Fracture, Fatigue and Failure of Materials
Professor Indrani Sen
Department of Metallurgical and Materials Engineering
Indian Institute of Technology, Kharagpur
Lecture 25
Fracture Toughness (Contd.)

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NPTEL ONLINE CERTIFICATION COURSES

Fracture, Fatigue and Failure of Materials

INDRANI SEN

DEPARTMENT OF METALLURGICAL AND MATERIALS ENGINEERING, IIT KHARAGPUR

Module 01: Fracture

Lecture 25 : Fracture Toughness

Hello everyone, welcome to the 25th lecture of the course Fracture Fatigue and Failure of Materials. And in this class, we will be again talking about fracture toughness. But, now on we will be talking about the fracture toughness of nonmetallic materials particularly in the last class, we have talked about fracture toughness and the toughening mechanism for ceramics and in this lecture, we will be talking about toughening of glass.

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Concepts Covered

- Toughening of Glass

Toughening of Glass

Long range order

No Plasticity Mechanism

Low Intrinsic Toughness

So, when we are talking about glass, we know that in glass they are actually long-range order and we have seen earlier that how long-range order could lead to brittle behavior and brittle behavior and toughness are inversely proportional, the more is a brittle behavior means lesser is the toughness.

So, apart from that glass also do not have any deformation mechanism that involves plasticity, as I mentioned that glass is typically brittle in nature and all this led to low intrinsic toughness of glass. We have seen this for the case of ceramics also that, because of the internal nature of the material, there could be low intrinsic toughness, but as we are always aiming for improving the toughness of any materials, we plan to enhance the darkness by some extrinsic mechanism.

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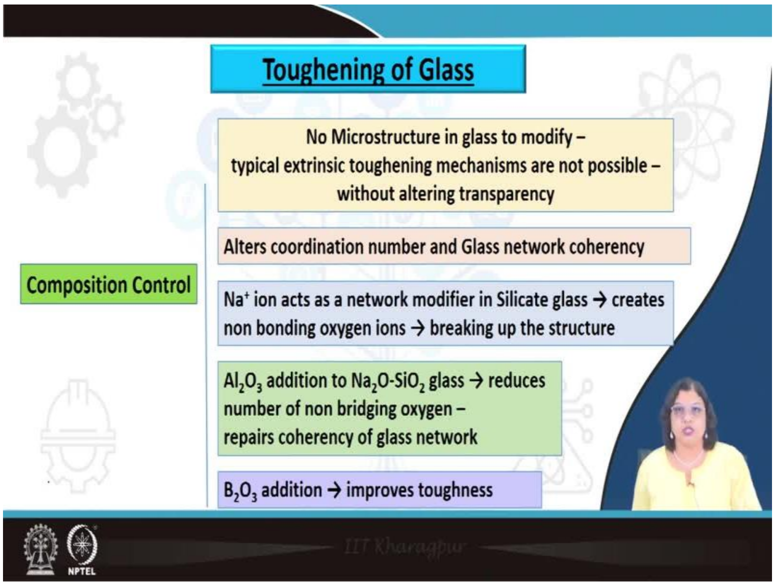

Toughening of Glass

No Microstructure in glass to modify – typical extrinsic toughening mechanisms are not possible – without altering transparency

Composition Control

Alters coordination number and Glass network coherency

Na^+ ion acts as a network modifier in Silicate glass → creates non bonding oxygen ions → breaking up the structure

Al_2O_3 addition to Na_2O-SiO_2 glass → reduces number of non bridging oxygen – repairs coherency of glass network

B_2O_3 addition → improves toughness

Now, for the case of glass, there is another problem in the sense that it does not have any routine microstructure. We have also seen in the previous lectures that how we can enhance the toughness or for that matter, we can modify the mechanical behavior of any materials by modifying or altering the microstructure of the material. We can refine the grain size and through that we can achieve both higher strength and toughness along with ductility and lower ductile to brittle transmission temperature, at least for metals we have seen that, but coming to the glass.

Since, there is no microstructure we cannot modify that also and hence, the typical extrinsic toughening mechanism are not possible to be achieved. And we can still do that kind of extrinsic toughening, but in that way, we have to let go the transparency of the glass which is one of the very valuable and important characteristics of glass. So, that means that microstructure modification and enhancement in toughness in case of glass is kind of ruled out. So, another thing by which we can enhance the toughness of class or control the mechanical behavior of glass is through altering the composition.

