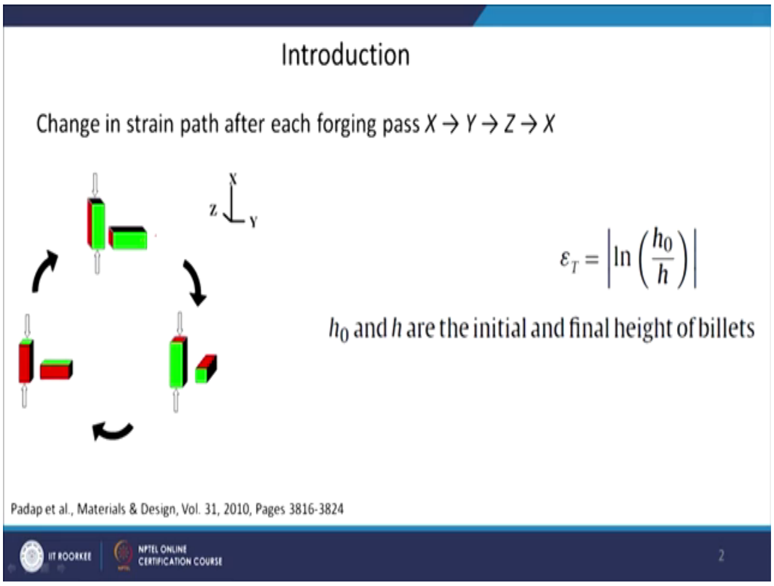

So, the idea is that, first the three nonparallel surfaces of the sample is shown by three colours here (in above figure). Black colour, red colour and green colour. So, you first deform on the black surface for example, if you are constraining in one dimension, so, what will happen, that there is a elongation of the material in this direction, perpendicular to the red plane because you have constrained the deformation where in the direction perpendicular to the green plane.

So the deform, the lengthening is there and the shortening is there where you have applied the compressive strain, or compressive deformation. Then in the next cycle, so, now, the this particular dimension is the longer one. So, now, we are going to deform on the red plane. In your constraining the deformation in the direction perpendicular to black plane. So, now, you can see lengthening is in the direction perpendicular to the green plane.

So, the next deformation will be on the green plane. And you are allowing it to have lengthening in the direction perpendicular to the black plane. And again you have come to the first stage. So, one complete cycle require these three passes. So, in multi axial forging always you will see that any property shown is in multiples of three, so, 3, 6, 9 and so on because you will reach the initial stage only after these three deformation pass.

So, in XYZ three different direction and the amount of strain which you put in is very simply the strain the logarithmic strain which is the true strain. So $\frac{\text{initial height}}{\text{the final height of bille}}$ that should give me the the strain which you are imposing in the material in each forging pass. Now, this is the microstructural evolution as a function of strain.

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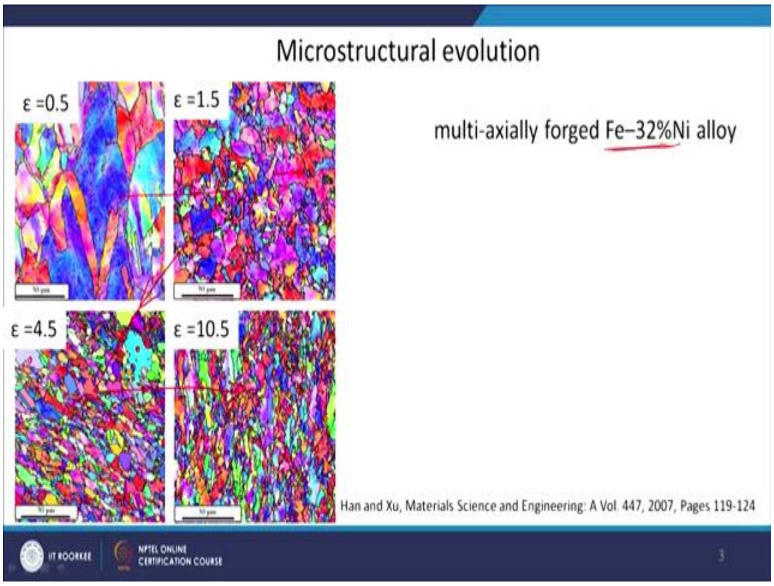

So, at 0.5 strain, 1.5 is strain, so, in this way the strain is increasing. And you can see the effect of a strain on the grain refinement. So, initially grains are coarse. Of course also looks elongated in one direction and there is some substructure development within the grain also. And then by next cycle by strain of 1.5, you can see that the grain is now getting fragmented into smaller grains.

