Thermo-Mechanical and Thermo-Chemical Processes
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Lecture-01
Introduction

Welcome friends to this course on thermomechanical processing and thermochemical processing and I hope this will help you in understanding the whole thermomechanical and thermochemical processing which is used in the industry.

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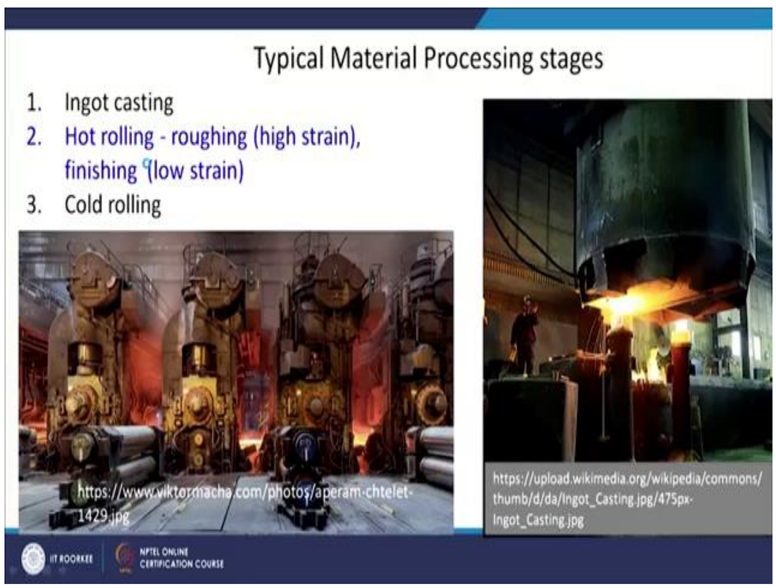

If you look at typical material processing stages, if you are doing any bulk processing, usually you start with a melt route that means you will do an ingot casting. so these are big ingots and you have to pour molten metal, which ever material we are working with i.e. aluminium or steel whatever. Then you allow it to cast and then this solid material will be processed further.

For example there can be a hot rolling process, where initial processing will be roughing and in that you will be supplying or you will be imposing higher strain in the material. This will be done at higher temperature obviously, and then you go further for finishing processes. In finishing process you apply lower strain and usually finishing operations are done at lower temperature.

So, that you can get good surface finish and also the dimensional tolerance will be much better. The last one as I was telling you that it can be cold rolling and there are some pictures (above picture) here just to give you an idea of the scale in which the industry work. In the laboratory, it will be a very small scale rolling mill. So, these are rolling mills and you can see there are continuous rolls are there.

So the strain will be imposed in multiple stages in the material, you do not want to impose very high strain in one go. Similarly this is a process where the molten metal from the ladle is being poured into the ingots. So, again you can see the size of a man standing there controlling the whole operation and the size of the ladle and ingot and the size of the rolling mill.

That gives you an idea of the scale in which industry works. So, it is always a challenge to do experiment in the laboratory scale and implement them where the processing will be done in a bulk condition. Control of temperature, strain and strain rate will not be that precise and for that we want to give some suggestion that if the processing will be done like this, you will get better properties, better microstructure and so on.

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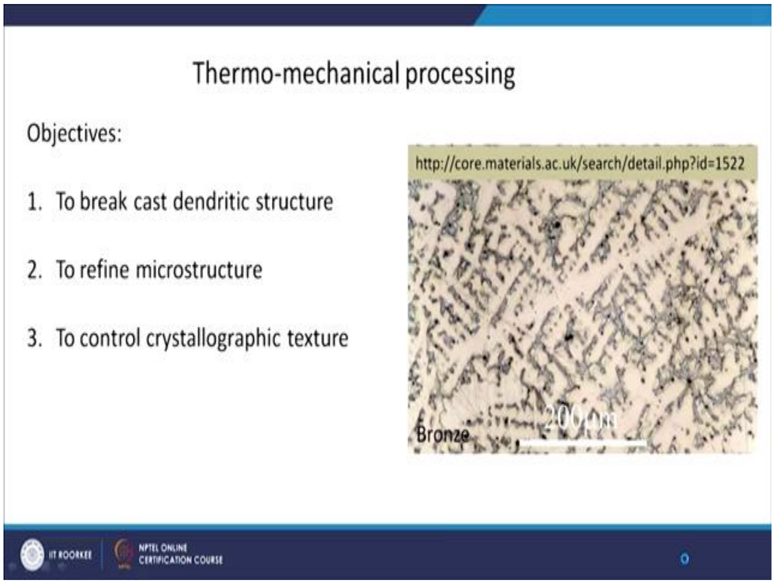

So, why we do thermomechanical processing? The thermochemical part will be introduced to you by professor Sai Ram Meka. His lectures will start after the lectures on thermomechanical processing will be over, i.e. after 30 lectures. Before his lectures starts, he will give you a brief introduction. So, I am taking right now the thermomechanical processing introduction. And the objective of thermomechanical processing is first is to break the cast dendritic structure.

