Advanced Materials and Processes
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Lecture – 14
Bulk Metallic Glass, Glassy and Amorphous Materials (Contd.)

Hello, welcome to NPTEL, myself Dr. Jayanta Das from Department of Metallurgical and Materials Engineering, Indian Institute of Technology, Kharagpur; I will be teaching you Advanced Materials and Process.

In the last class we have discussed about the atomic scale mechanism on deformation in glassy solid and we have just started our discussion on inhomogeneous deformation in disordered structure. Today, we will continue on these inhomogeneous deformation when localized deformation occurred that lead to the formation of shear band in metallic glasses.

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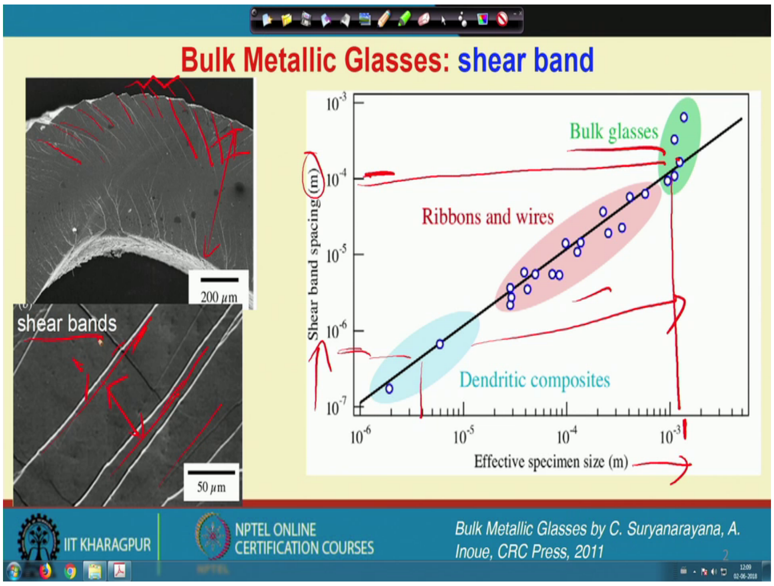

So, the formation of shear band has been observed by many researchers and there are many studies has came to some of the very basic and fundamental conclusions. Here one of the thinner plate microstructure of the thinner plate is shown here, which was bended on anvil and you can see that how the shear of sets has occurred near the surfaces ok.

So, they are like this and individual this slip of shear steps involve some amount of strain. In a more magnified view, this shear bands appear in a glass in this kind of way, where there is some steps involved and then there are some next plane.

We should remember that this particular deformation has been done at near room temperature where the shear localization has to occur definitely and we can also measure the distance between these two shear bands ok. So, which is somewhat a measure of the shear band spacing; that that what is somewhat the distance between two shear bands and since these are macroscopic event, so we can correlate with the effective specimen size.

Let us say we can simply think about a very thin ribbon or a wire made out of a metal glass or maybe we can think about a 2 mm or 10 mm size bulk metallic glass and we try to deform them and we simply measured these shear band spacing. Here this unit is in meter. So, somewhat here is in the range of few micro meter and people has looked at that in case of metallic glasses or bulk metallic glasses, the effective specimen size is higher, the spacing between this shear band is also higher.

In case of ribbon, one can get some bending plasticity means, if you have a very thin ribbon you can bend it, but in case of a bulk glass it is almost like a non-deformable means one or two such shear band is sufficient enough to fill the material catastrophically ok.

So, bigger the specimen size the bigger the spacing between the shear bands where strains are localized. And therefore people go for some composite which will discuss later on and there the relative size of this shear bands are somewhat less. However, these days it goes somewhere here. So, we understood that the inhomogeneous deformation will lead to the formation of some macroscopic shear bands and these shear bands appear under bending in different directions and they are visible under scanning electron microscope.

