Fracture, Fatigue and Failure of Materials
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Lecture 26
Fracture Toughness (Contd.)

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Hello everyone, this lecture 26 is the continuation of the previous lecture, where we will be talking again about Fracture Toughness of Materials.

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So, the concept that will be covered in this lecture is continuing with the toughening mechanism of glasses and then we will also look into the different factors that controls the toughness of even polymers. So, here is a small video which shows that how a glass which is toughened by tempering does not even break even if we are applying impact loading on this. So, this one is interesting video which kind of represents what we have seen in the last lecture.

So, you can see that there is a hammer that is hitting the glass panel and it kind of shakes the entire frame, but the glass is still not breaking. So, that is an amazing development in terms of the enhancement in the toughness and obviously, such a kind of toughened glass, which can be used for any kind of application which has a tendency to get fractured or has to solve the impact loading or so on.

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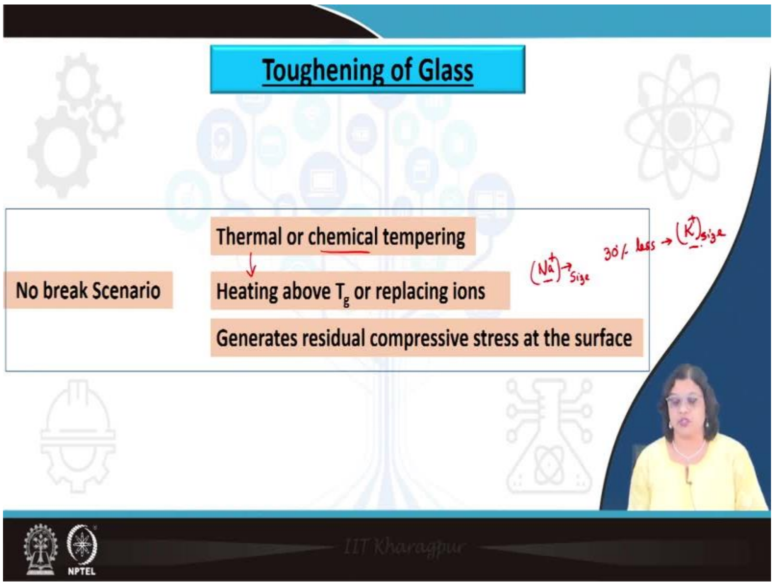

So, toughening of glass can be achieved as we have seen in the last lecture is by tempering. And this could be achieved by thermal or chemical tempering. Thermal tempering can be obtained by heating the glass above the glass transition temperature and then rapidly cooling it. So, that we develop a compressive residual stresses at the surface and which acts on increasing the necessity for applied stress such that fracture can materialize at a higher applied stress or tempering can also be done in a chemical way by which we replace the ions.

For example, sodium ion has been replaced by the potassium ion and we know that the size of the sodium ion is 30 percent less than that of the potassium ion size. So, obviously if we are replacing the sodium with the potassium ions, that is generating a compressive stress, it is kind of pushing the surrounding matrix and that leads to a compressive stresses and which acts in a beneficial way to enhance the toughness of the glass.

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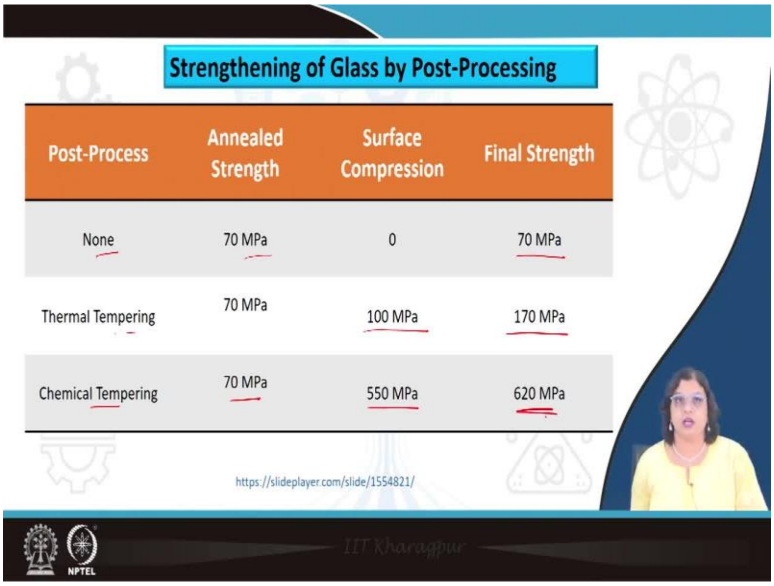

This is an example of how different kinds of toughness can be achieved or strengthening can be achieved just by tampering. For example, if no tempering operations are being done, we see that if the annealed strength of the glass component is 70 MPa, the final strength is also the same because there is no additional residual stresses in the glass.

But if you are doing thermal tempering and because of the generation of the compressive stress of the order of 100 MPa, we see that the total final strength now comes to around 170 MPa. So, there is a significant enhancement just by thermal tempering. By chemical tempering, we actually can enhance the strength to a much higher level.