Some fine grains are there and still some coarse grain with some sub structure is there. So, if you try to see the strain from here to here, you will see some strain gradient in the grain. Now, you start seeing even more fragmentation of the grain, some are very fine grain structures are there and still some coarse grains are there for example, this and this one. And of course, you have even more refinement after a strain of 10.5.

Though the structure look heterogeneous, there are coarse grain as well as fine grain. And this is the work done in Fe 32% Nickel alloy multi axially forged. So, the grain refinement is usually through dynamic recrystallization and slowly you can see the effect of strain on the recrystallization process, the grain refinement.

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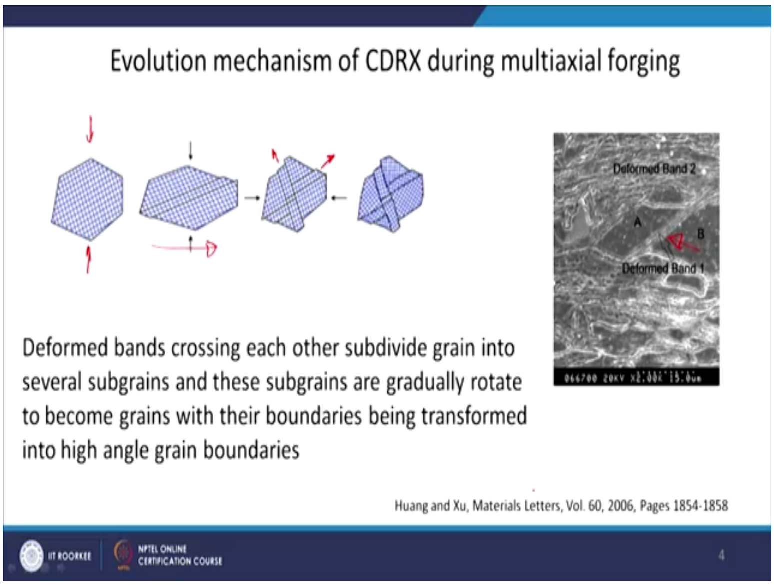

Now, how this recrystallization takes place in multi axial forging is shown schematically here one mechanism. So, you have this initial grain. So, when you are deforming from here, it is getting elongated in this direction and there are also some deformation bands which are being introduced in the material during the deformation process, usually at around 35 to 45° to the forging direction. Then now, in multiaxial forging you keep changing the loading direction.

So, what will happen in the next cycle, there is another band which will form at another angle to this initial deformation band. So, this is initial then another one which is created which is intersecting the initial one. And when this new deformation band is going to be created, so, it is like a dislocation movement. What it will create? It will create a kind of a kink in the first deformation band.

It will displace it because when you have a slip process, the slip process is like this, you when you have slip process there is going to be a offset. So, that kind of offset will be created in the first deformation band. Then again we will change the direction of the forging. Again a new band will create which will cut all the previous deformation bands and so on. And one example of deformation band is shown here in the in the micrograph (refer to above figure).

So, this is a big grain which is sheared into A and B two parts through the deformation band here. So, this now you can see the smaller subgrains will form and these deformation bands consist of high dislocation density. So, you can consider it as a low angle grain boundary. And so, you will divide the grain into subgrains and slowly there will be the CDRX process will be through subdivision into subgrains and then the subgrain rotation will create a create a high angle grain boundary.

So, this gradual change from low angle to high angle grain boundary takes place by subdivision plus subgrain rotation. That is what was proposed in this particular work and that is how you get grains with high angle grain boundaries.