So, after casting process usually the microstructure contains dendrites (above picture). So, dendrite is tree like structure, you can see there is a central branch then there are secondary branches coming out of it and sometime there will be tertiary branches and so on.

So, this is a typical dendritic structure and you can see the microstructure because of the etching effect. You can see between two dendritic structure there is some different contrast is there. Usually this is the dendrite, which has lower solute content and between two dendrites we call it is as a interdendritic region. It contains more solute and lot of intermetallics forms in this region.

So the dendrite will be relatively solute poor and interdendritic region will have more solute content. So, this structure is not good for mechanical properties, I will show you in the next couple of slides. So, the first objective is to break the cast dendritic structure, second objective is when you are breaking this cast dendritic structure, we also want to refine the microstructure.

So you can see these dendrites sometimes are very big in size, so we want to reduce the size of the dendrite first, break it and then we want to refine the microstructure. So, that is our second objective of thermomechanical processing to refine the microstructure and another very important objective gaining lot of importance now days is to control the crystallographic texture. So, we will see what do we mean by crystallographic texture and how it controls mechanical property to a great extent. Good choice of texture will give you much better properties.

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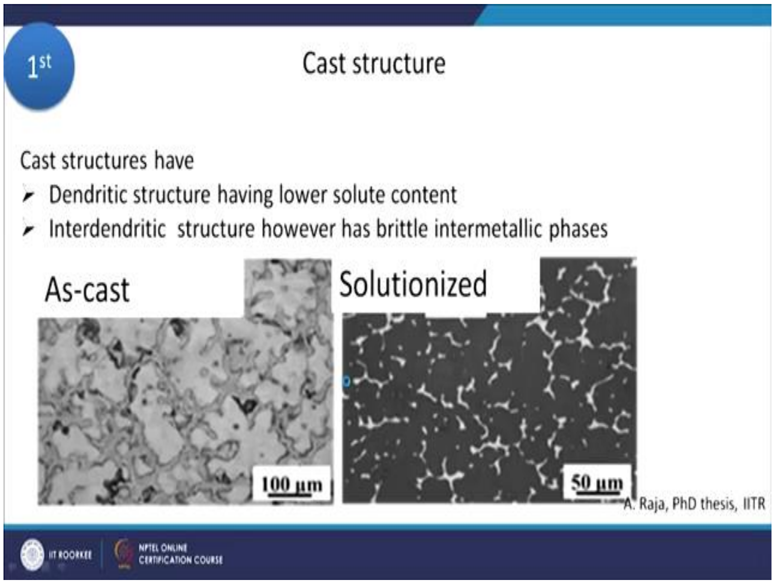

So, what is the problem with cast structure. So they have dendritic structure and as I told you they have lower solute content and interdendritic structure have higher solute content and usually intermetallic phases will be there which are brittle in nature. So, you can see this is a as-cast structure of AZ91 alloy (above picture) and the dendrites are relatively solute poor where the interdendritic regions are solute rich. If you do a solutionizing that means if you take this material to high temperature and keep it for sufficient amount of time. There is a segregation of solute because solute is having different composition at different places and there will be diffusion. The thickness of this layer if you see in the solutionized material has reduced considerably.

And the continuous network of interdendritic region will start breaking. so you have lot of places where there is break in the interdendritic regions. So, in the first process for any cast structure, we have is to redistribute the solute and have an more or less uniform or homogenized composition throughout the material. So that is the first thing but still you have that dendritic structure.
So the next one is to break this dendritic structure that is what is the objective of thermomechanical processing.

