Mechanical Behaviour of Materials
Prof. S. Sankaran
Department of Metallurgical and Materials Engineering
Indian Institute of Technology, Madras

Lecture - 40
Mechanical Testing - VIII

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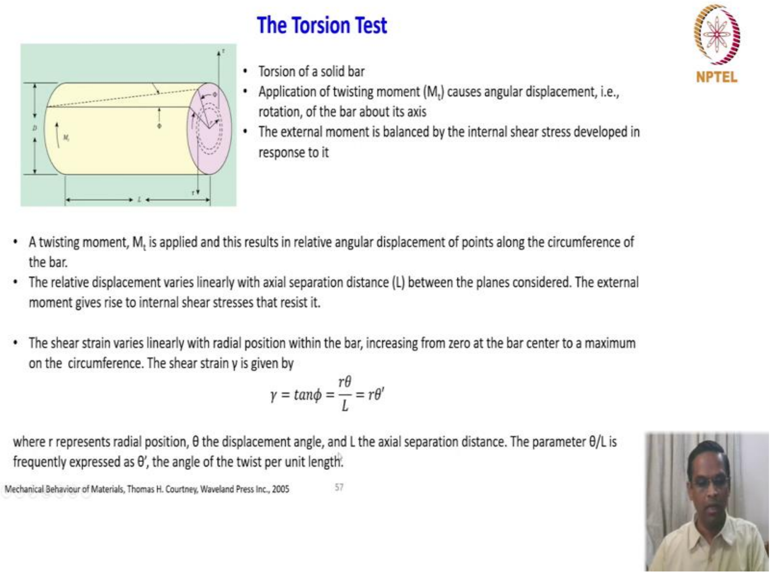

Hello, I am Professor Sankaran in the Department of Metallurgical and Materials Engineering. What is torsion test? So, torsion test is done on a solid bar which is shown like this and what is involved in this test basically application of twisting moment M_t, causes an angular displacement that is rotation of the bar about its axis. So, the twisting moment will have the units of Newton meter like force into distance that kind of unit you have which causes angular movement are angular displacement.

I will say rotation of the bar about its axis when you see that this is the angular displacement the external moment is balanced by the internal shear stress developed in the I mean internal shear stress developed in response to the external movement. So, basically the shear stress which is developed in the body resists the external moment, that is the idea. So, these two forces are balancing with each other.

So, now, we look at this that pretty closely. So, the twisting moment M_t is applied and this results in relative angular displacement of points along the circumference of the bar. So, this angular displacement occurs in the circumference of the bar. So, this is what it is and the relative displacement varies linearly with the axial separation distance. So, this is the axial separation distance. So, we are talking about the relative displacement which is varying linearly with the distance L.

So, the external moment gives raise to internal shear stress that resisted the shear strain varies linearly with the radial position within the bar increasing from 0 at the bar center to the maximum on the circumferences. So, it is from r is 0 here and then it goes to maximum on the circumference. So, that is basically a shear strain. So, what is this the before even getting into detail the torsion test is something you know you what the way in which we have to look at it is you look at the mechanical behaviour which involves a large shear strain.

One of the large shear strain which is involved and how the material behave. So, far we have looked at most of them are there is a plastic strain shear strain everything was there, but nothing compared to this kind of a larges strain. So, we are looking at material behaviour mechanical behaviour involving large strain that is something we have to look. So, the shear strain γ is given by so, you can simply look at this geometry this this curve length is θso, r θ/ L is tan ϕ.

So, this is tan ϕ. So, normally thisθ / L is denoted by θ' that is the θ' where r represents the radial position theta displacement angle and L the axial separation distance the parameter θ / L is frequently expressed as θ' , the angle of the twist per unit length.

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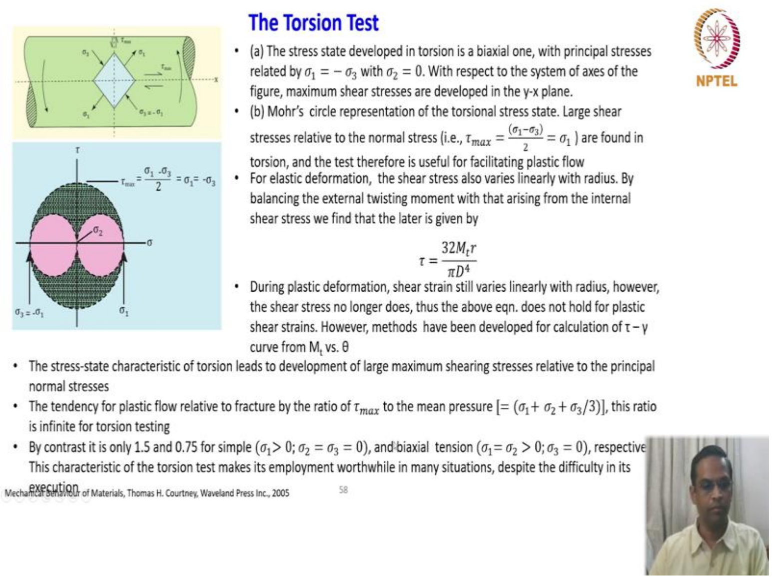

So, now, look at the mechanics as usual very important and interesting the stress state developed in torsion is a biaxial one very important with the principal stresses related by σ_1 is equal to -σ_3, σ_2 =0. So, you see this σ_3 and then σ_1 and then shear stress wherever it is so this schematic clearly shows the state of stress with respect to a system of axis of the figure, maximum shear stresses are developed indeed y-x plane.