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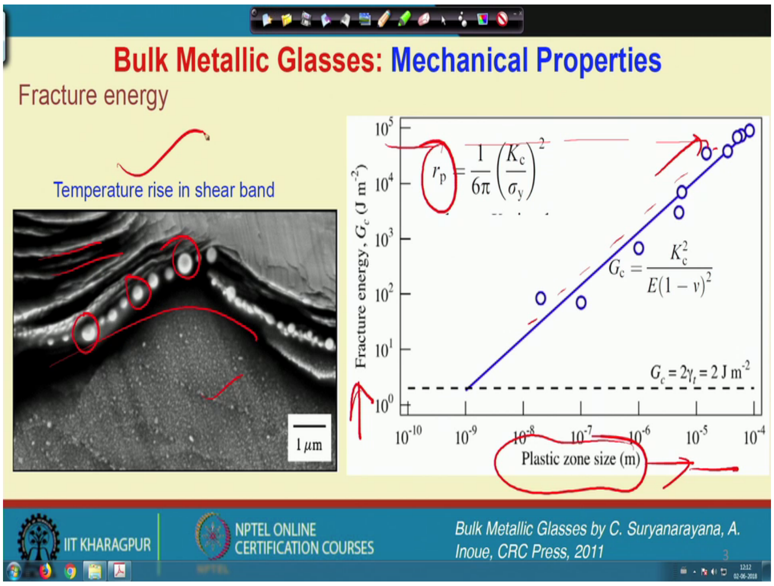

So, definitely the question will appear that these shear bands whether how temperature are related with formation of this shear bands, since the deformation and strain is localized whether there is any adiabatic heating. And one should look at the fracture energy of these bulk glassy solids and also the plastic zone size; People have measured all these values and observed that the plastic zone size definitely is higher in case of a higher a fracture energy which is also very very high.

So, plastic zone size at room temperature definitely require formation of the shear bands, and because that is the only one way that a metallic glass could accommodate the strain at low temperature, low temperature means I am talking about room temperature. However, the idea came that how to prove that there is really increase of the temperature in the shear band.

So, some researchers did a very clever experiment that they coated a metallic glass using tin. Since tin has a low melting temperature and if at all the shear band get heated then or increases the temperature, then it is expected that the tin will melt. So, they have chosen a Vitreloy glass and they have observed that in localized the shear bands, the tin has melted feature in the shear band near the shear bands.

So, it proves that even though it was a coated tin metallic glass, but temperature definitely has raised in this shear bands. So, the process is also adiabatic in nature.

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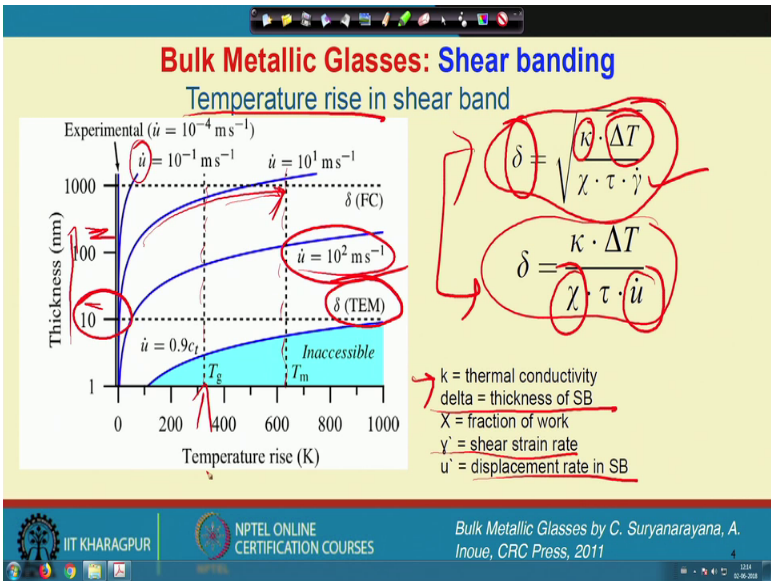

So, one has to has to estimate that a since it is a adiabatic process, the formation of shear band occur very very rapidly or strain is localized those event occur very very rapidly and so, in the order of some millisecond and so on.

So, if we convert this energy and how much increase of the temperature maybe raised. So, people came are with such kind of a equation where delta is the thickness of the shear band, and k is the thermal conductivity of the material and delta T is the expected rise and these are the shear strain rate or let us say displacement rate in the both the equations are very much a similar and we consider here psi, which is basically a fraction of work that is converted into the increase of the of the shear bands.