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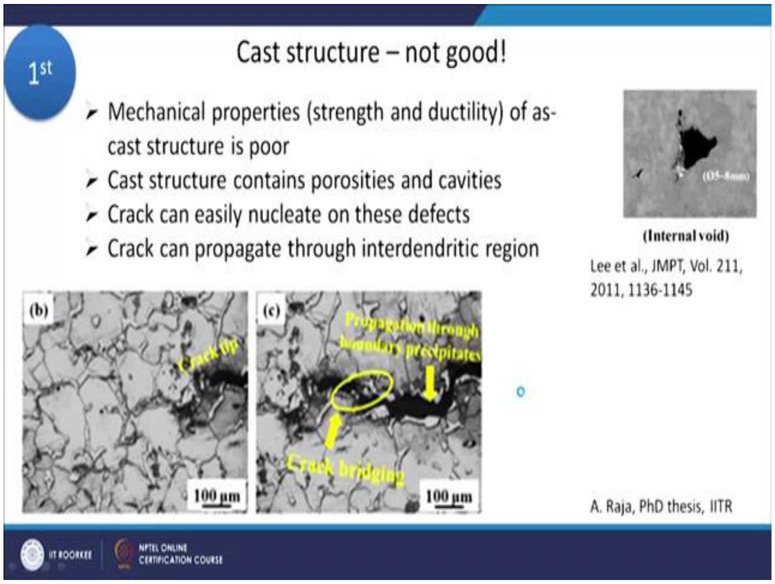

If you look at the mechanical properties of the cast structure, as I told you these are not very good. strength and ductility both will be very low and the reason is that cast structure contains porosities and cavities and also as I told you about dendritic region that crack can easily initiate on this porosities and cavities. Once it nucleates, it can easily propagate through interdendritic region. So, as I told you there is a interdendritic region which contains intermetallic particles, has a continuous structure and they are also brittle.

So once the crack is initiated, as you can see this crack is going through this interdendritic region in a very nice fashion (above picture). You can see that this crack is growing through the interdendritic region. It is separating two dendrites and also as you can see in this micrograph that cast structure contains large number of cavities and porosities, which can act as a nucleation sites and once it nucleates, the crack can easily propagate through the interdendritic region.

So, because of this the cast structure this is not considered a good choice for mechanical properties. However, in some cases where you cannot have any other way of fabricating a component you use cast structures but then you have to ensure that there are not very high stresses applied on the component.

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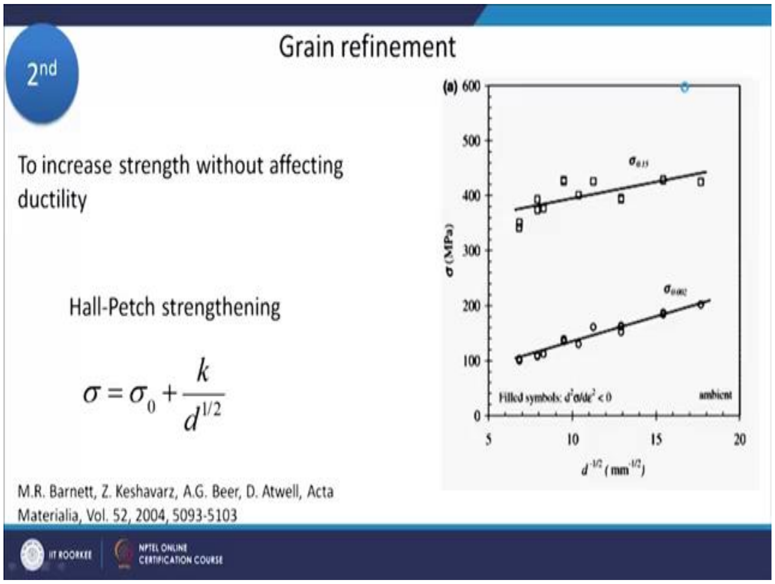

The other reason to do thermomechanical processing is grain refinement and why we want to do grain refinement or microstructure refinement is to increase the strength. And how the strength increase because of the Hall-Petch relationship, which says that the stress will be dependent on the $d^{1/2}$.

$$\sigma = \sigma_0 + k/d^{1/2}$$

And the grain size (d) is in the denominator so that means if you reduce the grain size, the flow stress will increase.And you can see that affect here in the micrograph. so on the x-axis you have $d^{-1/2}$ is plotted and on the y-axis we have stress and you can see as we are increasing $d^{-1/2}$ that means we are decreasing the grain size (abovepicture). The yield stress of the material is increasing. So, this is the effect of grain size reduction. That is always what we like to have. How I can do the grain refinement.