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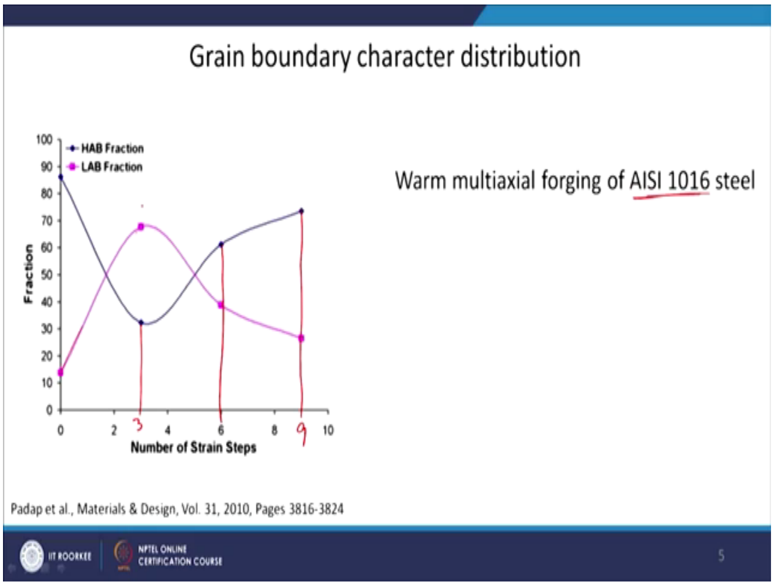

Now, what will be the effect on grain boundary character distribution? So, when you are having all these microstructural change for example, this work was on Warm multi axial forging on on a plane carbon steel (above figure) and as you can see that there is initially the grains are dividing into subgrains. So, obviously, there will be increase in the fraction of low angle grain boundary and later on these low angle grain boundaries are getting converted into high angle grain boundaries which can be through any of the CDRX mechanism grain rotation or conversion of these low angle grain boundary through continuous recovery of dislocation into high angle grain boundaries and so on. So, there are multiple mechanism of CDRX. So, this all this mechanism will operate and for different material different mechanism are proposed. So, obviously that if you see that what is the effect of number of passes on the deformation.

So, as I told you that in multi axial forging we will be doing in multiples of three, so, this is three pass, this is six and nine pass. So, initially the microstructure which was taken in this work was well recrystallized, annealed microstructure. So, the high angle grain boundary fraction was very high around 85% but as the deformation is progressing after third pass the high angle grain boundary fraction decreased from 85% to 30%.

And obviously, at the same time because these fractions are calculated for the total, the low angle grain boundary fraction is increasing and going up to 70% after third pass. So, this initial phase is the development of the substructure, grain subdivision by having low angle grain boundary within the grain. If you keep deforming, now, after six pass, you can see that the high angle grain boundary fraction is again increasing from 30% to around 60%.

And with further deformation it is increasing up to 70%. So, with the grain refinement now, initially, the grain is divided into subgrains and now these subgrain boundaries are converting into high angle grain boundaries. So, after nine pass for example, you will have now refined or ultrafine grain material with a very small grain size and most of the grain boundaries are high angle grain boundaries.

So, this is a typical grain boundary character distribution as a function of strain or as a function of passes in during any SPD process generally (refer to below figure).

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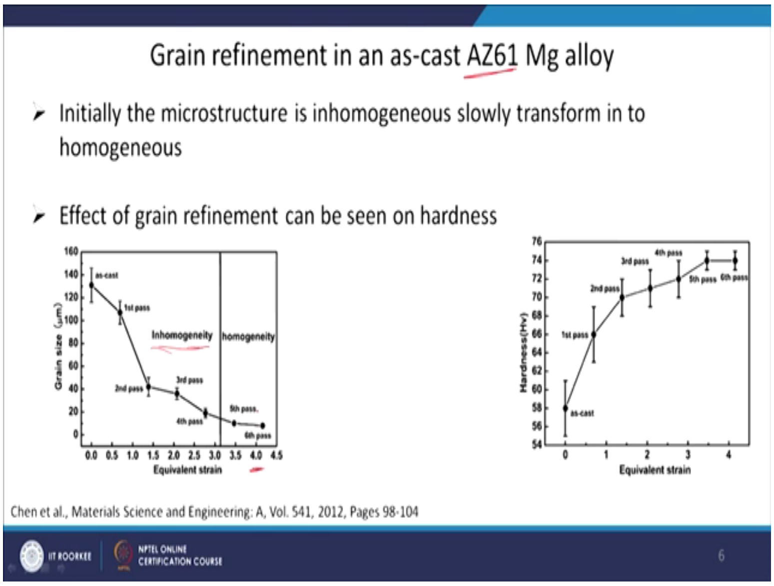

