Thermo-Mechanical and Thermo-Chemical Processes
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Lecture-26
Equal Channel Angular Pressing (ECAP)

Hello friends, today we will start with a new module that is on severe plastic deformation. In the first few lectures, we discussed about some non-conventional thermomechanical deformation processes nowadays which are coming up. And the category in which they are put called severe plastic deformation. So, as the name suggests the amount of deformation or amount of strain which you can put in the material is very high as compared to our conventional thermal mechanical processing like rolling forging, extrusion and so on.

So, the idea of deformation itself is different than what we do in case of conventional thermomechanical processing, there the primary strain is compression. So, basically all the conventional thermomechanical processing is based on the compression of the sample or they want to impose strain in form of compressive strain. We do not do any thermomechanical processing using tensile strain.

The reason is simple that when you apply tensile stresses, if any defect is there, it is going to open up. If you remember your basic fracture mechanics idea where if you compress the sample, you close the defect. So, compression is the primary mechanism of deformation in conventional thermomechanical processing. In severe plastic deformation the primary deformation mechanism is through shear process.

And because you are in shear mode you are able to apply much larger strain as compared to in compression because whenever you have compression, you also induce some tensile stresses and some cracking will takes place if you apply a very large strain. But in shear you are able to apply a very large strain without inducing any defect in the material. Defect in the form of cracking and so on.

Other defects which are based on deformation processes like shear bands and flow localization may occur if you are doing at very high strain rates. So, in this category the first one to what we are going to discuss today is called Equal Channel Angular pressing (ECAP). It is one of the most popular techniques to impose very high deformation. One of the first one to start, when people started talking about severe processing deformation. So, the process is very simple.

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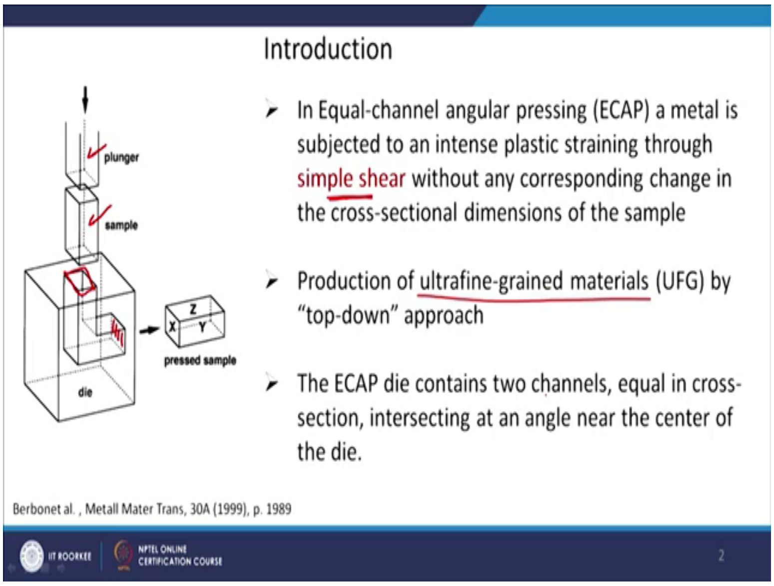

All these processes are actually very simple. So, in Equal Channel Angular pressing, basically, you as the name suggests, there are two channels (refer to above figure) and these two channels are equal channel and there is an angle to this channel. So, if you see this diagram here, this is my sample, this is the plunger with which you are pressing the sample and if you see the die, the die consists of this channel here through which the sample is going to go.

And this cross-sectional area of the channel and this cross-sectional area of the channel, both are the same. So, that is why they are equal and then there is an angle in the channel. So, when the material goes and take a turn here, you are imposing a very high amount of shear deformation in the material. And the shear deformation is in the form of simple shear. So, you have intense plastic deformation in in form of simple shear.

And these all these severe plastic deformation processes are usually used to produce ultra-fine grain materials, what we also call as UFG and in ultra-fine grain also there are two approaches from down to top and another is from top to down. So, this is a top to down approach where you have coarse grain material relatively in bulk. And then you are deforming it and refining the microstructure.