So, in this case, the surface compression leads to around 550 MPa of residual stresses. And so, the overall final strength that we are getting is 620 MPa. So, that is really amazing when we are increasing the strength value from 70 MP to 620 MPa just by tampering or altering the chemical composition of the glass.

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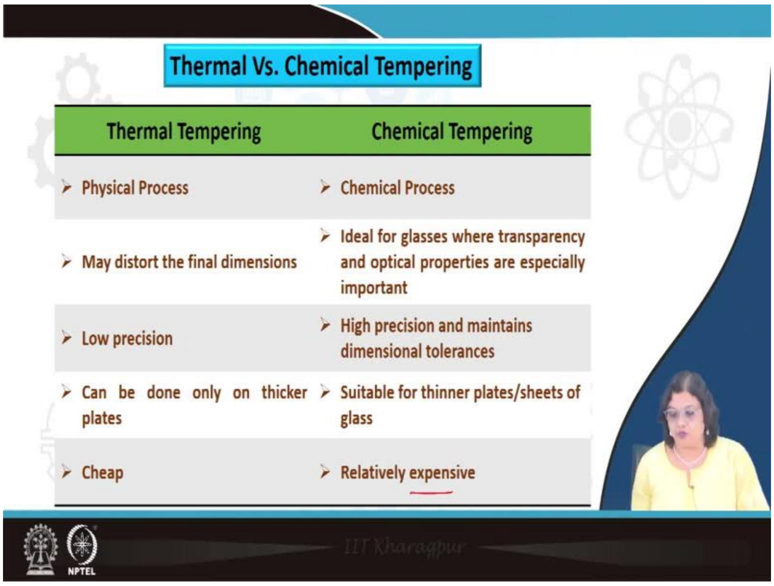

So, this certainly has a significant influence. Let us just look onto the differences between the thermal and the chemical tempering. First of all, thermal tempering is a physical process we are simply heating it above the glass transition temperature and cooling it so we are not altering or modifying the composition in any way.

On the other hand, chemical tempering is certainly a chemical process in which one of the ion is being replaced by another one and that changes or that modifies the entire composition of the glass. So, we also have to be careful in choosing the kind of ions that we want to replace the mother ions, so that we can achieve improved performances, but we should not lose on any of the typical characteristics of that glass.

Now, thermal tempering is associated with a strong strain gradient. So, there is obviously compressive residual stresses at the surface and internally there is a tensile residual stress that is there for the case of both kind of tempering both thermal and chemical tempering, but the gradient is pretty high for the case of thermal tempering.

So, this change from compressive to tensile residual stresses that is happening over a very small depth and that leads to distortion in the final dimension. Also, because we are heating it at a temperature above the glass transition temperature, so, that also makes it vulnerable to have a change in the actual dimension and that kind of limits the applicability of thermal tempering to some extent depending on the applications of course.

However, chemical tempering is ideal for glasses, where transparency and optical properties are especially important as we have seen the optical glasses, lenses, these are the smart devices these are all the glasses are toughened by the chemical way. So, that we do not lose any kind of properties of the glass that are necessary.

Thermal tempering actually leads to a low precision on the other hand, in chemical tempering, we achieve very high precision and it maintains the dimensional tolerances as well to the maximum extent. On the other hand, thermal tempering actually can be done only on thicker component we have seen that because of the strong radiant if we are doing this on thin plates that will be a difficult one.

While chemical tempering is actually suitable for even thinner plates and for any kind of complicated shapes, it should be toughened by chemical tempering. Overall however, thermal tempering is cheap process. So, we often need to use this when depending on the applications, when we can work on with the thicker component or there is not much concern about the dimensional distortion, we can go for thermal tempering, but for very high quality glasses or for applications, which mandates that there should not be any distortion in the dimension or any optical properties we should go for the chemical tempering although this one is a little expensive one.

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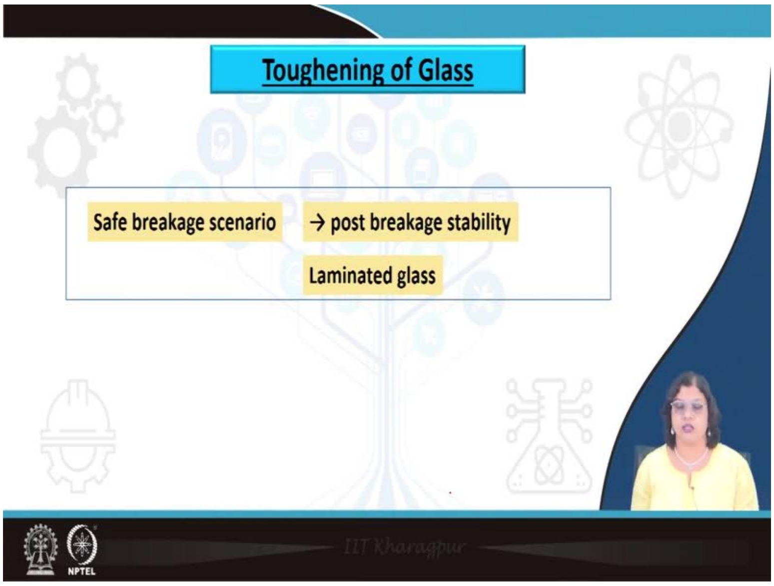