This is an example of grain refinement in As-cast AZ61 magnesium alloy. So, this is another good example that you can convert an as-cast material into wrought material and with very refined or very fine microstructure. As you know that magnesium alloys are HCP material. So, deformation is usually very difficult. So, in this case, because you are able to introduce lot of deformation through continuous change of the direction of deformation, you are able to introduce lot of strain in the material.

So, strain you can see on the x-axis here. So, they are able to achieve a strain of 4 after around six pass or so. So, in as-cast material, initially, they observed inhomogeneity in the microstructure. By third pass or fourth pass, the inhomogeneity is decreasing, in fifth and sixth pass, the microstructure is homogeneous. Obviously, considering the passes will be the amount of deformation or the change in the direction of the deformation also.

So, as as you are going to longer cycle or multiple deformation direction so, initially it will be homogeneous for first and second pass, by third pass because you have done the whole cycle the homogeneity will start coming in the material. So, which was not there in the rolling process, in the ARB process, because your continuously deformation directions are remaining same. So, there you will see these kind of elongated grains and so on.

But in ECAP, if you are using B_C route or multi actual forging you will start seeing that you are getting equiaxed microstructure. Of course, it will have effect on the mechanical properties of the material. So, as your passes are increasing and material is becoming homogeneous and of course getting refined also by fifth, sixth pass, your hardness is increased by from 58 HV to around 74 HV here, again as a function of equivalent strain.

Now, in some studies, there is also people have found out that there is a softening during the deformation process. So, actually they have measured the flow stress during the forging process itself. So, these are not stress-strain curve after the deformation, but during the deformation process.

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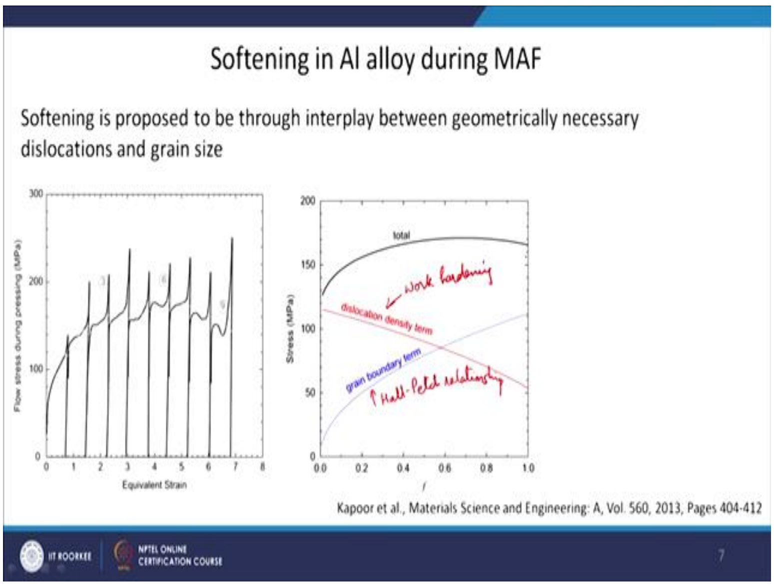

This is an aluminium alloy deformed at room temperature. So, you can see the effect of as you keep deforming, effect of strain on the flow stress property. So, the first cycle you can see the flow stress is around 100 MPa or so which in the next cycle it increased to around maybe 120 or 130 MPa. Then continuously the flow stress is increasing. And then we are changing the pass, so, again it will go up and come down and so on.