So, it is going from coarse to fine. And as I told you that ECAP die contains two channels, equal in cross section intersecting an angle near the centre of the die. So, this is the very very simple approach to the deformation process. If we want to look at the principle of the shearing process,

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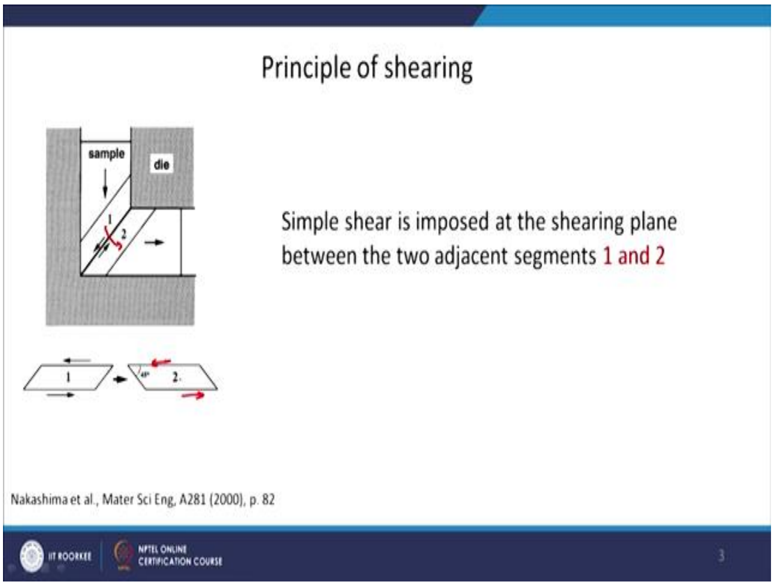

So, if you look in the diagram (refer to above figure), we are deforming the sample from the top, one element is taken here which is called 1, here before the deformation. And this is my shear plane basically and the element 2 is taken as after the deformation. So, if you see the element 1 which is a shown a rectangle plane here and when it is going through this angle here, what you are doing is you are applying a simple shear here, which is shown with these two arrows.

And when you look at the element 2, now the element 2 has deformed, so, now it has not remain a rectangle, it has become a parallelogram with a 45 ° angle here, so, the deformation here has taken this edge in front and this edge in the back. That is how the deformation is taking place and because of that, you have simple shear in the material. So, that is a very simple process like this, that how you can apply a shear strain in the material.

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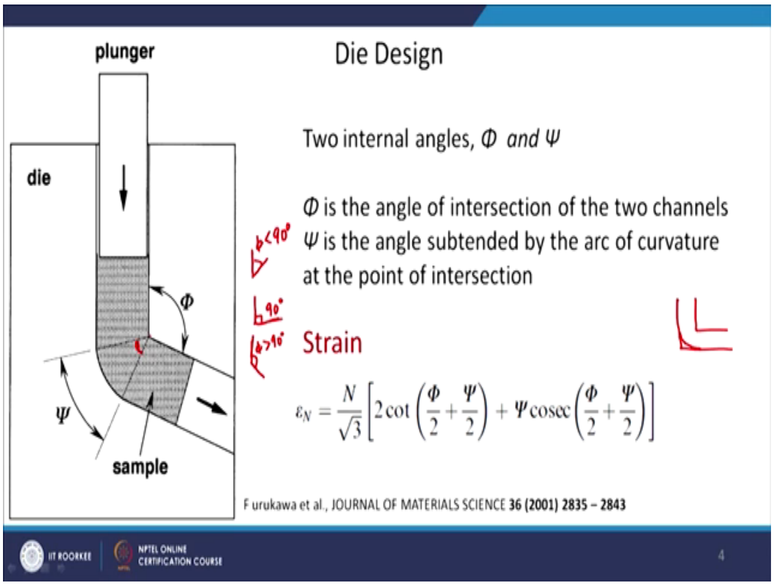

Now, the complexities will start coming in. So, we have to define few parameters for the die here. So, for example, the die shown here and there are two angles are shown here (refer to above figure) one is angle ϕ and another is angle Ψ. So, the ϕ angle is basically the intersection of the two channels. So, when there the two channels are meeting. If they are meeting at 90°, then of course, the angle will be ϕ angle will be 90° or it can meet it at some other angle like this or it can meet an angle like this.