So, by altering the composition basically what we aim for is to alter the coordination number and the glass network coherency. So, that we can achieve higher and higher toughness or make it more difficult to break in a brittle fashion. And for example, the most common kind of glass that is used even for daily lives is the soda lime silica glass.

And here, the Na^+ ion or the sodium ions actually acts as the network modifier and it creates the non-bonding oxygen ions thereby breaking up the structure and if that is so, the long-range order could have been broken to some extent and that can alter the toughness of the material.

Alternatively, addition of Al_2O_3 to this soda and silica glass reduces the number of non-bridging oxygen and that acts as repairing the coherency of glass network. And in this way, we can alter the properties as well. It is also seen that addition of B_2O_3 actually improves the toughness and there are several theories for the mechanism for that.

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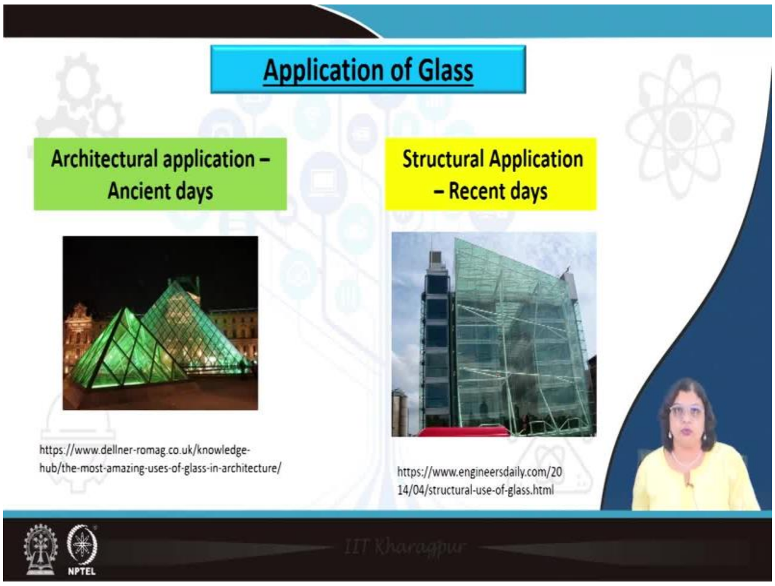

Application of Glass

Architectural application – Ancient days

https://www.dellner-romag.co.uk/knowledge-hub/the-most-amazing-uses-of-glass-in-architecture/

Structural Application – Recent days

https://www.engineersdaily.com/2014/04/structural-use-of-glass.html

Now, apart from altering the composition, we always target to achieve higher and higher toughness particularly for the following reason that glass is still used for many such application particularly because it has a very high hardness and strength is very high compared to any other metallic system.

So, for that reason glass is being used for several architectural applications since ancient days and not to mention glass is because of his transparent nature. It appears beautiful and we often use it for its aesthetic sense as well. So, this is the glass structure for the Louvre Museum, the famous one in Paris and you can see that the glass structure there is serving for several years and decades.

And it is still quite beautiful and the same. In recent days glass are also being used for several structural applications. This one here is the building made of glass and we can see many such buildings in the High-tech cities these days, where the external structure is made of glass. So, obviously, that means that the toughness of the glass has to be improved, it is definitely very, very strong. So, we can use it safely. But considering the lower toughness of a material can lead to unpredicted failure in a brittle manner, we somehow need to enhance the toughness of the class. So, let us see what are the different ways by which we can achieve improved toughness in case of glass?

