4Thermo-Mechanical and Thermo-Chemical Processes

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Lecture-28
Accumulative Roll Bonding (ARB)

Hello friends we were discussing about severe plastic deformation. So, we will discuss couple of more processes where you can use this idea of severe plastic deformation. In that series now today, we will discuss about one of the process called accumulative roll bonding (ARB). Again, the all these SPD processes are very simple to implement and the good thing about these processes is that you can use existing facilities which are usually available in the labs.

For example, this is based on rolling process so already if rolling mill is there you can easily adopt an SPD process like this using your rolling mill. So, what do we mean by this accumulative roll bonding? So, accumulation means you are continuously accumulating. Already I have told you that during conventional rolling whenever we do rolling we are reducing the cross sectional area and of course the length will increase.

Usually there is not much deformation in the width direction, so the deformation is only that thickness will be reduced and because volume constancy has to be there, the length will increase. And slowly the thickness will keep on reducing and it will become the sheet, will become very thin. So, for any structural application I need certain thickness also to take the load. So, if you I want to impose more strain another way is that you do this kind of deformation.

And you can then do the stacking, so as we said that length will increase so I can cut the sheet now and again put the one sheet over the another sheet and then again do the same rolling process. So, the issue which can arise here is that what will be the strength of bonding between the two sheets because the integrity of the sheet will depend on that what is the kind of bond which is forming between the two sheets.

Usually we know that very quickly some oxide layers form on the surface and also during the rolling process there may be some lubricant which will be on the rolls so you have to have a very good preparation of the surface whenever you are doing the stacking sequence. First kind of do some mechanical removal of the material, also you want to increase the roughness of the sheet.

So, that it can create more area for the bonding as well as there will be cleaning processes. So, it has its share of complexities in terms of the sample preparation or in terms of surface preparation.

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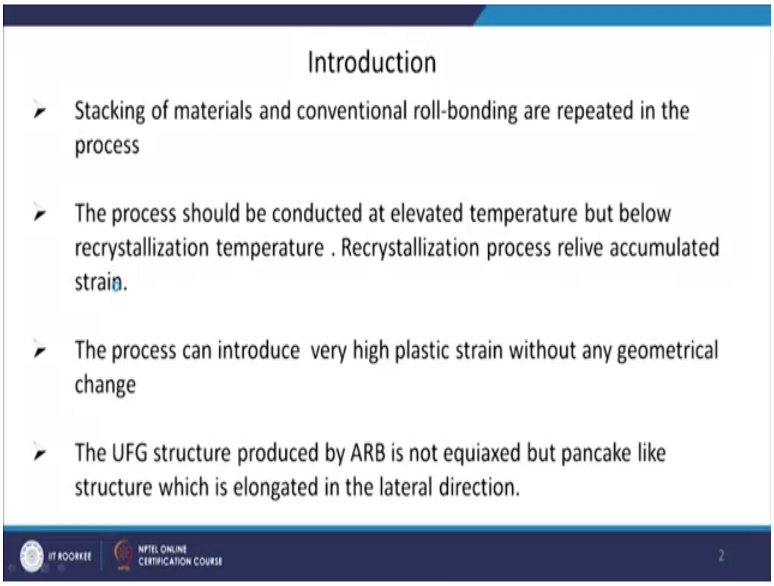

Introduction

- Stacking of materials and conventional roll-bonding are repeated in the process
- The process should be conducted at elevated temperature but below recrystallization temperature . Recrystallization process relive accumulated strain.
- The process can introduce very high plastic strain without any geometrical change
- The UFG structure produced by ARB is not equiaxed but pancake like structure which is elongated in the lateral direction.

So, it is like conventional, bonding is repeated continuously. However when we are selecting the temperature, the temperature of the rolling should be below the recrystallization temperature. Because the recrystallization temperature will relieve the accumulated strain with there is any recrystallization during the first rolling process then there would not be any accumulation of the strain in the material. So, recrystallization has to be avoided.

So, usually the accumulative roll bonding we do at temperature lower than the recrystallization temperature for that material and idea is to impose very high strain in the material through this process and we kind of because we are continuously repeating it we are saying that there is not going to be much change in the geometrical property of the material.