So, this is these are bigger angle more than 90°. So, this angle ϕ will be more than 90° whereas this angle ϕ will be less than 90° and this is my 90°. So, this is the intersection of the two channel that how they are intersecting at 90°, more than 90° or less than 90° (refer to above figure). The other angle is kind of how you are giving a curvature to the whole deformation process. So, you can have a very sharp curvature like this.

But you can understand that material is a solid material, it is not a fluid which can occupy all the spaces available to it. So, when you are deforming the material, it will not touch the very sharp edge of the die. It will deform something like this (refer to above figure). So, what kind of curvature we are providing to have a smooth deformation for the material. So, Ψ is the angle subtended by the arc of curvature at the point of intersection.

So, at the point of intersection what is this angle Ψ . Basically, this curvature and what is the angle of this curvature at the intersection point that defines the angle Ψ. So, these are the two important parameters of die design that what should be the angle ϕ and angle Ψ. And basically the amount of strain which we are going to put in depends on these two angles with an equation as shown here (refer to above figure). So, both angle ϕ and Ψ are coming in in the expression. And similarly the N is basically the number of passes.

So, if you keep doing so, this is Equal channel as you can understand, so, I can keep putting a strain in the material and there is not going to be any change in the cross sectional area. So, there is no limit to the amount of strain I can put in the material. Whereas, if you do any rolling, extrusion or these kind of processes as you keep putting strain in the material for example, if you are doing rolling it will the thickness of the material will keep reducing and after a certain point it is not possible to put a strain in the material.

By having a equal channel here, I can put any amount of strain in the material by continuously taking through the die and that represents the number of passes here.

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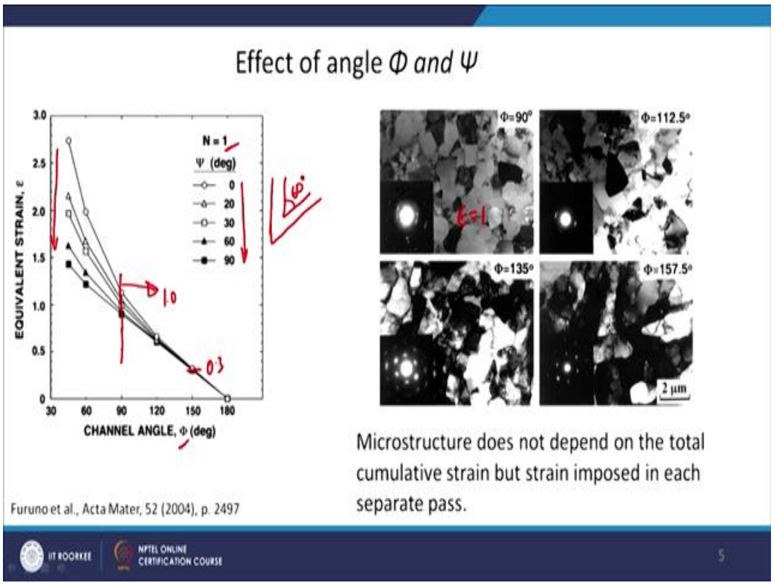

So, what is the effect of angle ϕ and Ψ? So, in terms of a strain for example, this (refer to above figure) is the strain measured by doing some grid methods. And the channel angle is on the x-axis, the ϕ and different curves are shown here for different Ψ angle so, from 0° to 90° here. So, you can see that for a very sharp angle that is Ψ zero and at very low ϕ angle 60° means the ϕ angle will be something like this. This is 60° (refer to above figure).

So, it is a very extreme amount of strain you are putting if your die is like this. So, the amount of strain is very high in this case and the N is only one that is only a single pass. So, the single pass I can put in the strain of around 2.6 or 2.7, very high strain. So, when you have a very sharp angle and Ψ is also 0°, the strain is very high. For the same 60° angle or I think 50° here.

If I reduce the Ψ that means I start providing it a curvature, the amount of strain goes from around 2.7 to around 1.4. So, a substantial reduction in the strain level, just by changing the angle Ψ here. Usually we do not use these kinds of angle ϕ, which are lower than 90° because it will impose very high amount of strain in the material and which can give rise to defects.