So, y-x plane, the maximum shear stresses produced we can now fix them in a Mohr's circle to understand more clearly the Mohr's circle representation of the torsional stress strain larger shear stresses related to the normal stress that is τ max is equal to $(\sigma_1 - \sigma_3)/2 = \sigma_1$. Normal so, the relative to normal shear stress are found that means larger shear stress found in the torsion and the test therefore, is useful for facilitating plastic flow.

So, you can see that $\sigma_1 = -\sigma_3$. So, σ_1 is this and then this is $-\sigma_3$ and σ_2 is 0 so, it is at the center the maximum is here. So, which is τ_{max} is equal to $(\sigma_1 - \sigma_3)/2$. So, this is nice. So, for the elastic deformation the shear stress also varies linearly with radius by balancing the external twist moment with the with that arising from the internal shear stress we find that the latter is given by this formula.

This is simple mechanics. So, $\tau = 32 M_t r / \pi D^2$. So, in the during the test possibly we see this during plastic deformations shear strain still variously linearly with radius however, the shear stress does not that is the equation does not hold for plastic shear strains. However, methods have been developed for calculation of τ-γ curve from the M_t versus θ.

So, the in a typical torsion test what we measure is M_t and θ from there, there are methods which are developed in the standards to how to conduct this test itself which is which will finally will evaluate at τ, shear stress versus shear strain. So, that is the idea. The stress state characteristic of torsion leads to development of large maximum shearing stresses related to the principal normal stresses.

The tendency of plastic flow related to the fracture the ratio of τ_{max} to the mean pressure that is $(\sigma_1 + \sigma_2 + \sigma_3)/3$, this ratio is infinite part of twisting very interesting observation here. So, it clearly shows that the large plastic flow or shear flow is involved in this test. So, that is about that is some basic mechanics about the test and test details. By contrast, it is only 1.5 and 0.75 for a simple that is, σ_1 is greater than 0, σ_2 and σ_3 is 0 and biaxial tension $\sigma_1 = \sigma_2$ which is greater than 0 and σ_3 is 0 respectively.

So, this is for 1.5 for the simple tension and the 0.75 for the biaxial tension. This characteristic of the torsion test makes it simpler employment worthwhile in many situations despite the difficulty in its execution. To look at the real you know, characteristic of how the material behaves under the large shape deformation, it gives much more useful information.

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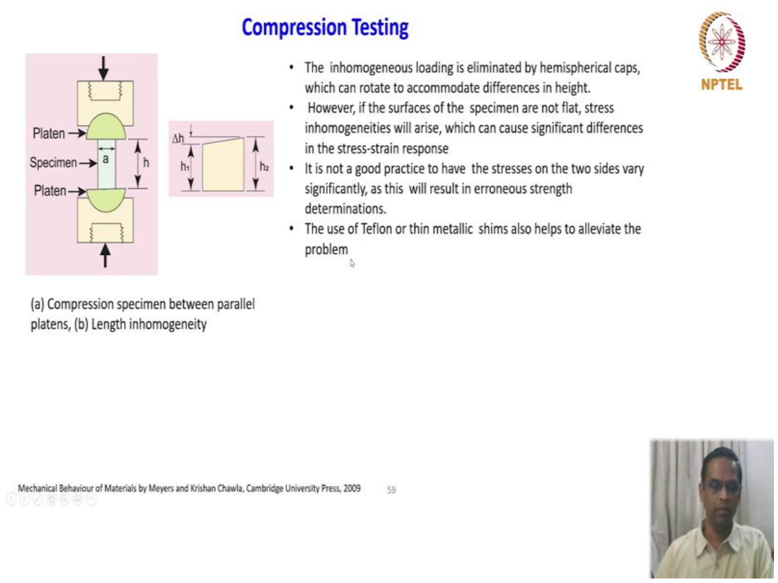

Now, move on to compression testing. This is also quite popular and important these days especially researchers who do not have sufficient material to produce bulk samples are normally they produce a synthesis material in the laboratory and then we make powders and then compact them produce small cylinders and then try to estimate the mechanical behaviour.

So, compression testing is quite popular in nanomaterials research because of the lack of availability and lack of material available. So, what is involved in compression testing? So, the cylindrical sample which is the diameter is about a and height is h is being compressed by the between the two platens and what is this special design is given here suppose if the cylinder what we are prepared after the compaction if it is not uniform and symmetrical.

That means the h_1 is smaller than h_2 then this delta h which has to be corrected otherwise the load distribution will not be uniform which may lead to abnormal. So, that is this is called length in homogeneity. So, the inhomogeneous loading is eliminated by hemispherical cap. So, now we understand so, this hemispherical cap really takes care of this kind of inhomogeneity which can rotate to accommodate the difference in height.