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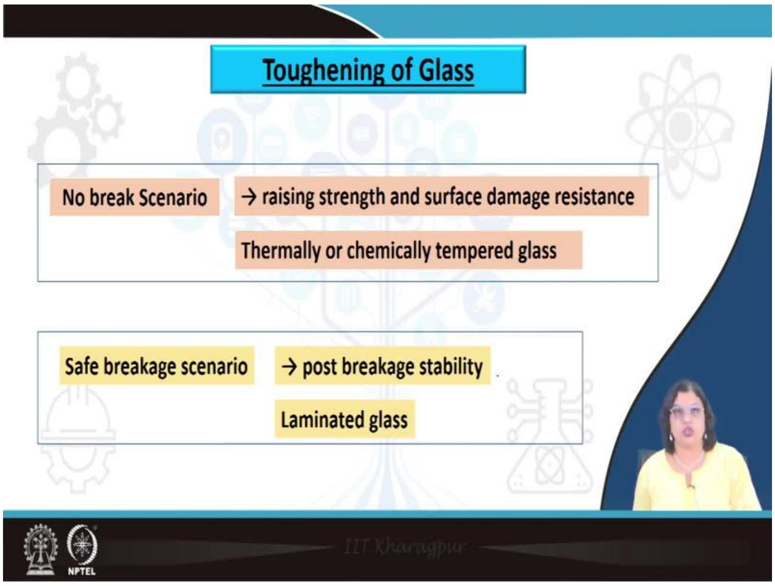

Toughening of Glass

No break Scenario → raising strength and surface damage resistance

Thermally or chemically tempered glass

Safe breakage scenario → post breakage stability

Laminated glass

First of all, there are two ways by which toughness can be improved and looking at the application point of view. The first one is no break scenario, which means that there will not be any breakage at all, we cannot affect or we cannot alter the behavior in such a way that it should not break under any circumstances or we can quote the maximum or the limit of the stress that has to be applied till it survives. So, for that, what we try to do is, we try to raise the strength and surface damage resistance, as we have seen that for the case of glass or such brittle failure, it is a surface defects which lead to the final failure.

If there is a surface defect and that acts as a stress concentrator and as we are applying stress, because of the presence of the stress concentrations, the stress the applied stress can rise many fold and that lead to a maximum stress that is sufficient to break the bones and lead to a catastrophic failure. So, when we want to have a no brakes scenario, what we aim for is to raise the strength particularly the surface damage resistance of the material and this can be achieved by either thermally or chemically tempering the glass. So, there is a mechanism called tempering, which I will emphasize soon after through which the toughness of the glass can be improved.

And the other way by which the toughness of the glass can be improved is a criteria known as safe breakup scenario. So, in this case, there could be breakage of the glass, but there could be some post breakage stability which means that even if the glass, plate or sheet or whatever we are talking about the glass component breaks, it should not lead to a catastrophic failure, there should be some stability even after the breakage and that can be achieved if we use a laminated glass. So, that we can have some structural stability even if the class breaks. So, let us see how each of these can be achieved.

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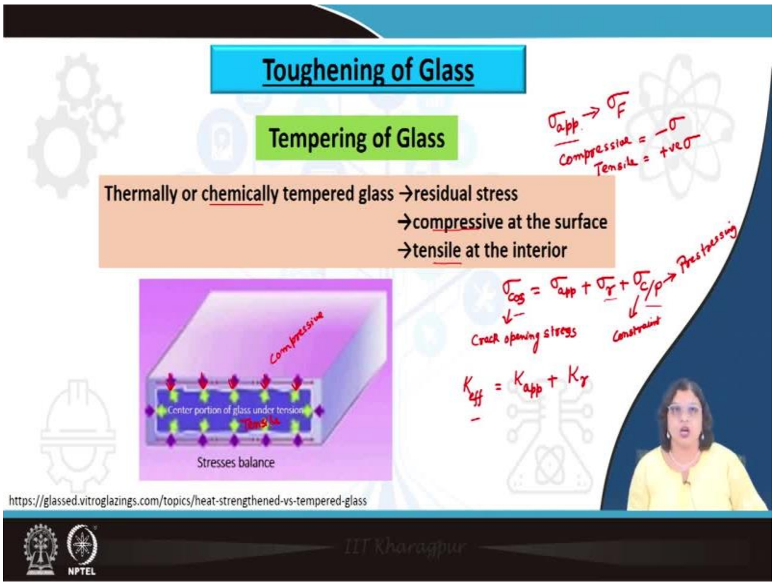