Usually if you see the ϕ angle in the literature, it is either 90° or more than 90°. So, if you go beyond 90° the effect of angle Ψ actually start reducing, in fact for very high angle like 120° and so on, there is no effect of Ψ. So, usually in the literature whatever you will find the angle ϕ is more than 90°. So, there the angle Ψ angle has not much influence on the strain values.

And if it has no effect on the strain value, then of course, it will not have any much effect on the microstructure also. So, there are 3, 4 microstructures are also shown here (refer to above figure) for ϕ angle more than 90°. So, 90°, 112°, 135° and 157° here. So, 90° is the one where you will have more strain as you can see from the figure. Whereas for 157° the strain values will be much lower which are in the range of what you get in conventional thermomechanical processing around 0.3, whereas in case of 90° it is around one or more than that .

So, the effect of strain you can see on the microstructure that when you have 90° the strain is close to one here. I can see very nice recrystallized microstructure and very fine microstructure. As you can see the scale is 2 micron and grains within that is much finer, so grain size must be around one micron or less than one micron whereas if you keep increasing the angle here, you see you do not see any recrystallized microstructure as such the grains are still coarse.

And also they have lot of dislocation density present in the material. That means, it has not undergone the recrystallization process or the recovery process is not very effective. So, you can see effect of the ϕ, the die design on the microstructure for the same amount of strain that if I have a sharper or smaller ϕ angle, I would be able to impose higher strain and that will be seen in the microstructure.

Now, there are different variants to how we are going to do the ECAP process because I can change the direction of the shear strain.

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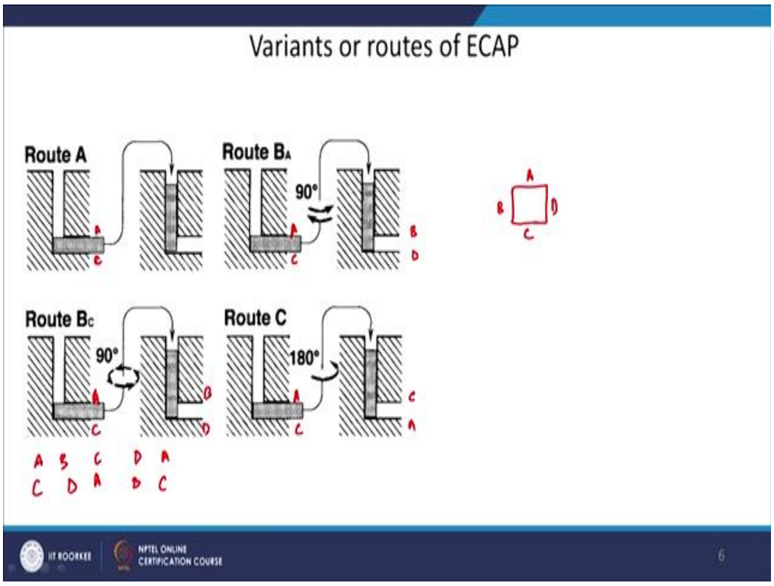

So, if I start with let us say some ingot here (refer to above figure) and let us say I can give them some name here, for example, let us call this as A B C and D. Now, suppose as you can see in Route A, suppose this is my top A top, the plane is A and the bottom plane is of course, it will be C then and I am doing one deformation. So, A will be on top C will be on bottom and again I am putting in the same configuration that A when it is going to come out A will be on top and C will be in the bottom then this will be a route A.

So I am not changing the direction of the shear. I am repeatedly doing in one way. If you see this route B_A, A is in subscript here. In this case, what you are doing is that you keep your sample alternating between the two different planes. So, for example, in first case if it is A here and here it is C, when you put it back then, and when it is coming out here then, the B will be on top and of course, then D will be in the bottom.

And again when you put the next time A will come on top and C will come in bottom. So, it is kind of alternating between this position and again coming back to this position. So, the arrow shows that you are again coming back to the first configuration. Then you have a route B_C in this case, you are continuously changing the position. If this is my first plane which is the A plane here.

So, now it goes here, then it goes here then it becomes here and again comes back to A. So, there is a continuous rotation here. So, AC here, then when it is coming out it is BD, then next cycle again it becomes CA and then next cycle it becomes DB and then another cycle it again becomes

AC. So, it starts from AC then become BD and so on. So, continuously you are changing the position.