So, people had looked that if we if we have a very high displacement rate in the shear band, then the thickness of the shear band which is in the order of let us say 10 nanometer to 100 nanometer length scale or the heat diffusive zone and then we can increase the temperature even somewhat up to glass transition temperature or we can even reach up to near the Tm ok. So, depending on the on the rate of a rate of rate of displacement in a shear band.

And therefore, people did lot of investigation to measure the thickness of the shear band and using the TEM people find out the 10 nano meter is a length scale of a shear band. So, it is already proved experimentally that temperature rises in the shear band and the temperature could even reach near to the glass transition temperature.

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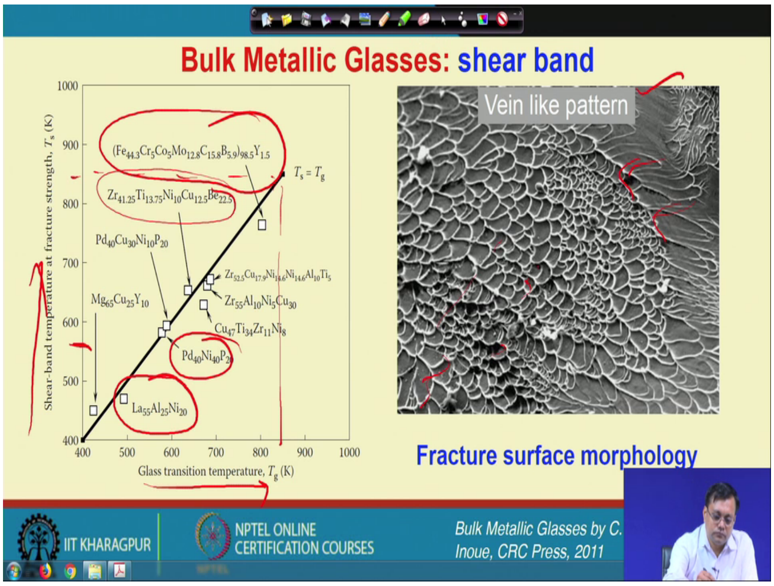

And therefore, when we study the fracture surfaces of a metallic glass, usually we observe such kind of vein like pattern. Even though they have some similarities of melting all let us say like separation of breeze ok. So, those kind of feature can be observed.

So, you can clearly see here some melting like a phenomena and a network like structure which is often called as vein like pattern and it simplifies and confirms that temperature must have raise in those shear bands. And if any crack has propagated along those direction, then due to the fresh appearance of the surface, the temperature and broken bones of those atoms lead to localize melting.

So, the glass transition temperature and the shear band temperature at fracture strength, people tried to correlate and people find out that in case of a glasses with low glass transition temperature like palladium or lanthanum, the temperature rise is also relatively less where as in case of a zirconium or iron base glassy alloy, which has a relatively higher T g the temperature rise is also quite higher which is a which is a quiet obvious.

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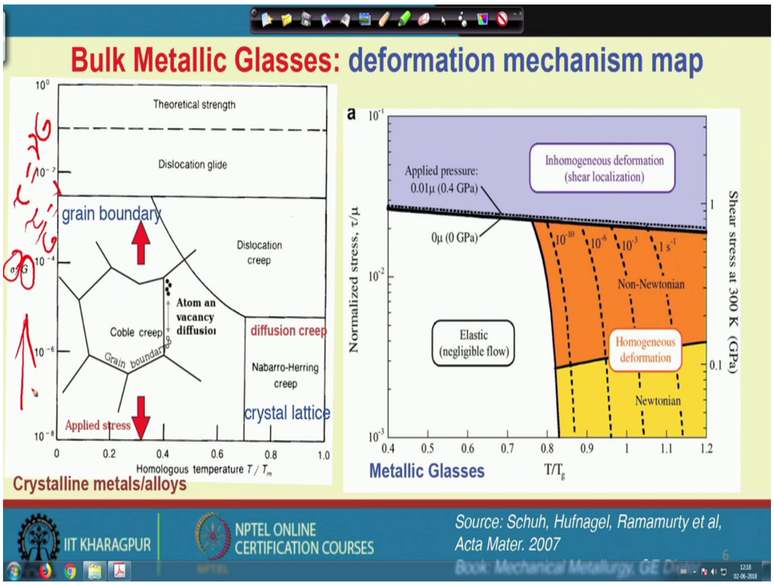

So, all these mechanism that I had discussed in this local deformation homogeneous inhomogeneous flow, recently it has been a summarized and a people come out with some deformation mechanism map. And this deformation mechanism map is also available in case of a crystalline metals and alloys. So, I think we can simply first have a look at the deformation mechanism that is available or existing for crystalline metals and alloy and then we can simply try to compare in case of a glass.