Toughening of Glass

Tempering of Glass

Thermally or chemically tempered glass →residual stress
→compressive at the surface
→tensile at the interior

https://glassed.vitroglazings.com/topics/heat-strengthened-vs-tempered-glass

$\sigma_{app} \rightarrow \sigma_F$

Compression = $-\sigma$

Tensile = $+ve\,\sigma$

$\sigma_{cos} = \sigma_{app} + \sigma_r + \sigma_{c/p} \rightarrow$ Prestressing

Crack opening stress

Constraint

$K_{eff} = K_{app} + K_r$

Now, coming to the first one the no break scenario, when we have seen that tempering is one of the ways by which the toughness of the glass can be improved. And this tempering can be done in two ways either we can do this thermally means by the application of temperature or by chemically means, we are doing some changes in the chemical composition by which we basically try to achieve some residual stresses particularly at the surface and these residual stresses is typically of comprehensive nature at the surface, whereas, the interior just for maintaining the stability it may have a tensile stress.

Now, when it comes to the residual stresses and particularly of comprehensive nature, we have also seen the influence of such stresses on the crack propagation or for that matter failure in general. So, when we apply stress of a magnitude let us say σ_{app}. So, that can lead to a fracture and if it does, that is equivalent to the fracture strength of the material.

Now, because of some residual stresses, this applied stress can be modified although we are still applying σ_{app}, but this can get either increased or decreased depending on the presence of the residual stress. If the residual stress is of tensile nature, then that should add up with the applied stress and if the residual stress is compressive in nature, so, that means that it is actually a negative stress. Tensile on the other hand is a positive stress.

So, eventually the stress that is necessary for crack opening. So, crack opening stress that is equivalent to the applied stress plus the residual stress again depending upon the nature of the residual stress tensile or compressive this could act as addition or subtraction from the applied stress and plus there could be some other stress related to the presence of constraints or pre-stressing which can also alter the applied stress or in general the crack opening strength.

So, let me write this term for better understanding and this stands for crack opening stress or strength at which fracture occurs or in a more general term, we can say that this leads to K_{eff} which is the stress effective stress intensity factor for fracture and that is related to the applied stress intensity factor plus the residual stress intensity factor or any kind of extra stress intensity factor that is arising because of the presence of the residual stress or due to the presence of some kind of constraint or pre stressing.

So, if this value is now match with the stress or the stress intensity factor that is required for fracture to materialize, that means the critical value then fracture will occur. Now, in case of tempering what happens is that because of some change in the thermal condition or the chemical nature that I am going to discuss now, it leads to generation of some stresses which is typically at the surface it should be comprehensive in nature. And that means that it will apply a compressive stress it will kind of press whatever crack or defect whatever is present there that compressive stress will add to close the crack.

So, in that sense compressive residual stress is always beneficial, on the other hand, interior part of the glass that should be in tensile stress, tensile residual stress. Now, this although you may think that because of the tensile residual stress that can in some way deteriorate the performance of the glass, but that is not true in the sense that since most of the defects arise at the surface, if by any way we can enhance the strength of the surface, so, those defects or those sites will not act as the region for stress concentration. And if the stress is not being maximized, then obviously, the chances for failure for catastrophic failure will be decreased to a lot extreme.

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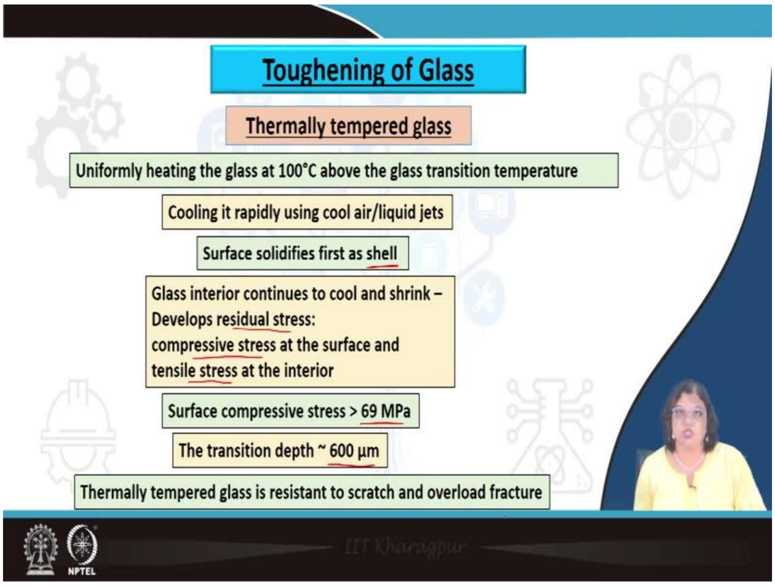