So, every time the shear plane direction is changing. Then, you have a route C, in which case you suppose if this is your A plane and this is your C plane, then next cycle it will be C above when A below. So, it is like 180° rotation you are doing so, one configuration like this and next configuration is directly like this. So, shear plane is getting 180° rotation every time.

And obviously, when you are doing these kinds of variations, it is going to change the microstructure which is going to be generated because your shear plane is continuously changing. So that there is a large amount of work on these variations also that the amount of strain will be same now. So, the only change will come because of the change in the shear plane and there is large amount of work and what will be the effect of these routes on the microstructure.

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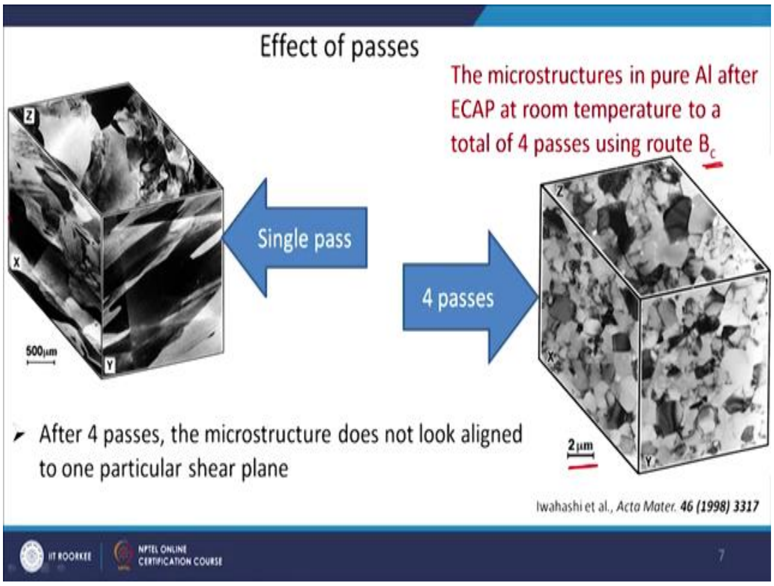

Now, what are the effects of passes for example, so, you have one microstructure nice microstructures are shown in three dimensions as you can see (refer to above figure). So, just to give you the idea about x, y and z, I will go back to previous slide. So, this is what x, y, z is. So, x is this plane, y is this plane and z is this plane, the top one. So, the shearing is taking place in this y-plane, like this. So, this is what you can see in the y-plane because of the shearing the grains are elongated and also they are at a certain angle which will be defined by the shear angle of the shear plane.

In the z-plane if you see all the grains are looking only as a kind of compressed, more or less equiaxed and compressed kind of in the x-plane, you can see the elongated grains in this direction because there you see the the shearing taking place in y-planes. So, these grains are getting elongated in the in this way. But the important is this particular y-plane because of shearing you have grains aligned in the direction of the shear plane.

Now, what will be the effect of passes using these routes? So, we are using route BC. So, in route BC, you are rotating the plane every time. So, it is, all the rotations are given to the plane. So, in four passes actually you have complete the whole cycle of deformation. So, shear plane has changed every time and it has completed the whole 360° rotation. So, if you do that you can see the difference between the two microstructure.

Here (refer to above figure) the microstructure, the grains are very coarse you can see the scale here 500 microns. So, very big grains, elongated grains and aligned in the deformation direction whereas if you see after four passes, the grain size has refined and the scale you can see, it is two micron here and more or less the grains are in that range. So it should be even less than one micron and in all the three planes the microstructure is looking uniform.

So, that is a very good way to if you want a uniform microstructure, if I follow this route BC, I should be able to get in four passes a very uniform ultra-fine grain microstructure. So, from 500 like maybe like the grains must be around 100 to 200 micron you have reduced it to two micron order of magnitude difference in the grain size. Now, this is the effect of pressing speed. So, how fast I am pressing it that that also will be a variable.

But in the in the literature we don't see much effect of the pressing speed on the, for example, yield stress here.