So, this hemisphere geometry will take care of this inhomogeneity. However, if the surfaces of the specimens are not flat stress inhomogeneity will arise which can cause significant differences in the stress-strain response. So, we have to be very careful about the flatness of the specimen surface before we can engage them into compression testing it is not a good practice to have the stresses on the two sides vary significantly as this will result in an erroneous strength deformation.

So, especially the strength between the two sides, the stresses between the two sides should not vary significantly the use of Teflon or a thin metallic shim also helps to alleviate the problem.

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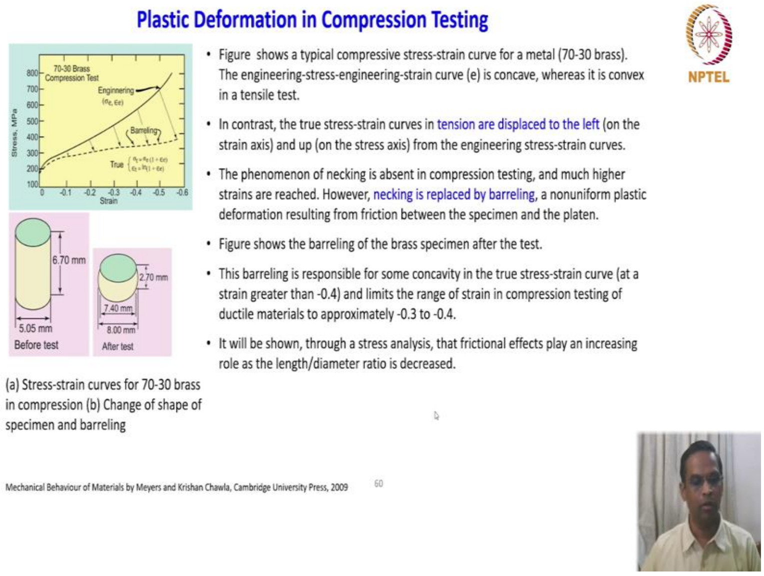

So, what is mechanics or plastic deformation. So, this is a typical stress strain curve or a compression testing. So, in this case it is 70-30 brass and we will see the details. The figure shows the typical compressive stress strain curve for a metal (70-30 brass) the engineering stress-engineering strain curve e is concave whereas, it is convex in tensile test. So, that is a simple and first observation.

It is a concave, in contrast the true stress and true strain curves in tension are displaced to the left on the strain axis and up on the stress axis from the engineering stress-strain curves. So, you can see that when you take the true stress true strain curve the engineering stress-strain curve, it looks very different here. See what you need to understand from this flow curves the basic mechanics involves yield criteria everything is same whether you pull it in attention complexion or pull it in biaxial triaxial and so on.

So, instead of the material response in terms of stress strain data in generally you can call it as the flow curve flow response flow properties that is why in some of the slides we have seen that the effect of strain rate and temperature on flow properties. So, we can see that the flow curve again compression load. The phenomenon of necking is absent in compression loading and much higher strains are reached. There is no necking in this test.

However, necking is replaced by barreling non-uniform plastic deformation resulting from friction between the specimen and the platen. So, what is this? This region is marked as barrel. So, which is very important how does it appear. So, suppose this is the initial sample with the E = 5.05 millimeter and height is 6.70 millimeter. So, after it subjected to compression, so, you can see that both sides are bulging that is called barrel.

That takes quite a bit of non-uniform plastic deformation and that is because of the friction between specimen and the platen. This barreling is responsible for some concavity in the true stress strain curve at a strain greater than 0.4. So, you can see that this region we are talking about and limit the range of strain in compression testing of ductile material to approximately - 0.3 to 0.4. It will be shown through a stress analysis that frictional effects play an increasing role as the length to diameter ratio is decreased.

So, this is one big challenge what kind of links to diameter want to choose for getting a reasonably good data which should describe the deformation characteristics in the compression mode we will see what are the challenges.

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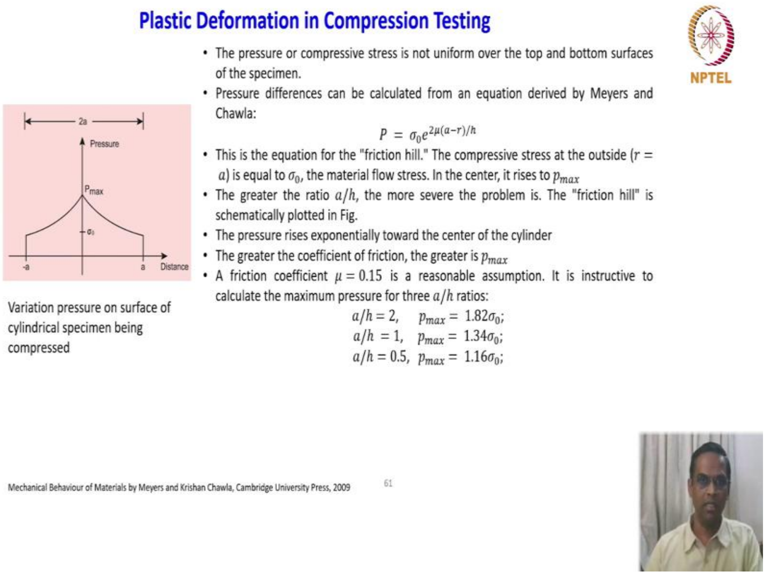

So, what you are see here is this is X axis is a distance and Y axis is pressure the pressure or a compressive stress is not uniform over the top and bottom surface of this specimen. This is a first limitation we have to understand it is not like the material you know subjected to almost uniform strain the gauge length in the tensile specimen but in compression the pressure or compressive stress is not uniform over the top and bottom surfaces.