Toughening of Glass

Thermally tempered glass

Uniformly heating the glass at 100°C above the glass transition temperature

Cooling it rapidly using cool air/liquid jets

Surface solidifies first as shell

Glass interior continues to cool and shrink – Develops residual stress: compressive stress at the surface and tensile stress at the interior

Surface compressive stress > 69 MPa

The transition depth ~ 600 μm

Thermally tempered glass is resistant to scratch and overload fracture

So, for the case of thermal tempering what is done is typically the glass component plate or sheet or whatever structure it is that is heated to a temperature as high as the glass transition and actually, it should exceed the glass transition temperature by around 100 degrees centigrade and after that it is rapidly cooled using either cooler air or even through liquid jets. Now, if it is cooled rapidly that leads to the solidification particularly of the surface because the surface is in direct contact with the coolant. So, that makes the surface to get hardened to get solidified faster and it forms a shell. A hard shell, like the egg that we can see with it has a hard shell and then the interior is still liquid, but it is also cooling continuously cooling but not at that at fast rate as the surface.

So, the interior continues to cool and shrink. And that leads to generation of residual stress because the surface has already cooled and it has changed its volume. However, the internal has not yet cooled or it is cooling at a slower rate and because of this change in the cooling rate that leads to the formation of residual stress which is of compressive nature at the surface, while to maintain the stability, it should have a tensile counterpart at the interior. The surface compressive stress for the thermal tempering could be higher than 70 MPa or so, it could be actually much higher than that, depending on the temperature, the composition of the glass the cooling rate, et cetera.

We can control the amount of stress that could be generated and the transmission depth, which means the depth in for the compressive residual stress and the tensile residual stress. So, that junction could be something like around 600 μm. So, because of this compressive residual stress since the surface is getting hardened or strong that leads to achieve resistance to scratch an overload fracture and as a result, this thermally tempered glass can be used for many niche applications which otherwise without tempering it would not have been used.

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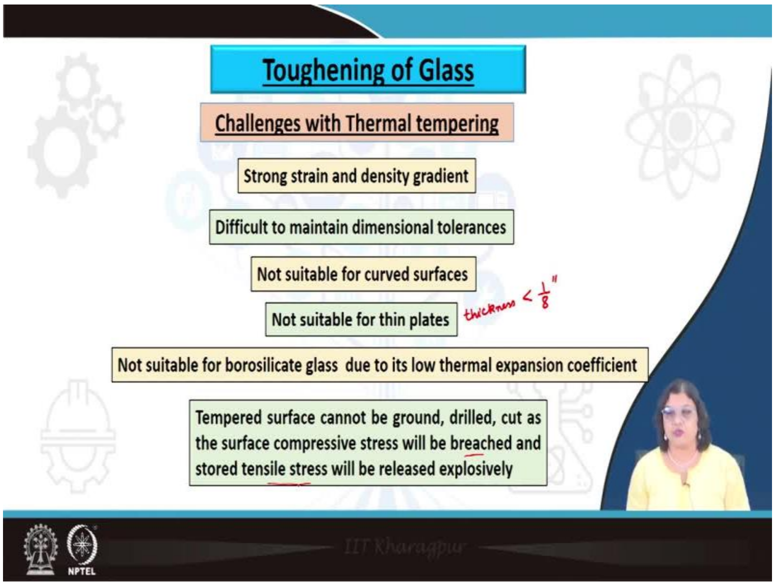

Toughening of Glass

Challenges with Thermal tempering

Strong strain and density gradient

Difficult to maintain dimensional tolerances

Not suitable for curved surfaces

Not suitable for thin plates thickness $< \frac{1}{8}''$

Not suitable for borosilicate glass due to its low thermal expansion coefficient

Tempered surface cannot be ground, drilled, cut as the surface compressive stress will be breached and stored tensile stress will be released explosively

But there are some challenges also for the case of thermal tempering. First of all, because of this residual stress generation and then changing the nature of the stress from compressive at the surface to tensile at the interior there develops a strong strain gradient and that also leads to a gradient in the density and because of this, this kind of strong gradient, it is often very difficult to maintain the dimensional tolerances, we know that for certain component if some shape has already been given to that and we are trying the tempering, thermal tempering may not be possible to give the exact complicated shape it may have and still maintain the dimensional tolerance.