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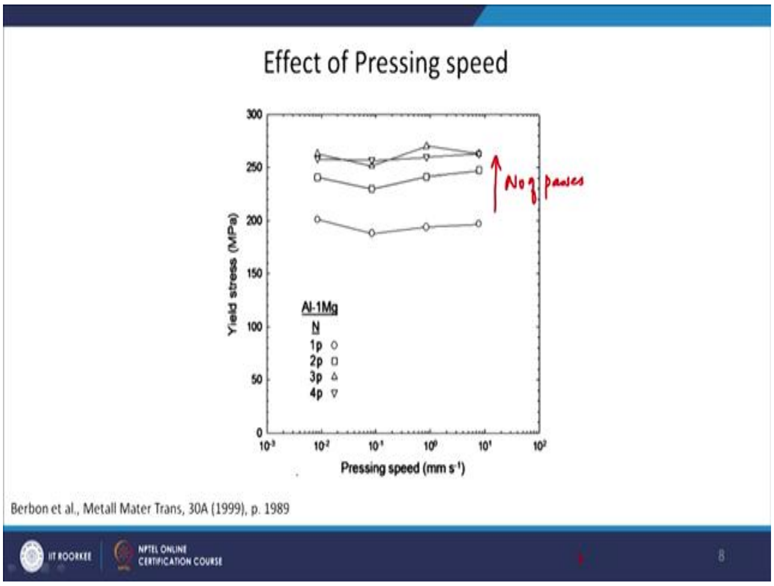

Microstructure will of course get refined. So, these are the number of passes the open circle is first pass and the inverted triangle is the fourth pass. So, obviously, as you increase the number of passes, number of passes is increasing is in this direction, my yield strength is increasing because I am refining the microstructure. So, from around 200 MPa it is going up to 260 or 270 MPa.

However, there is not much change because of the ram speed. How fast I am forcing it to deform because you can see that there is an order of magnitude difference between the strain rate or the ram speed which is in mm/sec here from 10^{-2} to 10^{1} so, a large difference in the ram speed. So, strain rate will be quite different in each of these cases, but there is not much effect on the yield strength of the material because of that.

So, mainly the strain is the more important parameter here for altering the properties of the material through ECAP process.

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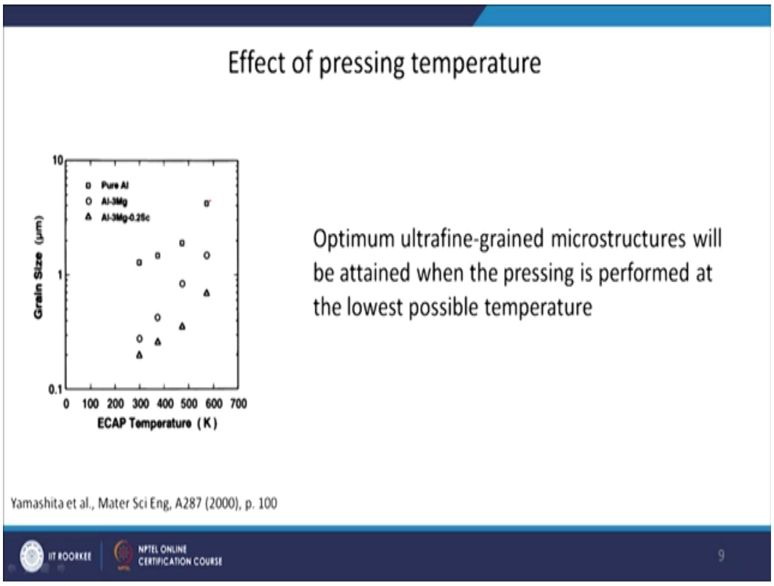

Effect of pressing temperature. At what temperature I am doing the deformation? So, if you see that again this is ECAP temperature in Kelvin and there is a grain size. And these data is for aluminium, aluminium-magnesium alloys and in one case scandium is also there. So, of course, there is as the temperature is changing from 300 to 600 Kelvin so, roughly around let's say up to 300° Celsius they are going.

And the grain size is less than one micron in case of scandium containing alloy. For pure aluminium the grain size is ranging from one micron to around four or five micron. So, huge reduction in the grain size through ECAP process and also the effect of temperature can be seen if temperature is more already we know that when temperature of deformation is high, your grain size which you achieve after the deformation process is going to be high. So, this is the effect of temperature on the grain size.