Usually we plot this deformation mechanism map with this 2 axis; here in case of a crystal we usually plot it in terms of a homologous temperature. A homologous temperature is the ratio of the deformation temperature with it is melting temperature. So, that is temperature of deformation by a temperature of melting. Now, the y axis if you look at the book then it is given σ/G which is in the book of the mechanical metallurgy by Dieters book.

Here we must know that the shear strain is basically a linked with a linked with the shear stress and may be little bit more clear. Shear stress is equal to the shear strain into the into the shear modulus. So, if I simply make a ratio of the shear stress versus G then I will get the shear strain. So, here you will see that there is a stress term and there is a G which is the ratio.

So, it basically somewhat represent a critical strain and this strain is somewhat linked with the mechanics of deformation in crystal.

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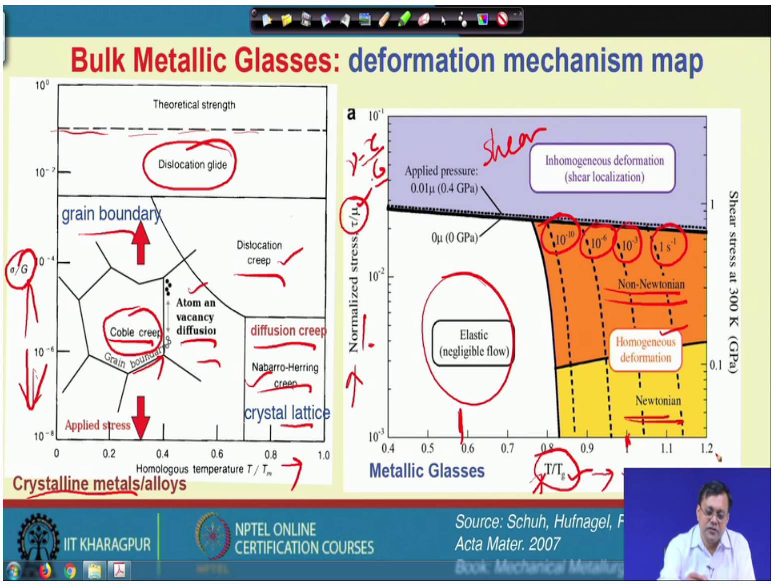

So, similarly here also this τ/μ is also give the same type of relation that is the shear stress by G, because G and tau are the same. So, instead of a calling it as a normalized stress, we can also call is something like it is equivalent to some sort of critical strain in the in the in the material and in case of metallic glass this deformation map has been designed because the T g is important here

So, glass is characterized by it is glass transition temperature and it is a normalized temperature with a T by T g. Now, let us have a look at in case of crystalline solid, here let us say if this is a value of some sort of theoretical strength limit, and if the value of these a normalized stress basically increases, then the material go for regular dislocation glide means dislocation glide on the slip plane ok. So, that is called as dislocation glide mechanism.

However if the strength is somewhat relatively lower then we can think about a temperature or higher temperature, then some grain boundary process or dislocation creep will appear or maybe if it is has a relatively lower value or a higher stress value given stress value, then we can also go for some sort of a diffusion creep, where low stress required for activating this process because this ratio has a lower value along this direction.

So, this is known as a coble creep, which is also a low temperature creep process and grain boundary is more activated in this particular process because for diffusion to occur the atomic diffusion to occur through grain boundary, does not require very very high temperature, where the bulk diffusion or crystal lattice diffusion relatively require a higher activation energy.