So, the variation of the pressure on surface of the cylindrical specimen being shown here. So, this is a pressure so, this is a, positive axis and negative axis the pressure differences can be calculated from an equation derived by Meyers and Chawla which is in this which is given in this $P = \sigma_0 e^{2\mu(a-r)/h}$ and this is the equation for the friction hill. So, what is friction hill.

So, this is the hill we are talking about friction hill, the pressure increases and reaches a maximum at p, p_{max} in the center of the specimen the top surface of specimen. So, it forms the; it comes basically because of the friction between the platen and the specimen surface. So, that is why it is called friction kills. So, the pressure reaches a maximum in the center the compressive stress at the outside that means when r = a.

We are talking about this center and if this becomes equal to a then if you put a, r = a then this equation become p is equal to σ_0. So, that means up to this point. So, there is no friction hill effect. But then as long as the compressive stress is are measured in this kind of a dimension, we are going to have this friction hill effect because it has got a different the effect of a / h ratio.

The greater the ratio of a / h the more severe the problem is what I just said the friction hill problem will be more for the higher a / h ratio. The pressure arises exponentially towards the center of the cylinder. The greater the coefficient of friction the greater is the p_{max}. So, the idea is, we can reduce the friction to reduce this effect and make sure that the proper gateway which is chosen and the geometry of the specimen is also taken care make it uniform flat and so on.

To get the reasonably good data. A friction coefficient $\mu = 0.15$ is a reasonable assumption it is instructive to calculate the maximum pressure for three a / h ratios. So, it is recommended to have at least by this authors Meyers and Kishan Chawla they recommend that you measure a / h for three which is a / h = 2, a / h= 1 and a/ h = 0.5. So, measure this p_{max}. So, this is the kind of you know some details about the compression testing which is quite different from the tensile testing. So, I thought you should know.

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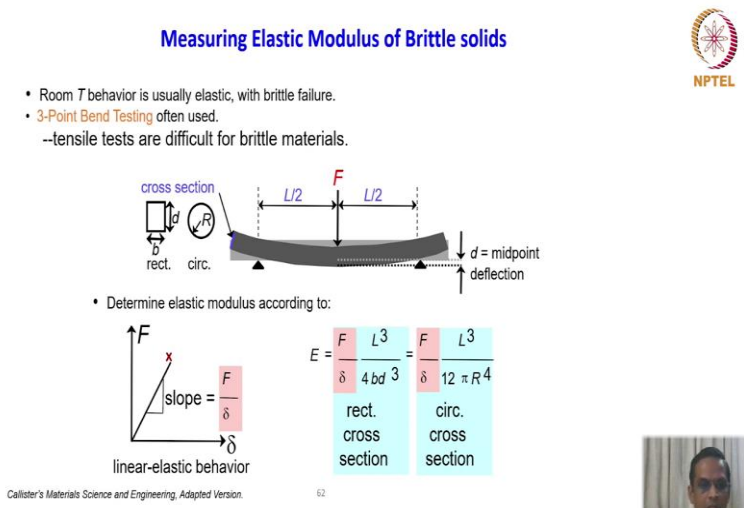

So, now we will move on to brittle solids. So, we looked at metals we looked at polymers and we also looked at compression testing for small specimens and we will now look at the brittle solids how do we measure tensile strength of a brittle solid because fabrication of sample itself is going to be a limitation we can fabricate them, we can machine them. So, the room temperature behaviour is usually elastic with the brittle failure.

So, we have a method called three point bending test which is often used. So, three point bending test is done with this kind of a geometry it can be the specimen can be of cross sectional I mean the specimen can have a cross section dimension like this or it could be a circular cross section and this is the geometry there were forces applied here and which is supported by these two you know fulcrum kind of set up here and this is a mid-point d, mis-point deflection is shown here from here to here, our deflection is measured.

So, this kind of geometry and the relations are given by the strength of materials concepts and we are just going to look at the equation straight away we are not interested in looking at this derivation because they are all available in standard hand books. So, here what we are seeing is force versus displacement data and slope is F / δ and the young's modulus is given by F / δ because it is elastic still so, which is equivalent to L^3 / 4 b d^3 for the rectangular cross section and the same can be given for the circular cross section which is L^3 / $12\pi r^4$. So, this these two relations will take care of the elastic modulus measurements for the brittle solids. This is also quite a common test people use.