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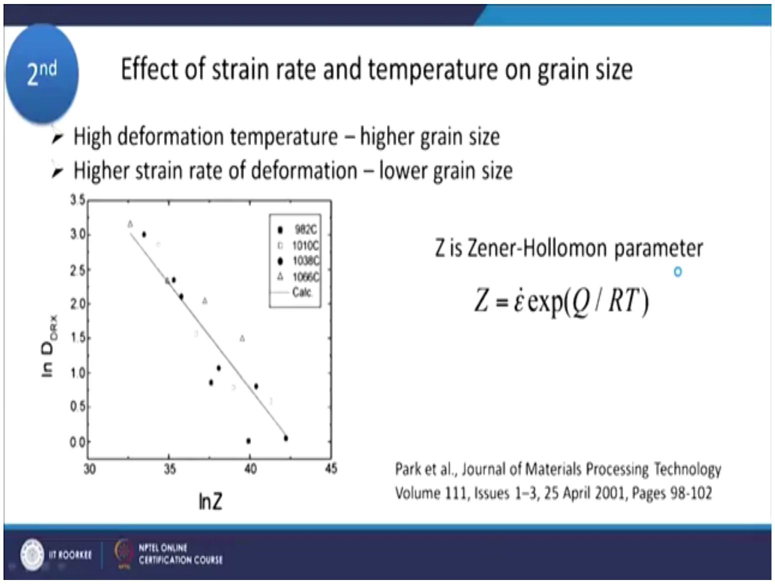

Now as I told you we want to do thermomechanical processing. So this is the effect of thermomechanical processing on the grain size. So, basically when we are doing thermomechanical processing, you are controlling strain rate and temperature and of course strain also. So, when you are deforming at higher temperatures and low strain rate then the grain size will be high or it will be more.

And both this effect can be easily captured by parameter called Zener-Hollomon parameter which has both temperature and strain rate ($\dot{\varepsilon}$ is strain and rate T is temperature).

$$Z = \dot{\varepsilon}\exp(Q/RT)$$

Because temperature is in the denominator and it is also within the exponential, so effect is exponential here of temperature. So, if you are increasing the temperature and reducing the strain rate then the Z will reduce.

If you are increasing the strain rate and reducing the temperature the Z will be more. So, higher strain rate and lower temperature will promote lower grain size, as you can see in this micrograph. In this graph where on x-axis lnZ is plotted and on y-axis lnD is plotted. You can see as the Z is increasing, grain size is reducing. So, that is the effect of thermomechanical processing that control of temperature, strain rate and of course strain also.

So, control of temperature and strain rate can refine the microstructure. So, if I do processing at lower temperature and higher strain rates, I will be able to get finer grain microstructure. Of course there are other effects also. We have to consider that while we are doing this, whether we are introducing any defect in the material. Then it makes no sense just to refine the microstructure if there are defects in the material because the defects will bring down the strength and ductility both.

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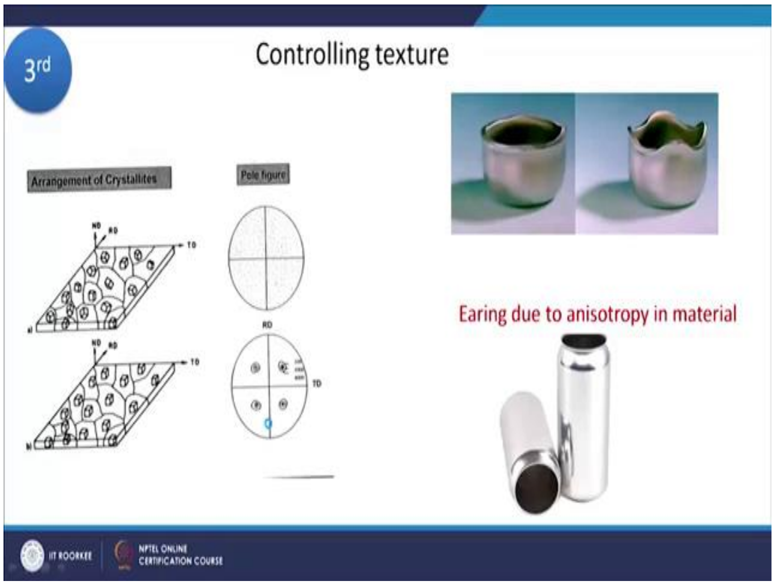

The other part is as I told you about controlling texture and the effect of that is shown here. You can see there are two cups which are drawn so we have a die and a punch. Punch is forcing the material to deform. In one case you can see a very nice cup is formed with uniform surface or uniform top. Whereas in this case you can see there is formation of ear. It is like our ear and due to the formation ear, you have more thinning in these regions.