Geometry will more or less remain same after each cycle. And one of the microstructural feature of ARB will be like it the microstructure will not be equiaxed. Already, we have seen in ECAP if you use B_C root then after the complete cycle the microstructure which was which was achieved was having a equiaxed microstructure, equiaxed grains in three dimension. But this is a rolling process and you are continuously rolling in one direction.

So, the grains or the microstructure will not be or grains will not be equiaxed here but it will more like a pancake shape. You can take it is like Pizza, so it will be like a shape of a Pizza. So, if you cut in the direction of the normal to that Pizza surface then the grains will look elongated in this direction as well as perpendicular to rolling direction, whereas if you look from the top it will be looking like a equiaxed structure.

So, this is a typical pancake shape that from one direction the grain will be equiaxed but from other two directions the grain will look elongated.

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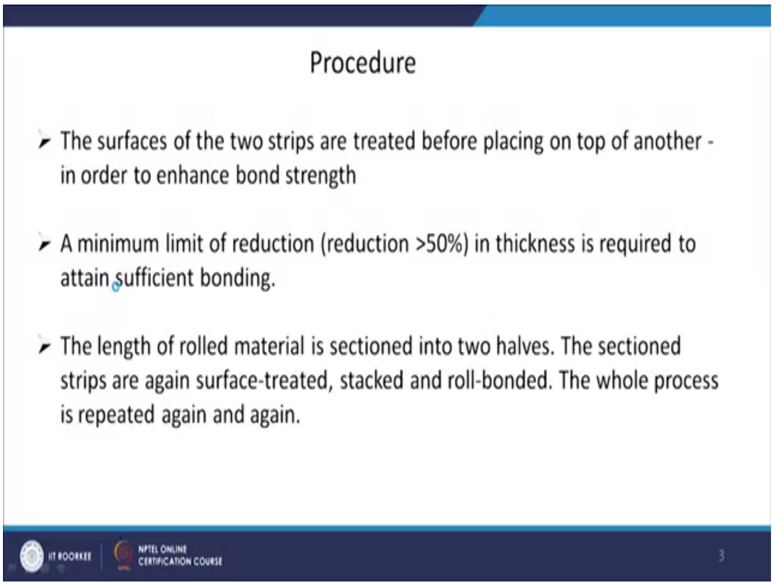

Procedure

- The surfaces of the two strips are treated before placing on top of another - in order to enhance bond strength
- A minimum limit of reduction (reduction >50%) in thickness is required to attain sufficient bonding.
- The length of rolled material is sectioned into two halves. The sectioned strips are again surface-treated, stacked and roll-bonded. The whole process is repeated again and again.

So, the procedure already as I told you that surface of the true strips is treated and then you place it on one over another. In each cycle the typically the reduction which we want to achieve is more than 50%. So, 50% reduction in thickness will be there and that is to attain sufficient bonding. So, bonding between the two layers will be through the strain, through the deformation.

So, through the flow of material and they are going to create a bond and every time as I told you that the length will increase, so you cut section into two halves put it back over one another and again do the deformation process at a temperature lower than recrystallization temperature and with reduction more than 50%.

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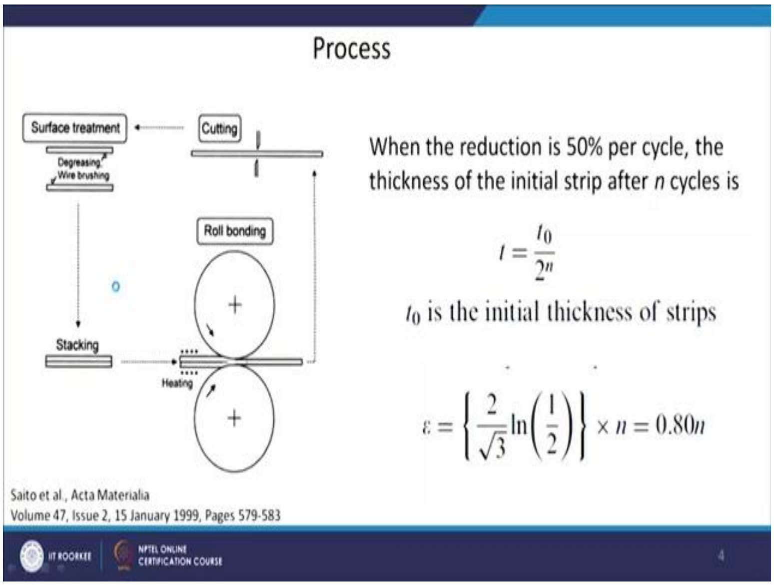