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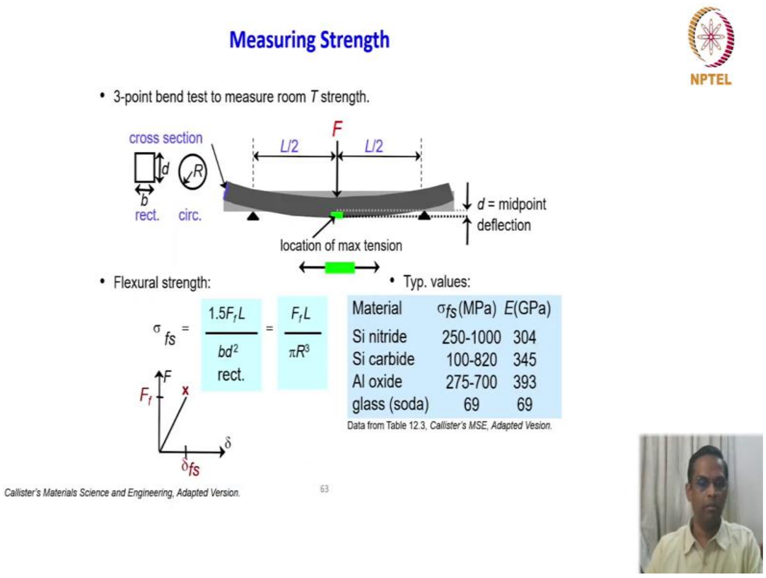

For measuring the same type again three point bend test the formula is different here it is called the flexural strength. This is not called the yield strength or tensile strength here it is called the flexural strength that is σ_{fs} is given $\boldsymbol{\sigma_{fs} = \frac{1.5F_f\ L}{bd^2}}$ for the rectangular cross section and $\boldsymbol{\sigma_{fs} = \frac{F_f\ L}{\pi R^3}}$ for the circular cross section.

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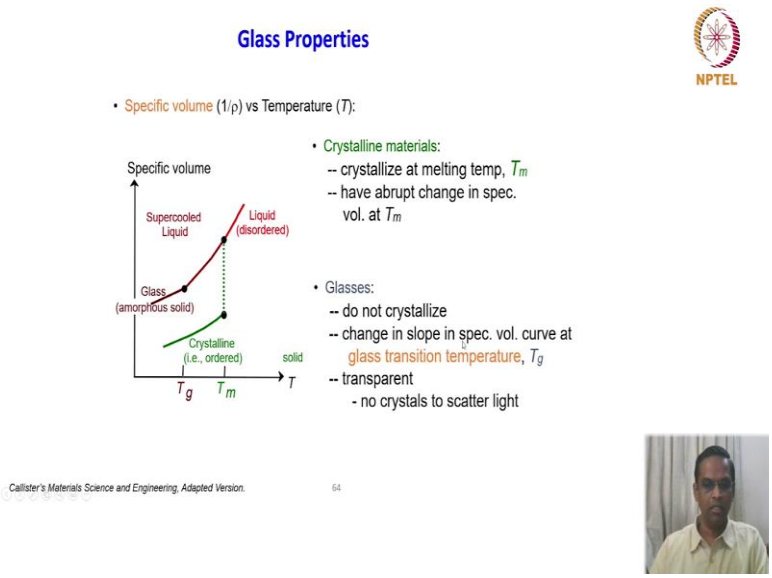

And we quickly look at glass properties because if you look at we are thinking about a definition of amorphous material then glasses very important to know. So, what is that we need to know about before even look at the mechanical behaviour this popular curve everybody should know first that this was specific volume versus temperature and the liquid is cooled and then it goes through you know this is a crystalline form and this is amorphous solid and this is super cool liquid.

So, the specific volume versus temperature plot and for crystalline materials you know we all know that it crystallizes that melting point and have an abrupt change in the specific volume and melting point. These and all we know that, for the glasses they do not crystallize the change in slope in the specific volume curve at the glass transition temperature T $_g$ and they are transparent and no crystals to scatter light they are all basic characteristics.

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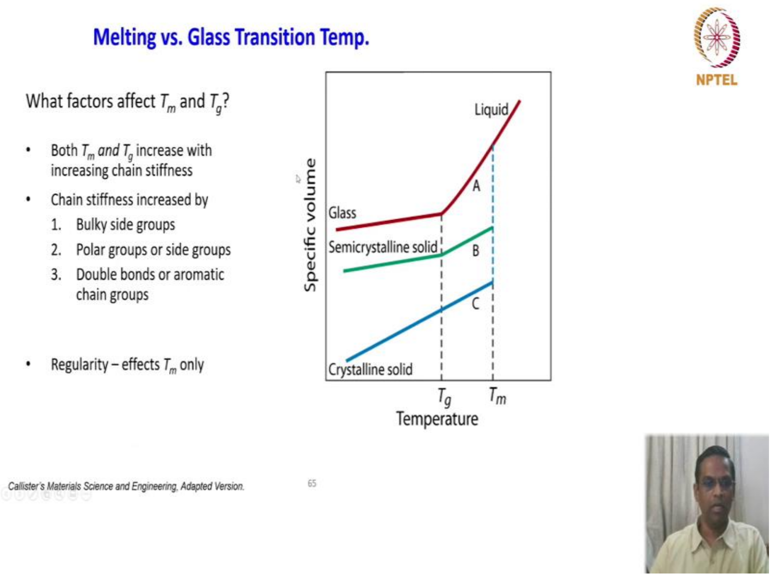

And again what we need to know is what factors affect the melting point and T $_g$ both T $_m$ and T $_g$ increased with increasing chain stiffness in the case of you know, when we talk about chain again we are talking about silicate molecular chain and all that and chain stiffness increased by bulk side groups or it could be related to some semi-crystalline polymer as well. So, that is why, I call this the molecular arrangements are come here polar groups or outside groups double bond rate and aromatic chain group. They are all going to increase the chain stiffness and which in turn have influence on T $_m$ and T $_g$. So, that is why not here.