So, that is a drawback of thermal tempering, which kind of limits the usage of thermal tempering for some cases. Also, it is not suitable for curved surfaces, since we are heating this we need a flat surface is preferable. So, that the heat is uniformly distributed all throughout the surface and then it is evenly getting stressed or getting the compressive stresses evenly at all parts because if there is any animal in the stress distribution, that may in fact act as the region of stress concentration if there is any such gradient even in the surface. So, it is also not suitable for very thin plates. So, if the thickness is less than $\frac{1''}{8}$, then it is not suitable to undergo thermal tempering.

So, that is makes it another drawback of thermal tempering since, we cannot use this for very thin sheet or plate. Also, it is not suitable for another common kind of glass that is used typically the borosilicate glass because of its low thermal expansion coefficient. So, that is also makes usage of thermal tempering very much challenging.

Tempered surface typically thermally tempered surface also cannot be ground or drilled or cut or machined for that sense, if we try to do that, that is actually leading to breaching the stresses and the particularly the compressive stresses at the surface will be breached and that will lead to the internal tensile stress to get released and that will happen in an explosive manner leading to a catastrophic failure. So, tempered glass is avoided to be machined in any way. So, that we should not have that kind of catastrophic failure.

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Application

- Automotive rear glass
- Side glass windows
- Household tables etc.

https://www.indiamart.com/proddetail/toughened-glass-installation-service-19995627648.html
https://www.walmart.com/ip/Lund-184805-In-Channel-Ventvisor-Elite-Light-Smoke-Front-Rear-Window-Deflector-for-2019-2020-Chevy-Silverado-1500/563620206

Application wise however, thermally tempered glass are very much used for different kinds of application which we see in our daily lives, which we see nearby places for example, in the automotive classes and the window glasses also are typically thermally tempered. So, these are of course made of glass.

But if you have noticed that this is hardened or toughened, so that just a little bit of scratching or if someone throws a stone or maybe something happens to that it should not break up easily. Household tables, we often use the even the dining table, centered table something like this made of glass, which looks nice has a good aesthetic sense, but it also needs to be toughened so that it should not break at any instance.

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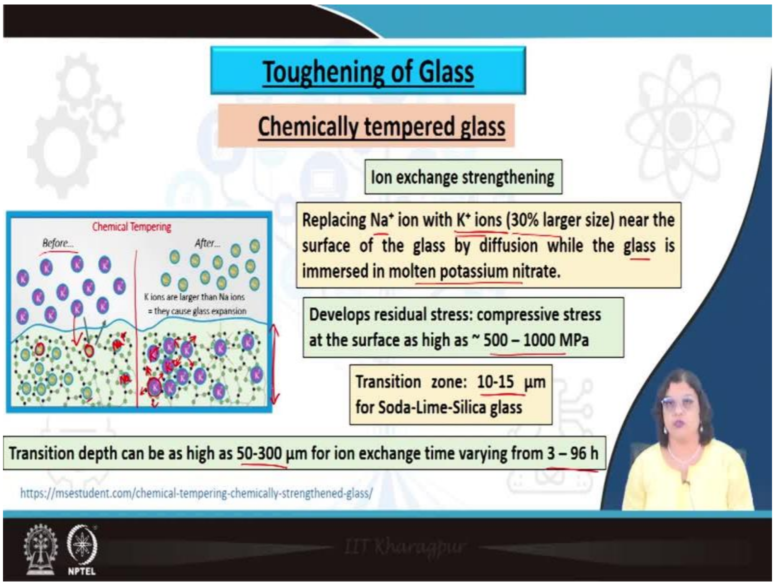

Toughening of Glass

Chemically tempered glass

Ion exchange strengthening

Replacing Na^+ ion with K^+ ions (30% larger size) near the surface of the glass by diffusion while the glass is immersed in molten potassium nitrate.