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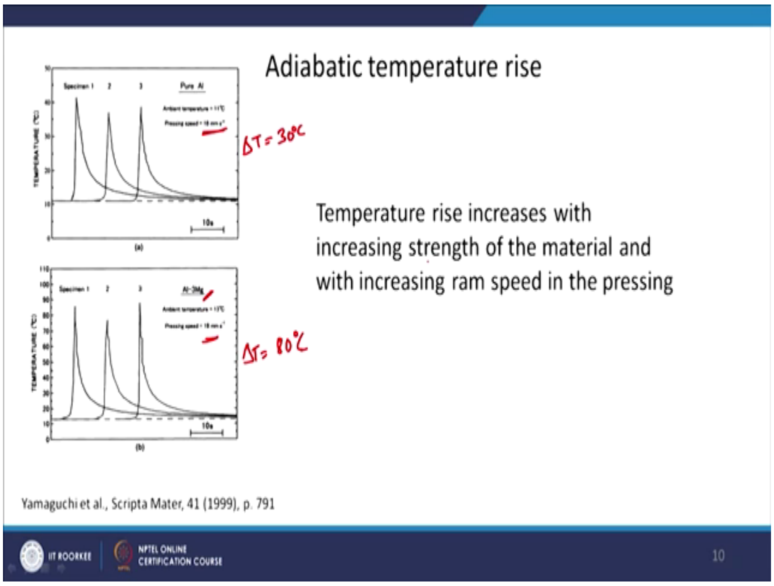

Another effect we already know about is what we call as adiabatic temperature rise. That is when you deform a material because of the deformation already we have seen in case of processing maps that when you put in any power, in terms of like we are going to deform the material here, some will be going into microstructural change and some will be going in heating the material. So, this is the adiabatic temperature rise as a function of deformation.

And pressing the speed is given as 18 mm/s here and the ambient temperature is around 11°. So, the adiabatic temperature rise in pure aluminium is around 30°. So, from 11 to it is going up to 40° and in different passes there is not much difference in the rise in temperature. So, it is a very consistent process in that way. In another alloy where you have 3 wt. % magnesium again pressing speed is same.

Again you can see now the temperature rise is around 80° from 11° or 13° in this case to around 90°. So, around 80° temperature rise is there. So, the ΔT here is around I would say 30° and ΔT here is around 80°. So, with the same pressing speed, this is important here, you are able to achieve more temperature in case of a material which has some alloying element.

So, we expect that when you have alloying element the strength of material will be high. So, the temperature rise in, in case of ECAP depends on the strength of the material as well as ram speed. So, as you increase the ram speed also there will be effect on the temperature rise. So, ram speed is not affecting that much the yield strength, but when you are deforming the material due to temperature rise, there it may affect slightly the microstructure of the material.

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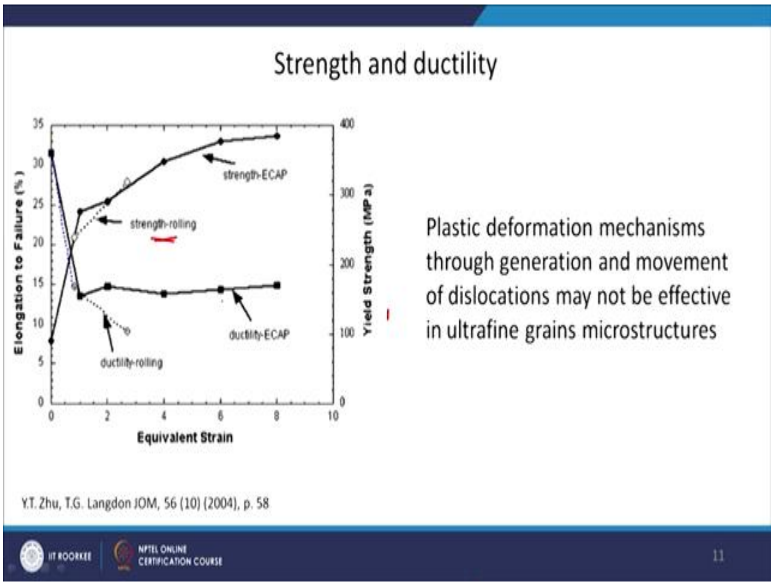

So, now, all these thing ultimately when you do anything like this processing to change the microstructure and so on, basically we ultimately do it to get some property. So, all these ultra-fine grain material or production of ultra-fine material started with Hall-Petch relationship which says that if you keep reducing the grain size, the strength of material will increase, the yield strength let us say of the material will keep increasing, as a function of the $D^{-\frac{1}{2}}$.