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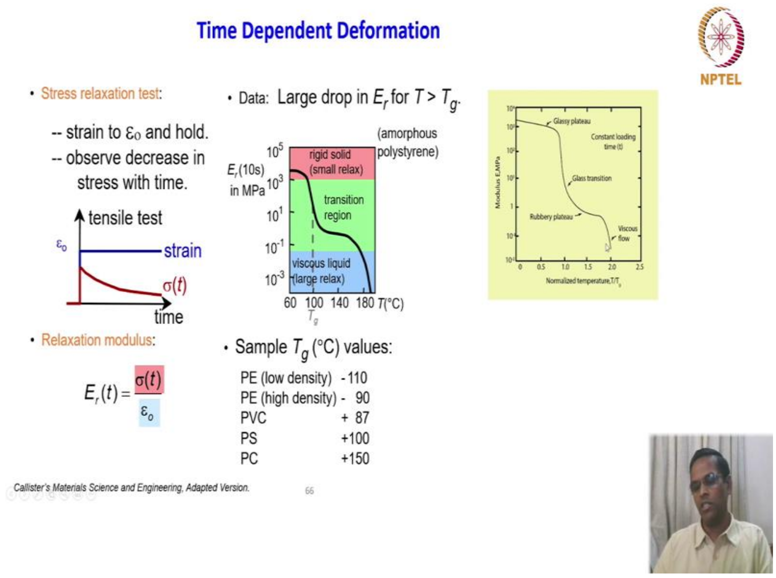

So, but our interest is deformation. So, whenever we are going to discuss about deformation about the semi-crystalline or uncrystalline materials, we should recall our initial lectures where we talked about time dependent deformation. How does it relate here? So, this is a young's modulus versus E versus T plot where you see that E_r is the reduced elastic modulus and why we are talking about it we will come back to in a minute.

So, there is something called you know stress relaxation, we have already seen this term. So, I mean I can do it pretty fast we know what is just relaxation. Relaxation time and all we have seen what is relaxation time. So, strain to ε_0 and hold. So, strain the material to a specific strain or fix the strain and hold it and observe they decrease in the stress with time. So, that is less stress relaxation tests typically it is done normally in the amorphous materials and then we try to calculate something called relaxation modulus.

That is E_r it is a function of time which is equal to σ_t / ε_0. So, that is what typically calculated in a stress relaxation test and then E versus T is measured here. So, that will show some kind of where all the polymeric materials will start. So, for the rigid solid the small relaxation and this is a transition region. So, this is a viscous liquid large relaxation. So, the T_g is somewhere here.

So, we can relate to the mechanical deformation behaviour where does this our material lie in this map. So, depending upon that it will you will see the mechanical response. So, some of the typical polymeric materials are given and the T_g values and then we will be able to can we can relate that to mechanical temperature. So, the same plot is given in a different form and but you can see that this region is a glassy plateau and this is a glass transition region and this is a rubbery plateau and then this is a viscous flow.

So, you can conceive that the different regions of this curve characteristics are different I mean I would say the glasses and how the material behaviour is going to change as a function of homologous temperature again this is it is not homologues here it is temperature normalized by T_g not melting point. If it is normalized by melting point it is called homologous temperature.

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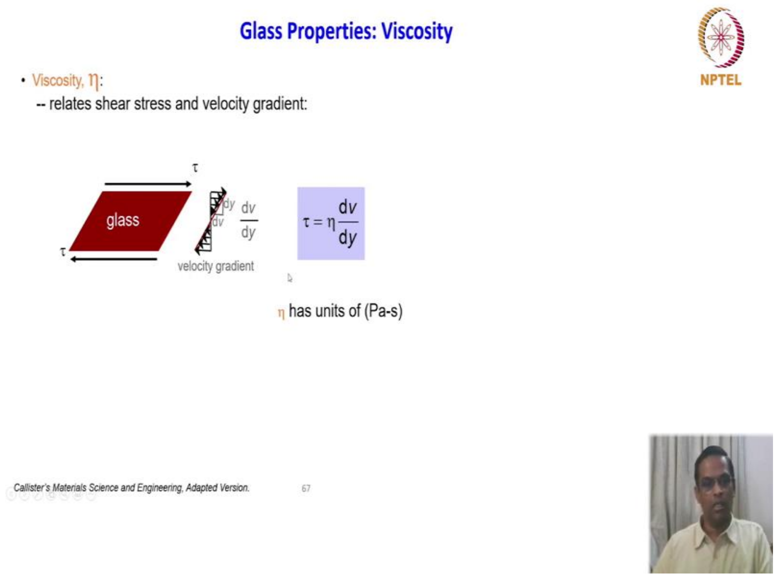

So, having discussed about the different temperature effects the viscosity in non-crystalline materials becomes important because, that only related which only can be related to the shear stress and the velocity gradient. So, whenever we talk about deformation. This is the one primary equation you are given by $\tau = \eta$ dv / dy. So, it is a velocity gradient suppose a glass can be subjected a shear stress and then this is the formula.