Develops residual stress: compressive stress at the surface as high as ~ 500 – 1000 MPa

Transition zone: 10-15 µm for Soda-Lime-Silica glass

Transition depth can be as high as 50-300 µm for ion exchange time varying from 3 – 96 h

https://msestudent.com/chemical-tempering-chemically-strengthened-glass/

So, that was one of the ways by which higher toughness can be achieved the other way is by chemical tempering. Now, what is chemical tempering? Chemical tempering can be achieved or it is obtained through ion exchange. So, it is also known as ion exchange strengthening, it is typically very smart way particularly let us say for soda lime silica glass again which is commonly used for glass bowl or any kind of glass that we typically use for household activities also used industrially and for many other application.

So, what is done there is that the Na^+ there is being replaced with the K^+ particularly near the surface and this is done while the glass plate or glass component or for that matter any kind of shape is immersed in a molten potassium nitrate solution and as a result the potassium is replacing the Na^+.

So, let us see what it is. So, this is the one which was before you can see that there are this is the glass structure and we have the sodium ion here. So, this article here are the sodium ion or 'Na^+' all these are the sodium ions and we are putting this in contact with a molten potassium nitrate.

Now, this potassium are coming into the class and it is replacing the sodium ions. So, now, you see that all those circular things now are turning purple that is just the K^+, representing the K^+ all throughout and this is happening only at the surface. Now, the beneficial effect of replacing the sodium with potassium is that this K^+ have a larger size or volume it is actually 30 % larger than that of the Na^+.

So, that means that instead of this small Na^+, we are having now the bigger K^+ and which is kind of applying the compressive stresses everywhere. And as a result, once again we are generating the compressive stresses all throughout the surface or throughout the depth over to which the sodium has been replaced by potassium. So, that leads to a compressive surface stress as high as around 500 to 1000 MPa.

So, that is pretty high and that will act as an additional to the applied stress to show that fracture could have been avoided. The transition zone for typical soda lime silica glass is around 10 to 15 μm but we can change this particularly depending on the nature of the glass and nature of the application we can vary this exchange time from 3 to 96 hour to get this transition zone as high as 50 to 300 μm. So, that is pretty high we if we have that, we now know that this entire depth of a few 100 μm is strengthened or toughened and which means that fracture could have been avoided significantly. Now, this depends on the kind of application we are looking for.

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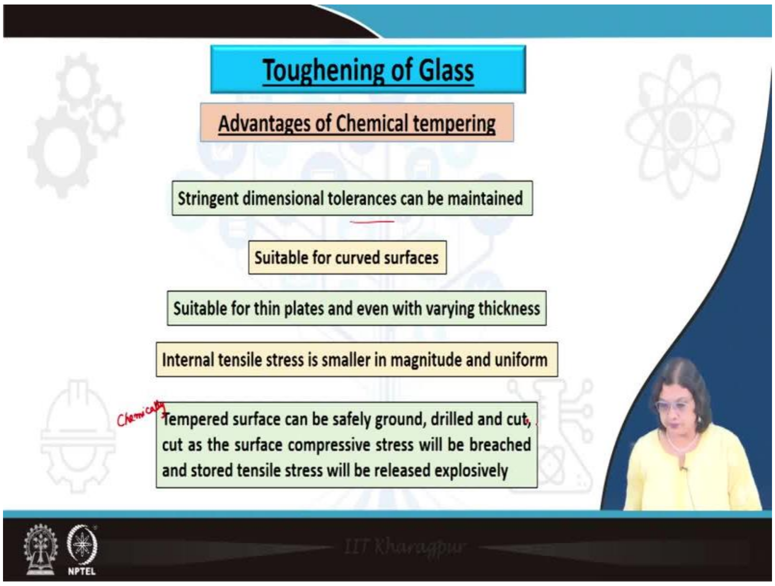

Toughening of Glass

Advantages of Chemical tempering

Stringent dimensional tolerances can be maintained

Suitable for curved surfaces

Suitable for thin plates and even with varying thickness

Internal tensile stress is smaller in magnitude and uniform

Chemically Tempered surface can be safely ground, drilled and cut, cut as the surface compressive stress will be breached and stored tensile stress will be released explosively

Advantages of chemical tempering particularly over the thermal tempering is that stringent dimensional tolerances can be maintained here. So, whatever was the dimension before tempering, the same will be there even after tempering because we are not doing any thermal treatment there. So, there is no possibility that there could be any kind of change in the dimension. It is also suitable for curved surfaces and actually for that matter, it is suitable for any kind of complicated shape because we simply need to immerse this in the potassium nitrate solution or some other kinds of things for different kinds of glasses. It is also suitable for thin plates.