Also when you want to use it, you have to remove the defected material from the cup. This will go as waste. You can see that nowadays the cold drinks which you get in aluminium cans, you can see that for this kind of deep drawing, you need good formability of the material where you want to have this size of the can.

So, you can’t afford to have ear formation and that can be reduced by having or by controlling the texture. We will see the details of texture and we will discuss that but right now you just take it from me that texture is basically the orientation of the unit cells which are there in each grain. So how this unit cells are oriented. If they are oriented randomly, you will see random texture you can see the points all over the place (above picture).

Where as in this case, all the cubes or all the unit cells are oriented in one particular fashion and that is why you can see a very strong texture in this material. So, you have to do processing to control this particular orientation of unit cell within each grain to have a forming property which is desirable.

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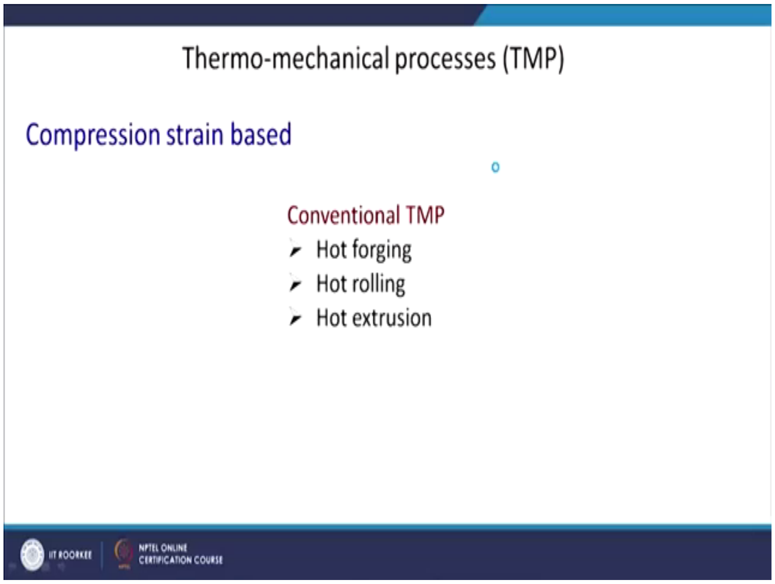

So, now just look at what are the different thermomechanical processes are there. I have divided this thermo-mechanical process in two categories, one what we called as conventional thermo-mechanical processing which is based on compressive stress, strains. That means when you want to deform the material to change the cross-sectional area, you are doing it under compression.

And for example of our conventional processing like forging ,rolling and extrusion comes in this category.

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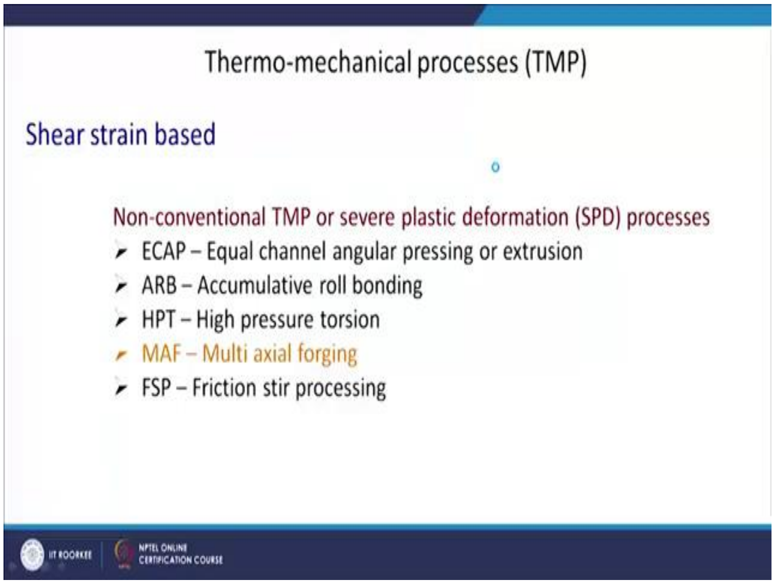

There is another category which is now what we call as non-conventional thermo-mechanical processing or more popular name is severe plastic deformation (SPD processes) (above picture). These are based on shear strain so the deformation or the strain is imposed is in under shear condition. So all these equal channel angular pressing or accumulative roll bonding of courses is through rolling, compression basis but lot of shear strain actually are induced in the material and which actually helps in bonding as well as grain refinement.