Process

When the reduction is 50% per cycle, the thickness of the initial strip after n cycles is

$$t = \frac{t_0}{2^n}$$

t_0 is the initial thickness of strips

$$\varepsilon = \left\{ \frac{2}{\sqrt{3}} \ln\left(\frac{1}{2}\right) \right\} \times n = 0.80n$$

Saito et al., Acta Materialia
Volume 47, Issue 2, 15 January 1999, Pages 579-583

So, this is a schematic diagram of the process. So, these were the two sheets which you have cleaned with wire brushing and so on. So, actually we will start from here, you have done rolling of the sheet, so the thickness is reduced, length has increased then you have cut the sheet into two halves. Then you have cleaned the sheet, surface treatment and then again stacking and then again it will be repeated.

So, this whole cycle will be repeated every time and in each case the thickness will be dependent on the amount of or the number of cycles which you are putting. So, we are already considering here that we are doing 50% reduction. So, it will be dependent on the number of cycles. So, if you have done 10 cycle you can easily calculate what will be the thickness of the sheet and where T_0 is the initial thickness.

And this (refer to above figure) is the relationship for the strain in the material which will also depend on the number of cycles and again the relationship is assuming that you are giving 50% reduction every time. If it is not so then you have to change this particular value, half is taken from the idea that you are giving it 50% reduction in the thickness. So, simply if these are all constant if you do the mathematics here ultimately you will get an expression like this that ε will be dependent on number of cycle multiplied by 0.8.

So, assuming if it is 50%, if you have you are putting 60% you have to change the relationship accordingly.

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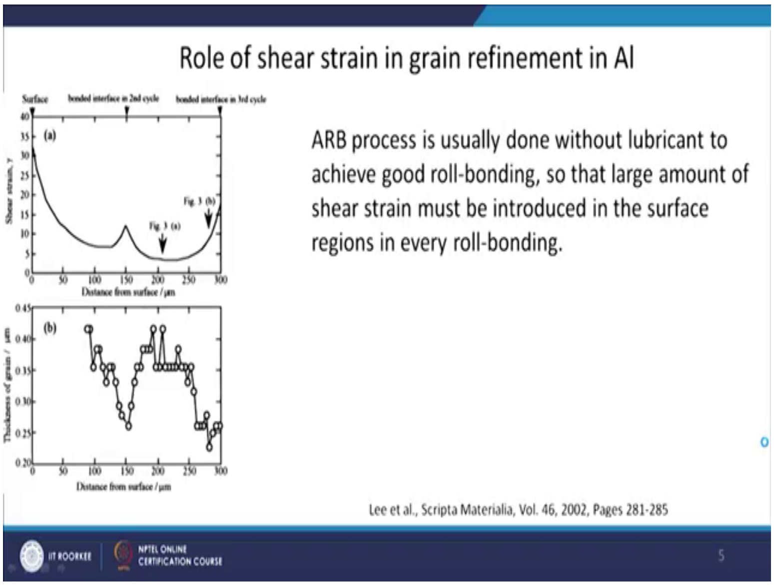

Role of shear strain in grain refinement in Al

ARB process is usually done without lubricant to achieve good roll-bonding, so that large amount of shear strain must be introduced in the surface regions in every roll-bonding.

Lee et al., Scripta Materialia, Vol. 46, 2002, Pages 281-285

Now as I told you that you are doing deformation and through deformation the bonding is taking place. So, there is a very strong role of shear strain in the bonding as well as grain refinement in aluminium or in any material. Usually this particular technique is done without use of lubricant. So, that you can have good roll bonding by avoiding lubricant. What you are doing is you are introducing lot of shear strain on the surface of the sheet which is coming in contact of the roll.