So, in case of coble creep, the atomic vacancy and diffusion that a proceeds through the grain boundary and we get a coble creep. And dislocation creep will occur when dislocation bypasses and does not move on it is plane, but a through the lattice itself; whereas at higher homologous temperature we get a diffusion creep. So, this is a diffusion which occur through the bulk of the grain inside the grain. So, that is also known as the Nabarro-Herring type of creep.

Now, if we simply come the same way to a glassy solid, we learned about inhomogeneous deformation and inhomogeneous deformation lead to formation of shear bands and this is let us say a shear bands region and if we simply go for a higher temperature one is basically glass transition temperature ok. So, we will get a homogenous deformation in a relatively low normalized stress.

Where there will be negligible flow at lower temperature, we are talking about some and they are like a mostly like a elastic. However, at a higher normalized stress in Non-Newtonian type of behaviour can be achieved where as at a at a lower normalized stress level we will get a Newtonian type of flow.

So, this is an overall deformation mechanism map people have observed by looking at the strain of deformation different strain rate and so on where these are the values of the strain rate that is given and at different different temperature in order to measure these normalized stress level. And therefore, people came up with such kind of idea that we can make a deformation mechanism map very similar to crystalline solid.

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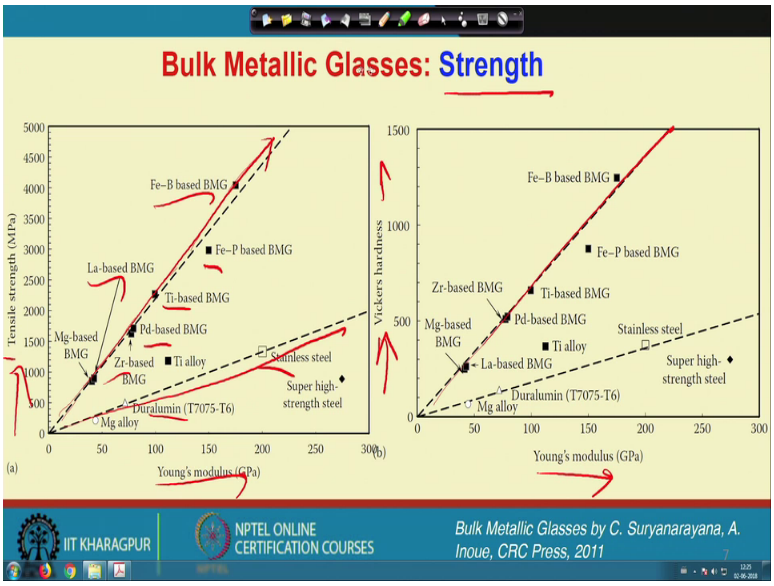

Now, let us try to discuss some of the very basic, mechanical properties that one has observed in case of a metallic glasses. So, the strength value has a very similar behaviour which shows very similar behviour with the Young's modulus. Because in case of crystalline alloy also we see that Young's modulus and strength they follow some linear type of relationship. So, in case of a metallic glasses also the trend is very similar like iron base glass, lanthanum base glass, palladium, titanium and so on.

So, they follow such kind of behaviour whereas, in case of a crystalline alloy since the elastic strain limit is relatively low. So, we will get a lower slope and this is very similar to tensile strength or it could be the Vickers hardness. So, in both the cases we have observed that the as the Young's modulus and the hardness or the strength shows such kind of linear type of behaviour.

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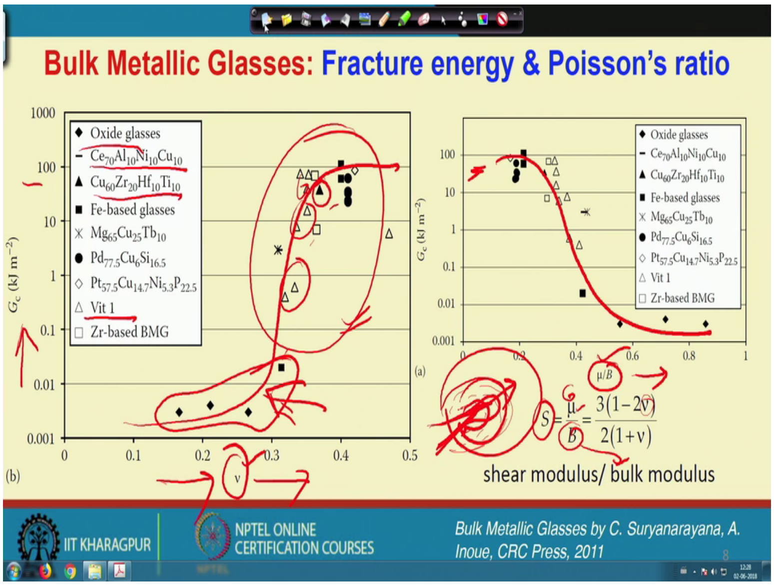