High pressure torsion, multi-axle forging is of course based on compression method that is why I have coloured it in a different way. Then you have friction stir processing and so on. All these processes are based on Shear Strain idea. That is why you are able to impose more strain in one cycle in this process as compared to compression based deformation processes. So basically as I told you the scale in the first slide so we want to give suggestion to industry based on what we are doing in the lab.

So, basically we are trying to physically simulate the process in the lab so if it is a compression based process then we will do a simple compression test at different strain rate, temperature and so on. For different strain levels to find out that what is the change in the flow stress or any change in the microstructure and then we have to implement these results in the industry. And if you are doing any SPD based process then we will try to simulate that using some torsion experiment where we are applying the shear strain in the material.

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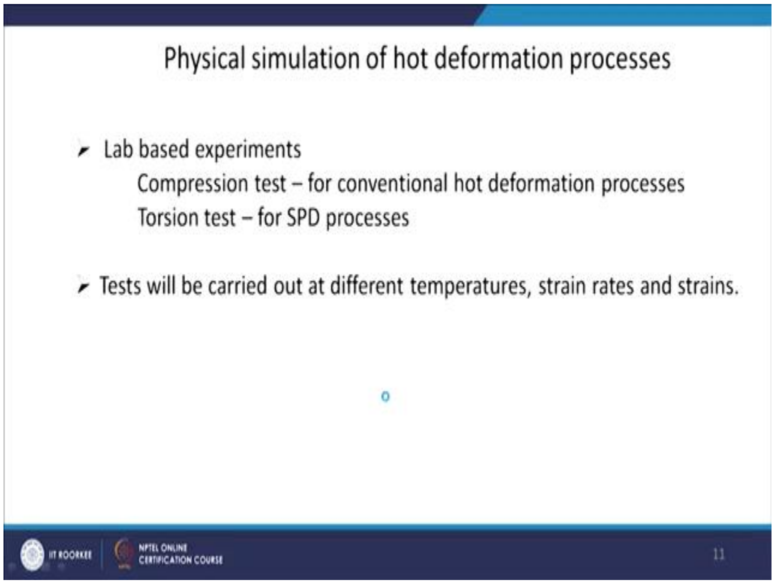

This type of physical simulations are usually done in laboratory to implement the solution in the industry.

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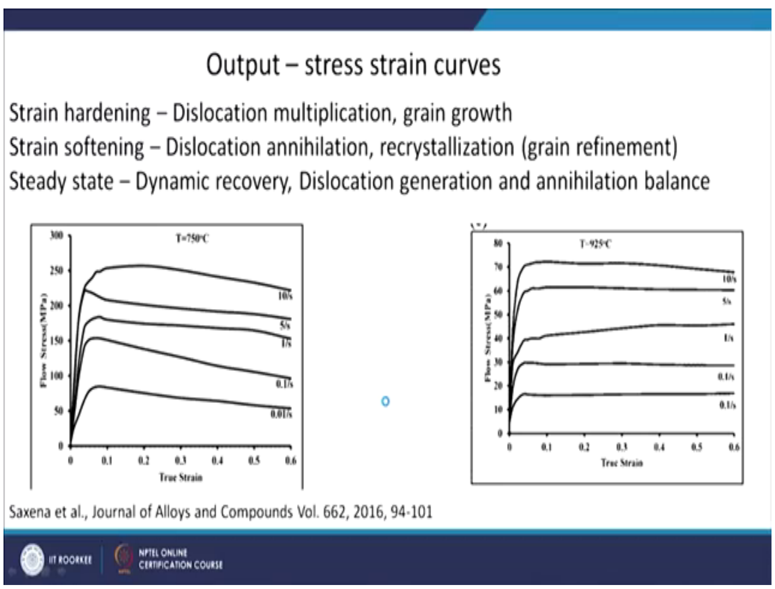

And the output when you do this simulations is basically in terms of flow stress curves. So, as you can see there are two flow stress curves shown here at two different temperature the deformation was carried out and the strain rates are shown here. So, strain rate is increasing in this direction so two different temperatures at different strain rates you get flow stress curves and through that we kind of try to understand that what are the mechanics involved during deformation process.

So, for example if there is any strain hardening then we know that there is dislocation multiplication or grain growth is taking place or if there is any strain softening as a function of strain if the flow stress is coming down then we know that dislocation annihilation is there through recovery process or recrystallization is taking place or if any steady state is there then you know dynamic recovery or basically generation and annihilation have balanced each other.So, that is the steady state condition.

So the all these type of flow stress curves you can see when you are doing this kind of deformation and then we use this output to to get what we called as constitutive equations.