So, like I mentioned that chemical the thermal tempering is suitable only for plate thickness above $\frac{1"}{8}$ for even thinner plates and very thin very fine sheets we can use the chemical tempering safely and even if there is a varying thickness that also can be very uniformly tempered by chemical ways. Internal tensile stress is smaller in magnitude and uniform all throughout. So, that is another advantage of chemical temporary. So, chemically tempered surface can be safely ground or drilled and cut as the stress distribution is uniform throughout.

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Application

- **Optical glasses**

https://www.google.com/url?sa=i&url=https%3A%2F%2Fmsestudent.com%2Fchemical-tempering-chemically-strengthened-glass%2F&psig=AOvVaw36fL-8W9B5u6yYs5P5PA_e&ust=1651066466736000&source=images&cd=vfe&ved=0CA0QjhxqFwoTCJjC8PjssfcCFQAAAAAdAAAAABAD

https://www.catiglass.com/chemical-strengthening/

So, this is the typical application of chemically tempered glass we can use this for optical glasses for several kinds of screens which are toughened and at the same time it maintains his dimensional tolerances and all kinds of other features that are necessary to be maintained.

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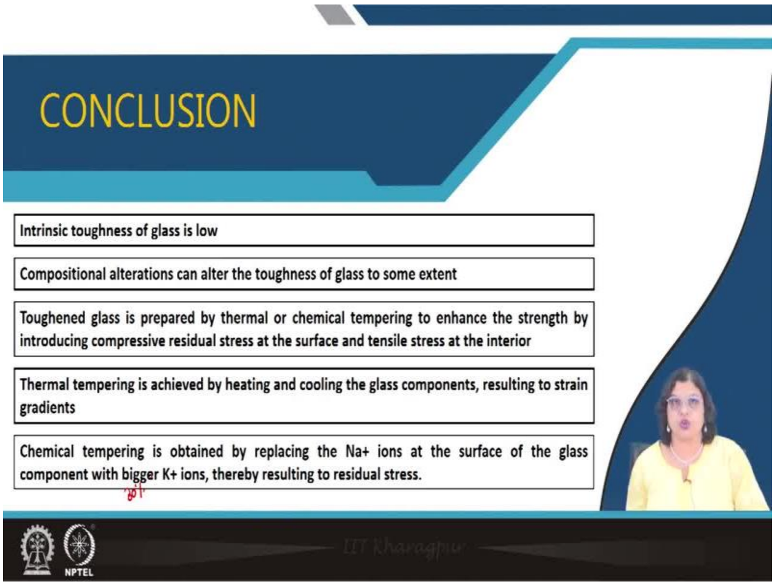

CONCLUSION

Intrinsic toughness of glass is low

Compositional alterations can alter the toughness of glass to some extent

Toughened glass is prepared by thermal or chemical tempering to enhance the strength by introducing compressive residual stress at the surface and tensile stress at the interior

Thermal tempering is achieved by heating and cooling the glass components, resulting to strain gradients

Chemical tempering is obtained by replacing the Na+ ions at the surface of the glass component with bigger K+ ions, thereby resulting to residual stress.

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https://www.catiglass.com/chemical-strengthening/

So, coming to the conclusion for this lecture, we have seen that the intrinsic toughness of glass is low, however, we can do some compositional alteration that can also modify the toughness of the glass to some extent and particularly toughened glass is prepared by thermal or chemical tempering that enhances the strength of the overall structure by introducing compressive residual stresses particularly at the surface and the internal there is a tensile stress which is also residual in nature. Thermal tempering typically is achieved by heating and cooling the glass component heating above the glass transition temperature and then rapidly cooling it.

So, that there is a strain gradient that generates and surface is getting a compressive residual stress whereas, the internal section is under tensile stresses. Chemical tempering is typically obtained by replacing the Na^+ at the surface of the glass with much bigger actually 30 % bigger. K^+ thereby resulting to the residual stresses and we have also seen that chemical tempering can be done on even thinner plates or of any curved surfaces or for that matter any kind of complicated shape and that way we can achieve overall toughness of a glass component. So, these are the references that are used for this lecture. Thank you very much.