And now there are some people who have measured the fracture energy related with that metallic glasses and this fracture energy for different glasses the values are quite different. So, let us say like a cerium base glass, this is like a copper base glass. So, cerium based glasses copper based glasses. So, copper based glasses are somewhere here and a oxide glasses shows a very low fracture energy.

We have discussed that oxide glasses are ceramic in nature and definitely it has a very low value of a fracture toughness of 2 $MPa.m^{0.5}$ only. In case of metallic glasses since the bonding is metallic, usually a little bit of higher value of a fracture toughness is absorbed and also the fracture energy is also higher. So, like a Vitreloy glass which is a zirconium base glass these values like somewhere here.

And people tried to correlate with some of the elastic constant and here Poisson's ratio or let say the S which is the ratio of the shear modulus G or mu, mu and G are the same and B is the bulk modulus which is also a function of Poisson's ratio. So, people have observed as the Poisson's ratio of the glass increases the fracture energy is somehow linked with ok.

So, the fracture energy could reach up to 100 kJ/m^2, which is a very high value. So, definitely the metallic glasses that occupy this domain which is not at all similar like a oxide glasses or the fracture energy decreases with increase of the μ/B with the increase of the μ/B and there must be some of the mechanics involve for showing such kind of behavior.

So, if at all there is some crack and there are some large plastic zone, then it is expected that a material will show you a higher fracture energy. However, if this zone gets smaller and smaller and if it reaches to micrometer, then you will get such kind of behaviour with a low fracture energy. However, these Poisson's ratio has some indication that a crack tip which is little bit sharp if the Poisson's ratio increases this sharpness and crack tip get blunted.

So, instead of a very sharp; so, we can increase the higher plastic zone and you will get a higher fracture energy. So, this is the physical significance of μ/B ratio that a crack tip instead of a crack tip to extend, it basically get blunted.

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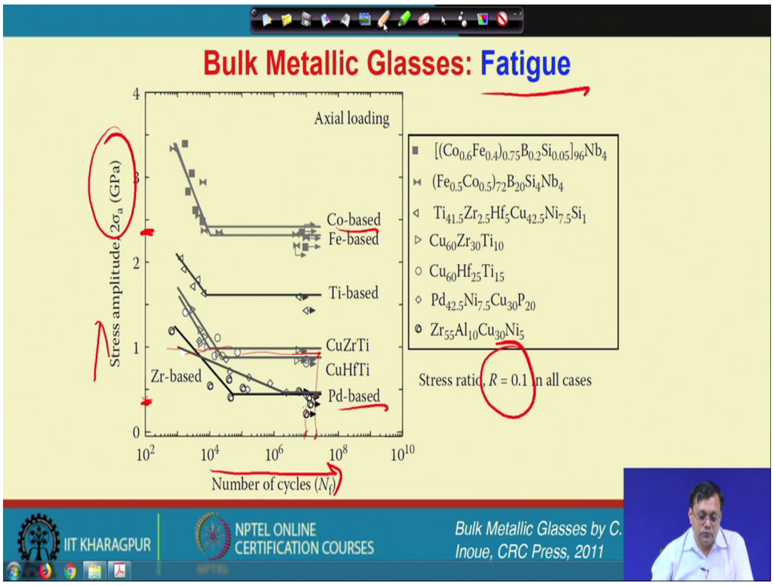

A very similar type of a behavior people have observed in case of a fatigue of this glassy alloys and you can see that the number of cycles at a stress ratio R is equal to 0.1. We get a quiet a good a stress amplitude value of let us say somewhat like 1 a GPa, we will get a quite large stress cycle, number of cycle is somewhat like 10 to the power 8 and which is a something like a high cycle a fatigue behavior.