And also, there is a shear strain between the two layers. So at that interface also, there is large shear strain is acting as well as on the surface of the sheets which is coming in contact of the roll. And this shear strain actually kind of achieves the reduction in the grain size. So, there is a strong relationship between the shear strain. So, for example this shows a shear strain diagram here, a graph here.

So, the shear strain is more where you have second interface in the second cycle. Again, the shear strain is increasing where you have the third cycle between the two interfaces. And wherever the shear strain is high you can see the thickness of grain, so they have not measured grain size, why it is because you are continuously flattening the grains here through rolling process. So, what is the thickness of the grain that is showing a sharp deep wherever the shear strain is very high.

So, and again when the next shear strain cycle is there again there is a dip. So, there this is effect of this distance from the surface. So, only on the surfaces you will have high amount of shear strain and there you will have very small thickness of the grain as you go away from the surface where the shear strain effect will be small again the thickness of the grain is increasing. Again, there is a dip wherever the shear strain close to the surface is high.

So, shear strain is being applied both through contact between the roll and the sheet which becomes the interface when you cut it and again stack it over one another and there is also shear strain between the layers.

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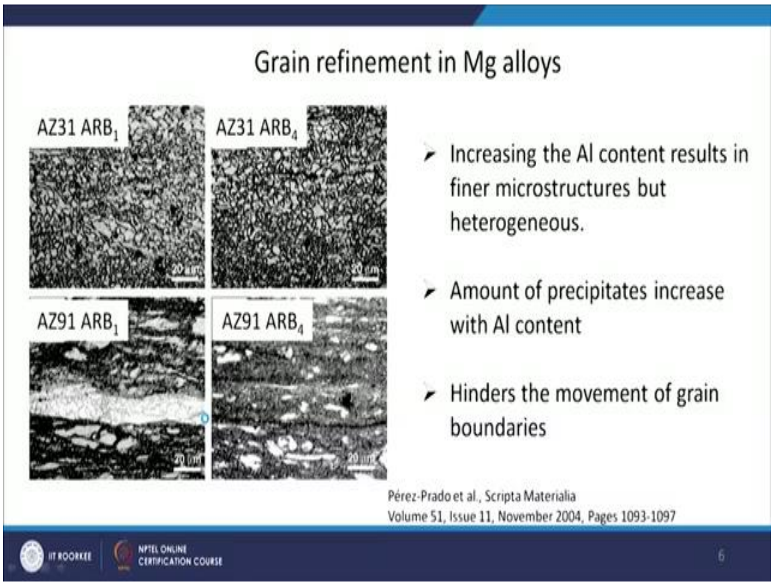

Grain refinement in Mg alloys

- Increasing the Al content results in finer microstructures but heterogeneous.
- Amount of precipitates increase with Al content
- Hinders the movement of grain boundaries

Pérez-Prado et al., Scripta Materialia
Volume 51, Issue 11, November 2004, Pages 1093-1097

This is an example of grain refinement in magnesium alloys. I am just kind of giving you is a kind of a very brief overview of use of this particular technique in different materials. So, these are comparison between two magnesium alloys here so AZ31 and AZ91. So AZ31 has 3% aluminium whereas AZ91 has 9% aluminium. So aluminium content is increasing zinc content is same in both the case which is 1% and you can clearly see the effect of the alloying content on the on the microstructure.

This is after first pass and this direction your strain is increasing. So, this is after fourth pass and in this direction your aluminium content is increasing. And again, your strain is increasing because this fourth pass, this is first pass and you can see clearly the effect of the strain on the microstructure the grain refinement is increasing. And you can very clearly see the effect of aluminium content also that as you are increasing the aluminium content, the microstructure refinement is more you can see that refinement in this case is more here in fact you are not able to even resolve the microstructure. Whereas here I can see clearly the grains however there is more heterogeneity here, you can see some big grains are there and some very fine grain microstructure is there, so there is a heterogeneity with more refinement. The reason maybe is because as aluminium is increasing there, a greater number of precipitates will be there and this precipitate pin the grain boundaries.