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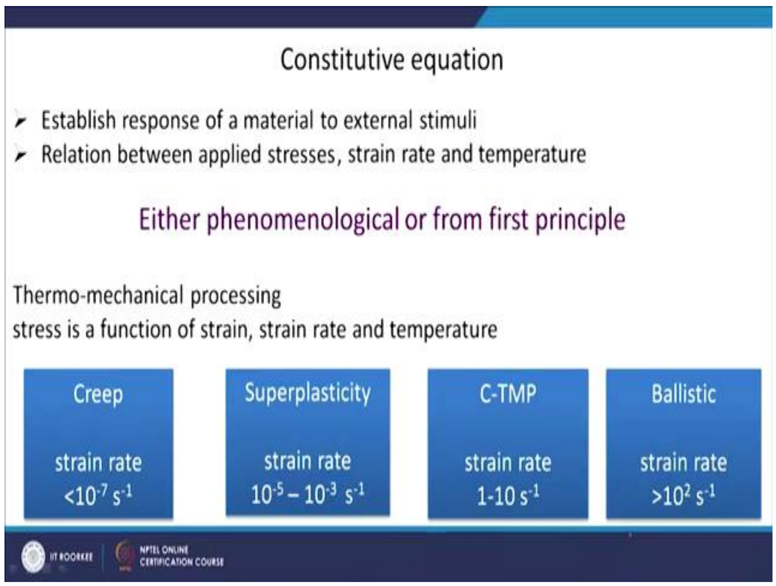

So, basically constitutive equation is the relation between the stress, strain rate and temperature. So, we established the constitutive equation for each material that what is the response of material in terms of stress as a function of strain rate and temperature. So, that helps us to develop some equations and this equation then can be to kind of model the process. So once you have this data constitutive equation you can use this data to model for example forging, extrusion or rolling process.

You can you FEM model and then then then in FEM model you will need that to know that what is the constitution relation this material follows that is how the model will be able to calculate that what will be the strain, strain rate at different location and flow stress. So, you can divide the whole thermomechanical processing based on strain rate in different segments so you have creep at very low strain rates. So strain rate in this direction your strain rate is going down and in this direction your strain rate is increasing so you have creep then superplasticity then conventional thermomechanical processing then you have ballistic kind of deformation very high strain rate.

So, there are different ranges of strain rate here and that define different type of processes which you can model or which you can you can create constitutive equation for this different deformation conditions.

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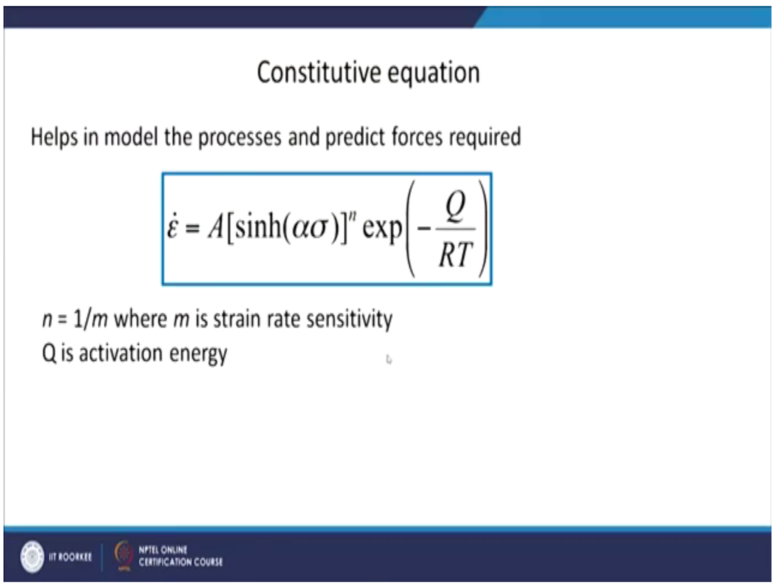

So, this is the constitutive equation, one of the types which is what will try to develop to then predict that what will be the response of the material as a function of strain rate and temperature.