That we know from Hall-Petch relationship. So, the production of ultra-fine grain material started from the Hall-Petch relationship that let us increase the strength of material just by reducing the grain size. So, what is the effect of all these ECAP process on strength and ductility that is shown here in this graph (refer to above figure). So, the on the x-axis you have equivalent strain and y-axis you have elongation to failure.

So, equivalent strain means already we have seen the relationship for the strain. So that is the amount of strain, which you are putting in the material and after putting different amount of strain, the strength of the material is is noted down. The dotted circle here gives the strength after the rolling. So, in rolling you can achieve, maybe the maximum strain of around 2.2 or so 2.2 or 2.4 whereas, in case of ECAP, you can go up to strain of 8 in this case, in fact you can go more also.

So, what is the effect of this imposition of strain, the elongation, the yield strength is on the other side so, yield strength is increasing from 100 MPa to around 380 MPa. So, big jump in the strength of the material by doing by imposing the strain through ECAP process whereas, if you see the ductility, ductility reduces substantially. So, initial material the ductility was around 31%.

And that got reduced to somewhere around 14% so, almost half the ductility, but the strength is more than three times. So, this this kind of balance between strength and ductility is always there whenever you want to produce ultra-fine grain materials. That although the strength increases following the Hall-Petch relationship, but the ductility of the material reduces and the reason for that is that the plastic deformation is through generation and movement of dislocations.

If you keep reducing the size, the generation of dislocation becomes that much difficult then the dislocation as a deformation mechanism will not be an effective mechanism as you reduce the grain size. So, when it does not become an important mechanism, then the problem comes that what will carry the deformation process. So, if there is no other alternative deformation mechanism, then the ductility of the material will come down.

So, though the strength is more because you now require much higher stresses to generate dislocation or move dislocation because of the reduction in grain size, the ductility will reduce. So, there are now people have tried ways to improve the ductility without compromising the strength. So, there are a couple of approaches there. So, the first approach is that do not stop grain refinement up to a certain level, you keep reducing the grain size to even more smaller sizes and with very high fraction of high angle grain boundary.

So, have a fine grain size with very high fraction of high angular grain boundaries. If you do that, then the deformation mechanism change from dislocation based to grain boundary sliding. If you remember grain boundary sliding we discussed when we were discussing about the creep deformations. So, in creep and especially in super-plasticity, the grain boundary sliding is a very important deformation mechanism.

And as I told you that deformation will not be through dislocation movement within the grain, but the grain itself will have a rigid body or there will be a grain boundary sliding. So, grain one and grain two will have a movement related to each other without having any dislocation movement inside the grain. Some dislocation movement can be there to accommodate the stress concentration, but mainly that deformation will be through grain boundary sliding.

So, if dislocation not effective when you have fine grain material, so, you can look for some alternate deformation mechanism by designing the microstructure and that can be grain boundary sliding and in grain boundary sliding the ductility can be very high which is possible in superplastic material also. The second approach is to have bi-model grain size arrangement distribution.

So, you have you can have fine grain as well as some few coarse grains. Some proportion of fine and coarse grain can be there and this combination of fine and coarse grain will give you the required strength and ductility. So, the finer grain will provide you the strength whereas the coarser grain will provide you the stability during the deformation through dislocation moment. So, this is another approach to have to compensate for the reduction in ductility.

So, both the strength and ductility will be high when you have bi-model grain size distribution. So, these are the few basic ideas about equal channel angular pressing. Of course, this is not a very exhaustive lecture, but if you are interested, lot of literature is available, and you can start working on that. So, with that I will close this particular lecture on ECAP. So, thank you for your attention.

Keywords- Equal Channel Angular Processing, severe plastic deformation, strain, fine grain structure, mechanical property