So when you have the recrystallization process you have nucleation and and the growth process, so movement of grain boundary is required. So if grain boundary is pinned then it cannot grow. So, therefore the grain size which you will achieve will be very fine. And if there is any maybe heterogeneous distribution of precipitate maybe that is why you are getting a heterogeneous microstructure here.

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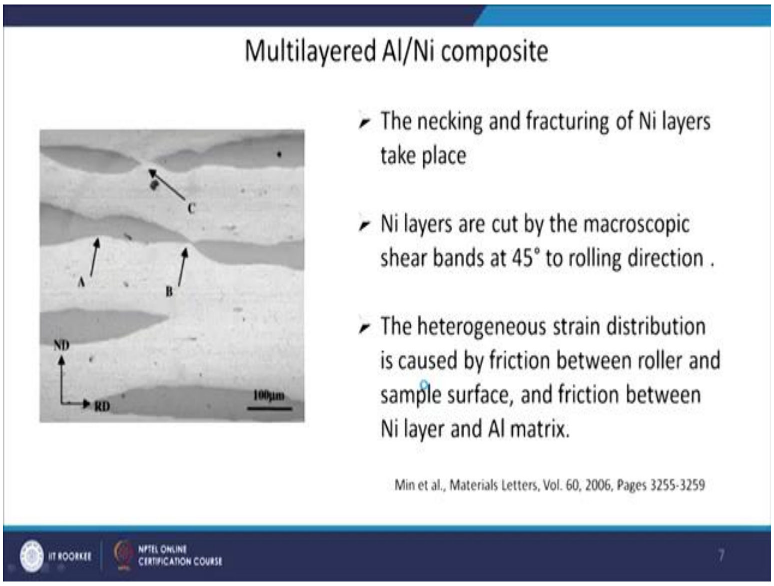

Multilayered Al/Ni composite

- The necking and fracturing of Ni layers take place
- Ni layers are cut by the macroscopic shear bands at 45° to rolling direction .
- The heterogeneous strain distribution is caused by friction between roller and sample surface, and friction between Ni layer and Al matrix.

Min et al., Materials Letters, Vol. 60, 2006, Pages 3255-3259

Now you can also interestingly with this particular process you can create multi layers. So, suppose you want to do a solid state what we call as mechanical alloying. So, one alloying technique is that you take everything into liquid phase and through phase transformation you create the alloy. But in that the amount of one material can go in another material depends upon the free energy or the basically phase diagram.

Phase diagram decides that how much material will go into solid solution and so on. So, if you want to have material where you want to have more content of one alloying element into another, one way is to do mechanical alloying and or you can also create multi layers. So, you can have kind of composite structure of metals, both can be metals and have multi layers of one alloy and another alloy.

And the bonding between the two material will create this multi-layer. So, this is an example of preparation of a multi-layer aluminium nickel composite here. This one is aluminium and this one is the dark one is nickel. Nickel is harder compared to aluminium. So, aluminium is able to flow whereas nickel is showing the necking phenomena.

You can see a very nice necking is forming here. Here already necking has taken place and there is now aluminium is continuous here whereas in this case it is in the process of that necking. So, necking and fracture of nickel layer takes place and this nickel layer is actually cut by these shear bands and usually the shear bands are at 45° to the rolling direction.

So, the fracturing takes place through this shear band formation and which is at 45° direction to the rolling and the heterogeneous distribution as we have already seen earlier also that there is a large shear strain heterogeneity in the material. Which is due to friction between roll and sample surfaces. So, this create a very large strain wherever the interfaces are there and that is causing these shear bands and fracturing of nickel layer. So, this is how you can create a aluminium nickel multi-layer composites.