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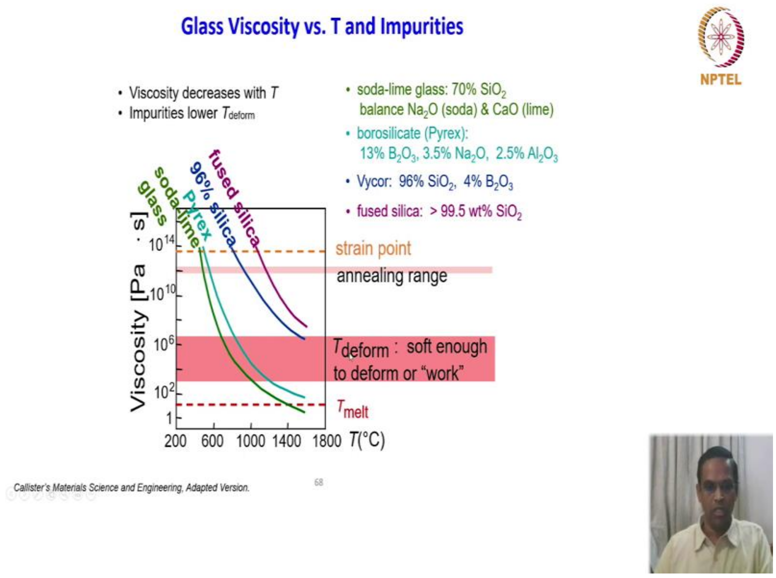

So, how the viscosity decreases with the temperature cell shown from the, this plot because viscosity as long as the material is not in the viscous form that you cannot just work the material or even deform them. So, some of the examples of different types of silicates and glass and soda-lime are given and then it is just given the red region where the temperature with under which the material exhibits a softness.

Or soft at least soft enough to deform our work we can a glass forming the plant will have the typical you know viscosity of the glass melt and then they blow it. So, if the glass blowing. So, this is quite important and kind of application.

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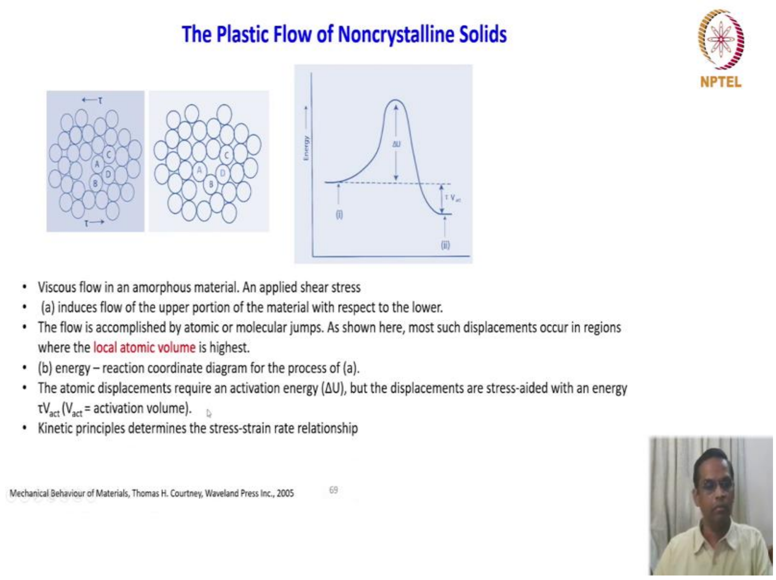

So, let us now look at the plastic flow of non-crystalline solids in a much more fundamental what I have shown is like an application point of view, but let us look at the science behind it what is the wall so, it is a non-crystalline solid. So, you can see this atomic configuration is not done by any order the atomic configuration will be completely disorder. So, we are going to look at the effect of you know shear stress I suppose, if you apply the shear stress to this kind of a cluster of atoms then what happens so, what is that we are basically seen.

So, suppose if you follow this A, B, C, D atoms in a disordered range and then when we try to apply the shear stress what happens, so, these atoms are now trying to redistribute in the nearby regions. So, what is the driving force the driving forces the free volume which is available next to this cluster. So, that is the A atom you can see that it is coming it come to this and then it creates another you know configuration then again it created free volume theorem there. So, that is how the deformation takes place. So, the amorphous materials respond to the shear stress in this manner with respect to the free volume available. So, this is called the viscous flow in an amorphous material and this is a response to applied shear stress which induces a flow of upper portion of the material with respect to the lower the flow is accompanied by the atomic or molecule jumps as shown here the most such displacements occur in regions where the local atomic volume is highest.