So, in case of a palladium based glass, cobalt based glass, so to achieve such a high cycle of fatigue we can get a quite a higher stress a amplitude value ok. So, that is a 2 into sigma is in the level of half GPa to for a cobalt or iron based glass we can reach up to something like 2.5 GPa and these values are quite high compared to the crystalline alloys that you will see in the next slide.

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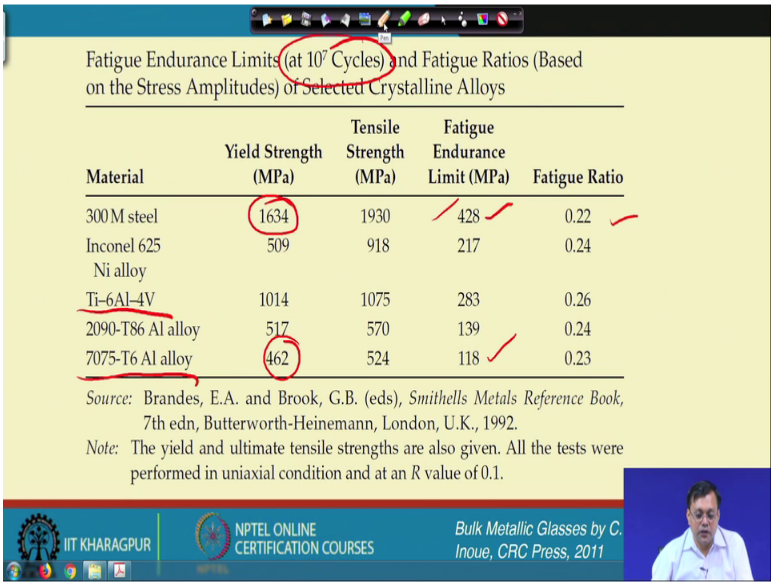

So, please have a look at in case of a conventional steel or inconel or let us say titanium, aluminium, vanadium or let us say some of the aluminium alloys, where the yield strength lies from 1600 to 462 and here the fatigue endurance limit in mega pascal is somewhat like 111 or a 428 mega pascal only, at a fatigue ratio of 0.22.

So, for a cycle of 10^7 cycle for fatigue endurance and fatigue ratios, we can get a much higher stress amplitude in case of a metallic glass and a definitely these material could be could be used at a at a much and much higher fatigue ratios.

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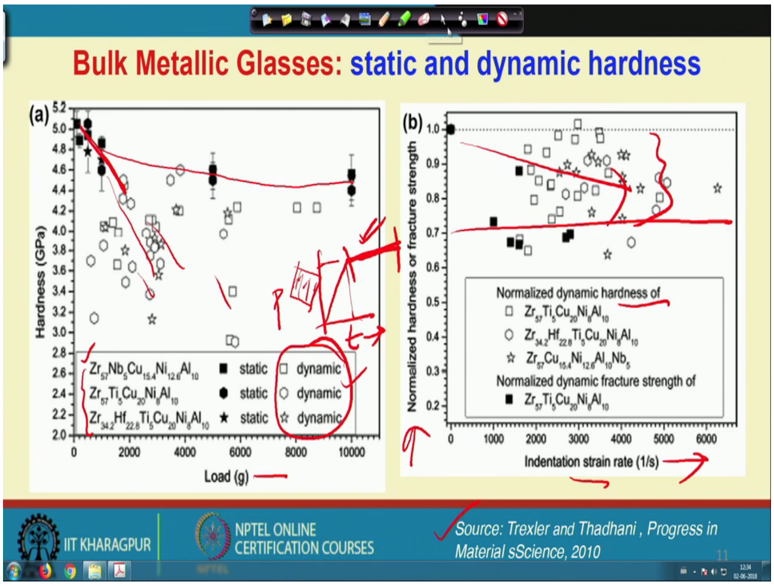

Now, we can also do some indentation studies and to look at the static and dynamic behaviour of this glassy alloys.

And here there are some interesting article on that that in case of this let us say as an example of this zirconium based glasses, the hardness actually a decreases with the increase of the load value. This is a very a typical indentation size effect, a indentation size effect means if we increase the load the size of the indentation will increase; Even though theoretically the hardness should not change but since the mechanism changes with the size of the indentation.