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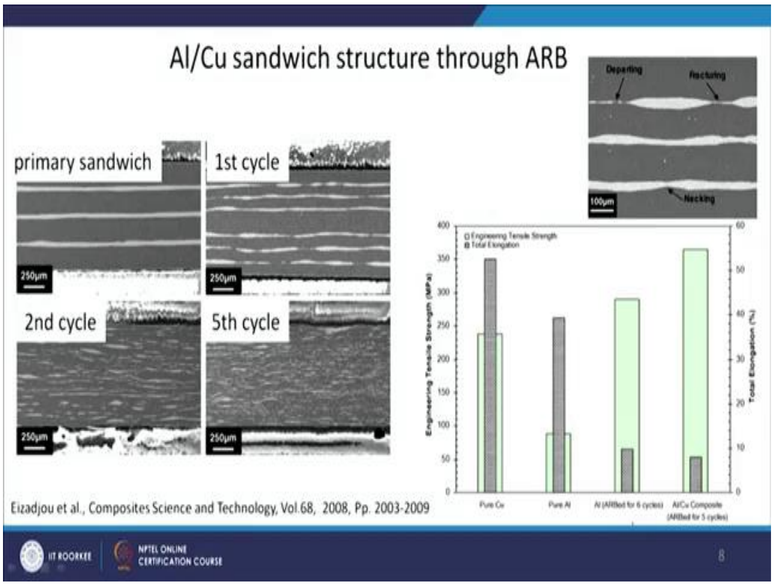

Al/Cu sandwich structure through ARB

Eizadjou et al., Composites Science and Technology, Vol.68, 2008, Pp. 2003-2009

This is another example of aluminium copper sandwich structure through ARB. This is the primary sandwich. So, this light one is the copper and dark one is aluminium. This is a SEM micrograph so you will have more in contrast the copper should look bright and aluminium should look dark. Whereas earlier one was an optical micrograph and again you can see the effect of copper being harder phase, so it is getting broken down.

And slowly, slowly you can see it is almost getting refined to very small sizes and having a kind of a continuous distribution throughout the aluminium matrix and again the same necking and fracturing is taking place in copper at different places. So, you can see that necking is there, necking is started here almost about to complete here and there is kind of break in the copper layer.

Here also you can see after first cycle itself there is a break in the copper layer. And the effect of this composite if you can see on the strength. So, for pure copper, the strength is around 250 MPa and for pure aluminium the strength is around 70 or 80 MPa. Aluminium if you just do accumulated roll bonding in aluminium, the strength increases to 300 MPa. So, from here it can go up to here.

For aluminium copper composite the strength is even higher. You can see that now the strength is around 360 MPa. So, again there is an increase from 300 MPa if you just compare with ARB in pure aluminium to ARB with aluminium and copper composite. However, the total elongation is continuously decreasing in this all cases though there is a increase in the strength which is a usual phenomena in all the SPD processes.

We have seen that. So here also by having composite like this you can achieve higher strength in the aluminium copper composite structure.

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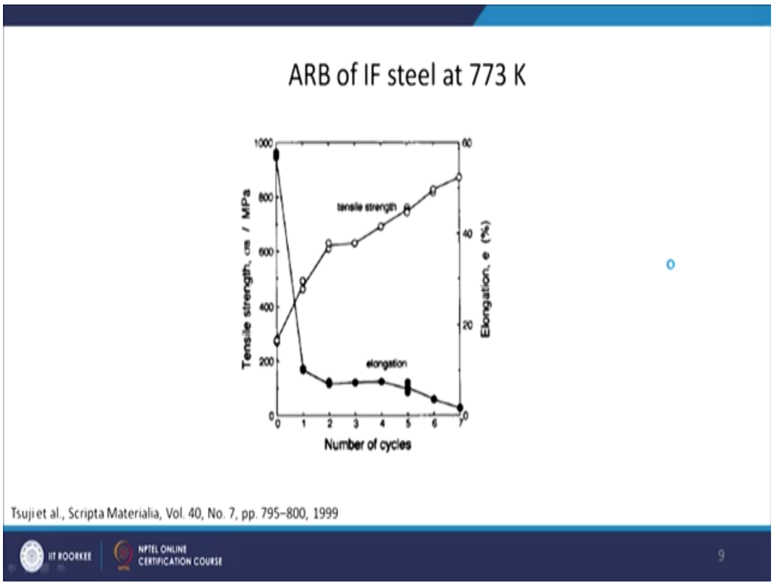

ARB of IF steel at 773 K

Tsuji et al., Scripta Materialia, Vol. 40, No. 7, pp. 795–800, 1999

So, again coming back to the same our story where we are saying that the severe plastic deformation processes, actually, though they increase the strength, the ductility is reduced. So in this case also ARB case also as the number of cycles are increasing, the though the strength is increasing but the ductility of the material is going down. So, this result is in IF Steel which is called interstitial free steel that means you have removed all the alloying element from the interstitial sites.