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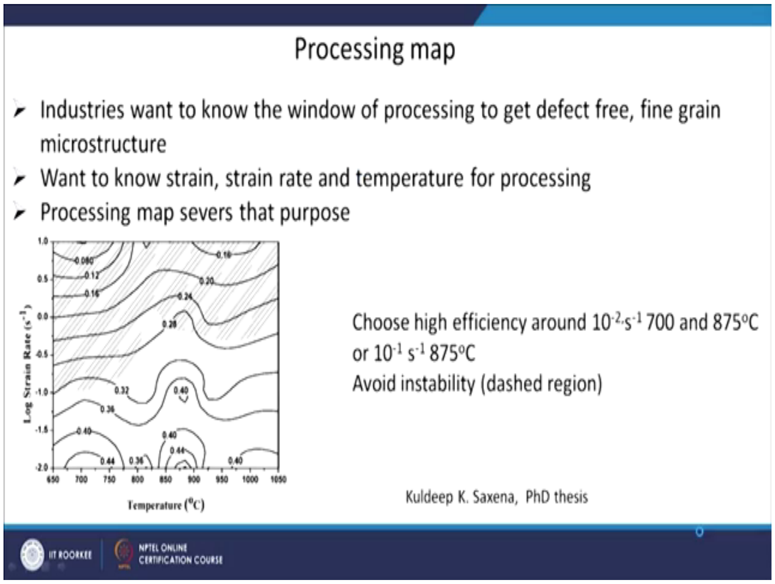

Another thing we try to do through this laboratory experiments is what we call as development of processing map. So, why we want to do that is for the for an engineer who is practicing or who is in the industry looking after the processes. For him knowing all these conditions stress, strain rate does not make sense. He wants a very clear instruction that what will be the window within which he can process the materials.

What temperature he should keep or he should heat the ingot before deformation what amount of strain he has to give and what will be the velocity of deformation process that means what will be the strain rate window for him. So, if he can get a window like that where we can get a defect free material and also which gives you a refinement in the grain size that means it should have recrystallization zone condition at that particular window.

Then that is a window ideally we would like to give it to to the industry or to the process engineer and to know that we have to develop using all these output of stress, strain rate output of stress as a function of strain, strain rate and temperature we developed what we call as processing map.

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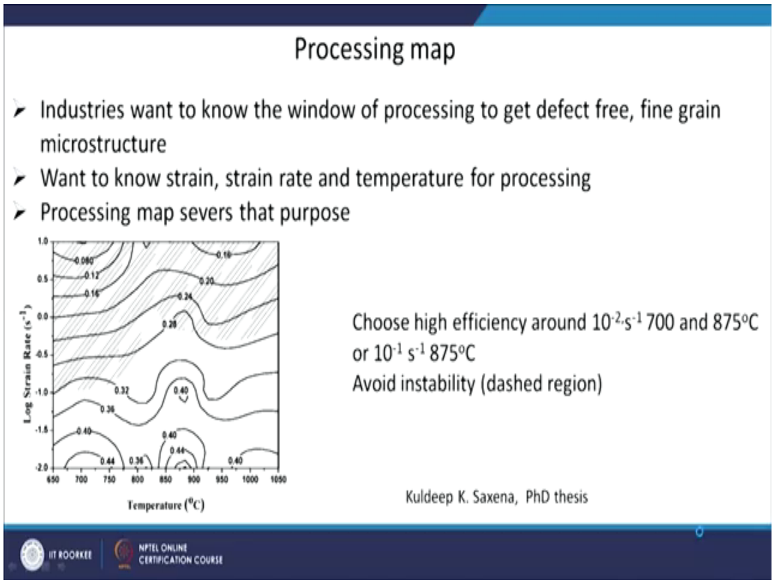

So, you can see on the x-axis it has temperature y-axis it has strain rate and some contours are shown here we will discuss this later on when we will discuss about processing map just to give you an idea that basically we are looking for the regions which gives you higher efficiency. This efficiency translate into the microstructural changes in the material so we look for all these high efficiency zone and this will give you an idea that ok this kind of window if I work in that will give me the defect free microstructure.

And I want to avoid all this region which is showing with hatching, grey area. This regions I want to avoid and I want to do the processing in the high efficiency region. So, in this particular course basically what we are going to do, we are going to understand all this how to develop constitutive equation, how to develop processing map and understanding of texture and what are the different process. So, that when we do laboratory experiments we should be able to translate those result into industry.

And development of all this will be carried out as modules so one module will be on constitutive equation and one module will be on processing map one module will be on understanding of cryptographic texture and so on. So, overall that will be able to help you and in implementing the laboratory experiments to the industry. So, with that I would want to thank you for attention to this particular lecture.

And I hope that you will be able to get benefit out of this particular course for your course work as well as if you are or if you want to go in industry or if any engineer who is already practicing engineer I hope you should be able to get some benefit of this particular course, thank you.

Keywords- Thermomechanical processing, Strain, Strain rate, Temperature, Texture.