So, wherever the local atomic volume is highest, this kind of rearrangement is going to happen or a displacement is going to happen that is how the deformation is being accommodated. So, what is the driving force the energy reaction on coordinate diagram is for the process is given here whatever the process we are talking about this is the energy reaction coordinate. So, what you are seeing is the atomic displacements require activation energy that is Δu. But the displacements are stress aided with an energy τV_{act} , V_{act} is the activation volume. So, though the atomic displacement requires activation energy Δu, the displacements are stress aided with an energy again it is also aided with this shear stress times the activation volume what is activation volume we will see this aspect in the next lecture especially, basically the volume under which the complete disorder can be taken.
Wherever the most disordered regions are there, the volume there the in a typical way in a crystalline material we can talk about the most dislocation the volume, the dislocated volume we can support so, here it is about highly disordered volume because in amorphous material we do not talk about dislocations. So, that is why we are talking about a free volume. So, wherever the disorder is maximum.

So, here that is activation volume, which the same terminology we used in crystalline material also, but there they we relate that with the dislocation density configuration. So, what we will see in the next lecture when we talk about basically kinetic principle determines this stress strain rate relationship. So, what is the how do we understand this.

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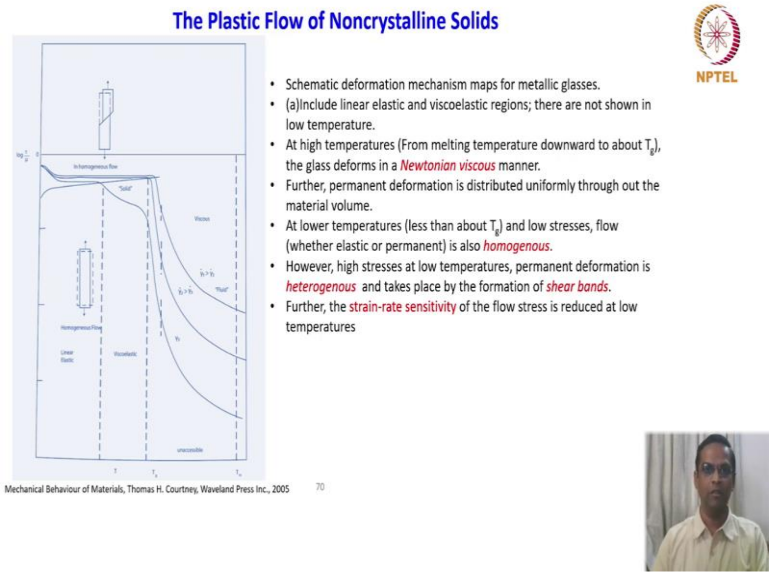

If you look at this diagram this is quite interesting and though it is quite, you know a lot of information is there but if you slowly understand what is plotted here this is shear stress normalized with the shear modulus τ / μ versus temperature. Since, we just discussed about you know the deformation of non-crystalline material completely depend on the temperature at only as a function of temperature, we can talk about it because these materials have to undergo a different transformation to know basically elastic to visco elastic and then plastic and so on. So, if you look at these different boundaries marked in this region it is quite interesting. So, at the low temperature, the noncrystalline solids exhibiting a homogeneous flow. So, this is a temperature range and then it will be a linear elastic behaviour in this range and then little below the T_g then it is visco elastic behaviour.

So, it is visco elastic behaviour and then just a little above the higher stresses it is solid and above this, it is at high stresses, it is inhomogeneous flow. So, how do we understand inhomogeneous flow in a non-crystalline material? So, this is typically this plot is drawn for a typical metallic glass. Metallic glass is a non-crystalline amorphous metal. So, we will just see trying to see what is each boundary will describe.

It is called deformation mechanism maps for metallic glasses, which include the linear elastic visco elastic regions and there are not shown in the low temperature. Suppose, if you plot this same graph in low temperatures, these are all not there, that is what is shown here, which are not discussed in the very low temperatures at high temperatures from the melting temperature downward to about T g. So, this region we are talking about this region the glass deforms in a Newtonian viscous manner so, just below the T g about this stress range the material will obey the Newtonian viscous flow just 2 slides before we have seen that how the shear stress is equal to ηtimes dv / dy that strain gradient, shear gradient we have seen that. So, that is the Newtonian flow for that the permanent deformation is distributed uniformly throughout the material volume. So, this is about how it will deform after that, at lower temperature that is less than the T g and lower stresses this corner, the flow, whether elastic or permanent is also homogenous. So, it could be elastic or permanent, but it is homogeneous flow here. However, at high stresses, at low temperature so high stresses here at low temperature so this is a region permanent deformation is heterogenous and takes place by the formation of shear bonds. Very important point. So metallic glasses are non-crystalline solids at high stresses and low temperatures they deform are the permanent deformation is heterogenous and they are characterized by the shear bands, very important point. So, we were talking about crystalline material, slip and shear bands and all that. There also we talk about shear bands, deformation max and so on. Here there is nothing like that. Here we are only talking about the shear band formation. Further the strain-rate sensitivity of the flow stress is reduced at low temperatures. Obviously, this week we have already seen at the high temperature deformation when m is the you know we characterize the m at high temperature it is almost equal to 1.

We have seen that. There also we talked about the Newtonian flow. When m = 1 it becomes Newtonian flow. But at the low temperature, it will obviously will get reduced. So, we will stop the discussion on the tensile behaviour with this. Because I thought I will just bring in little more material other than metals to get the basic ideas about how the deformation takes place in the other class of materials. So, we will stop here and then we will continue in the next lecture. Thank you.