But as you can see after six pass again you can see that there is a decrease in the flow stress. And they have kind of attributed this change in the flow stress to these two terms. So, when you are deforming, so, of course, you are increasing the dislocation density in the material but if there is a recrystallization process also going on simultaneously, there will be refinement in the grain size.

So, so grain boundary term that means effect of grain boundary is increasing whereas the dislocation density is decreasing and the effect of these two terms. So, dislocation density will contribute to work hardening or strain hardening and this grain boundary will contribute to effect of Hall-petch relationship. So, that contribution is increasing, dislocation density term is decreasing.

So, when both are contributing, initially there is increase in the flow stress. But later on when this is coming down the dislocation term is coming out and there is not much contribution from the from the refinement in grain size, the softening is taking place. Of course, in some other cases, when the grain refinement is very fine or grain size is very fine, people have attributed this softening behaviour to the change in the deformation mechanism.

Earlier we discussed about grain boundary sliding. So, some time the softening can be due to change in the deformation mechanism or it may be due to the effect of the microstructural properties that whether dislocation density, how it is changing in grain boundary or grain size, how it is affecting the overall stress.

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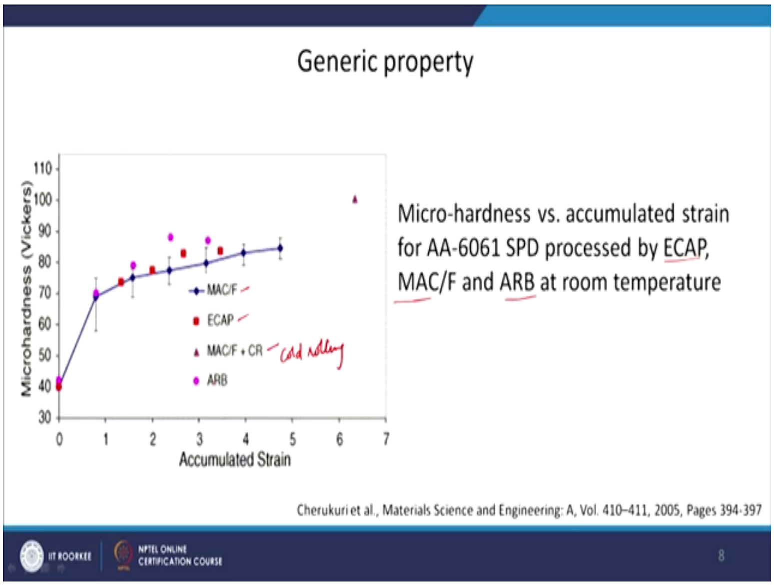

Now, as we are continuously discussing this part. So, there is a very nice study about effect of different SPD processes. So, you have ECAP, you have multi axial forging and you have accumulated roll bonding and the accumulated strain in each of these processes was noted down. And what is the effect of that on the microhardness is plotted here. So, you can see there are four different conditions.

One is Multi axial forging, ECAP in this case, after multi axial forging, cold rolling was also done. So, CR is Cold Rolling here and fourth process is, the accumulated roll bonding. So, if you see all these four processes, they are nicely following one kind of a generic behaviour that the accumulated strain in all these cases is same, the effect on microhardness or the mechanical property is same. So, they will all contribute to the hardness in a same way.

So, it does not depend a by which route you are able or you are putting the strain in the material. Their contribution to the hardness or mechanical property will remain same. And we have also seen that when the strength is increasing, the elongation to failure or ductility is decreasing, which is also kind of true for all the processes. So, this is a very interesting thing that how I am putting strain is not an important factor here. But if the strain is same in all the processes, I am going to achieve the same mechanical property irrespective of what process I have used for for introducing strain in the material.

So, this is kind of a generic phenomena and it is true for all the SPD processes. So, with this I am completing all the different processes of SPD. The last lecture in this particular module will be on a case study, where we have used friction stir processing and its effect on the superplastic deformation will be discussed. So with that, thank you for your attention.

Keywords- Multi axial forging, severe plastic deformation, strain, fine grain structure, mechanical property.