So, there is a decrease ok; however, we can also go for let us say a loading during indentation of a material loading means let us say this the time and this is the load and then we can hold for some time and measure the hardness during the holding time. And this is the hardness we call it as a dynamic hardness; it means that with time we reach to a peak load and we hold it for some time and we can measure the hardness in this particular case and we call it as a dynamic hardness.

So, the static hardness static hardness for a given alloy system that basically decreases slightly, where dynamic hardness also decreases ok; So, definitely there is a such kind of explanation came on that a free volume creation and the effect of these free volume a in those kind of a pressure effect, that lead to decrease of the static and dynamic hardness in case of a metallic glass.

And on the other hand there are there are some fractures strength that people try to look at. So, normally dynamic fracture strength because if we have to use this glassy alloys as a kinetic penetrator, both the static as well as the dynamic hardness is very much important.

So, if we increase the indentation strain rate. So, very very high indentation strain rate may lead to decrease of the overall fracture strength of the material, and this decrease if somewhat in the scale of 30 percent from the ideal strength. And a compared to a crystalline alloys these values are very very high and so, we can use these material as a kinetic penetrator also.

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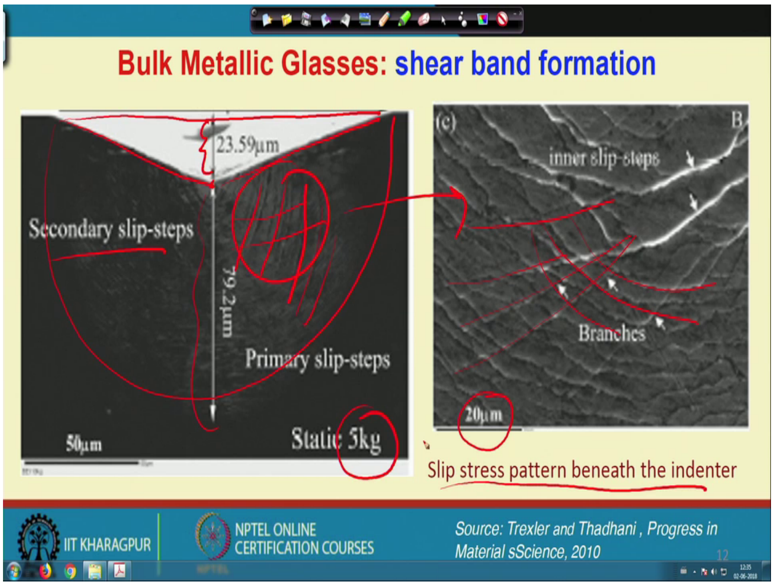

Now, one can also look at the evolution of the shear band beneath the indenter. So, here this is a laminated sample that has been indented and this is the indentation impression and the indentation penetration depth was something like 23 micrometer and definitely we will get a large plastic zone of such at a static load of 5 kilogram force. So, we can see this kind of a primary slip stresses of something like 80 or such kind of large zone and also some of the secondary stresses and that is a branching around the inner slip stresses.

So, a magnified view of such is shown in the right hand side, where we can see some of the slip stress pattern. So, it is radiating from the centre and we can see how the evolution of the slip stresses can evolve at a length scale of 20 micro meter. So, definitely the plastic deformation in these glassy alloys occur by the evolution of by the evolution of the shear bands.

And this inhomogeneous deformation occur at a temperature lower than the glass transition temperature however, the deformation could be homogenous, if we increase the temperature or that homogenous or let us say a steady state or non steady state flow can be seen which depending on the value of the n constant. And we try to look at the overall deformation mechanism map depending on the normalized stress as well as the temperature of deformation or a homologous temperature in case of a crystalline alloy, which is very similar in case of a glassy solid that is T by T g.

Temperature of deformation by glass transition temperature that is a normalized temperature; so, we try to look at all the different ways of a deformation of the glassy solids and tried to look at the fundamental ideas behind the deformation in those disordered structure. In the next class we will be discussing about the ideas of making composite out of these glassy solids and bulk metallic glasses and how we can exploit their properties.

Thank you.