So, it is usually very soft material. You can see that at without ARB in normal condition the strength is maybe around 250 MPa but with ARB you can increase it to 800 MPa but at the cost of reduction in elongation from around 60% to very low maybe around 5% or so after seven number of cycles. So, this is a usual story getting repeated in all SPD processes that though the grain refinement, achieve very high strength in the material but the ductility comes sharply with the introduction of strain in the material.

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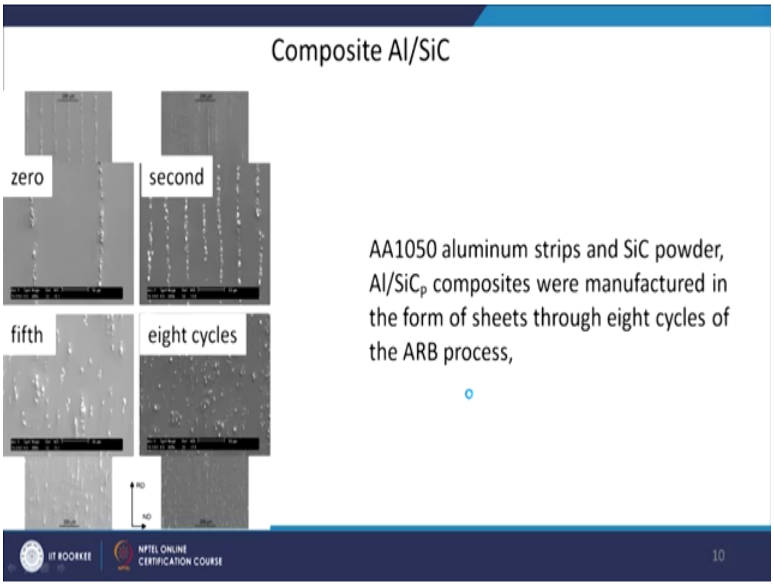

Composite Al/SiC

AA1050 aluminum strips and SiC powder, Al/SiC$_p$ composites were manufactured in the form of sheets through eight cycles of the ARB process,

Now as already we have seen that this is also a very good technique to create composite where the other part is may be ceramic particles for example in this case silicon carbide particles are there. So, again when you are doing is stacking you can put this silicon carbide particle between two layers. So, they will get embedded in the in the matrix. So, this is of course the first one.

Then you have second one, still you can very clearly see the effect of the stacking. There in one all the silicon carbide particles are in one line. By fifth pass they are getting distributed because as we already know that there are lot of shear strains acting at the interfaces. So, the distribution and the breaking of this linear arrangement starts. By 8th cycle it is almost uniformly distributed throughout the matrix.

So, a very nice method to make composite of some ceramic particle in the metal matrix. So, the material is aluminum 1050 and of course silicon carbide is put in this, so, this ARB process can be also used for making easily, you can make composite of this kind. So, all these processes have lot of flexibility. You can create different type of materials metal-metal composite, metal-ceramic composites, also by introducing in the same material multiple times we are able to achieve very high strain and very fine grain microstructure which increases the strength of course with at the cost of ductility. So, that balancing has to be done through microstructural control and that is where your knowledge of metallurgy comes handy that how you can do that to as we have already discussed there are couple of approaches to increase the ductility. One is creation of bi-model structure or through that was another approach was there.

So bi-model structure and these approaches are based on your metallurgical knowledge so that can be used for creating a material with good ductility also. Thank you.

Keywords – Accumulative roll bonding, severe plastic deformation, sandwich structure, fine grain structure.