Now, so, that was no break scenario. And the next one that we are going to discuss about now is the safe breakage scenario. So, in this case, although if the glass component breaks, there should be some mechanism of load sharing such that the entire component should not fail catastrophically and this can be obtained by different way and so that we can achieve a post breakage stability although the glass breaks, but there could be some stability of the structure it should not fall apart all at once. And this is can be obtained through laminated glass. So, let us see what is this laminated glass?

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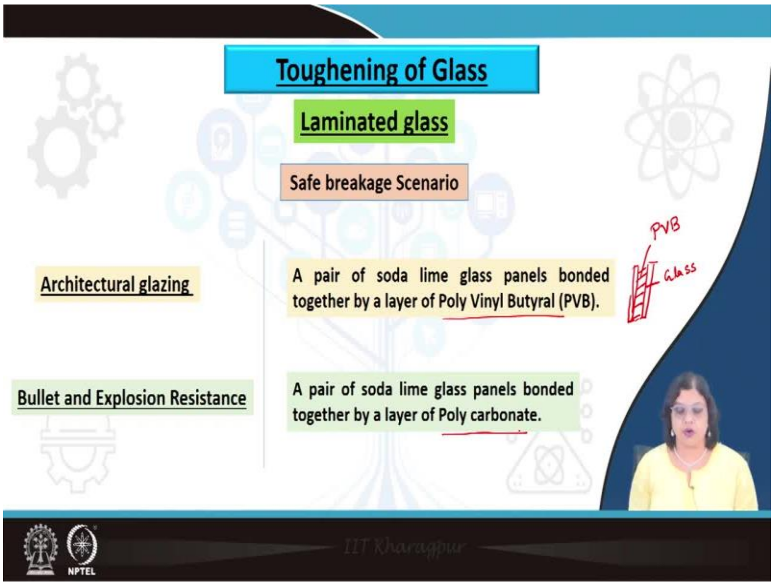

So, a laminated glass is often used for architectural glazing, in which case a pair of soda lime glass panels, so we have two pieces or two sheets of soda lime glass and that is bonded together by a layer of PVB, polyvinyl butyral. So, it is a kind of sandwich structure in which there are two layers of glass. So, there is two other glass layers and then there is this BVB that is a polymer that is used for sandwiching this glass plates or sheets.

Now, this is used for architectural glazing where we need some kind of toughness there. On the other hand, if we are talking about a very highly toughened glass for bullet and explosion resistance often used in the case of armors or even for the windshields of cars or such kind of applications, we use a pair of once again a soda lime silica glass, but in this case it is bonded with a polycarbonate. So, depending on the applications, we can change these polymers or we can even change the glass plates and we can achieve different kinds of properties.

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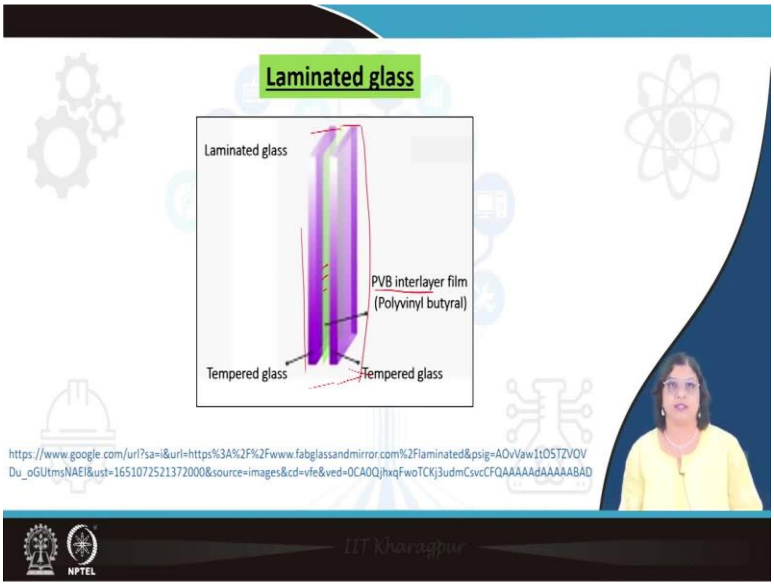

So, this is how it is done this are the tempered glass can be used one which is already tempered by thermal or chemical way and then in between if we are using this polymer sheets here, so, in this case, this is a PVB that is shown here and if you make a sandwich structure and this entire one is a laminated glass, which is used for making some kind of component. So, if we are using that the toughness will be increased to a very high extent.

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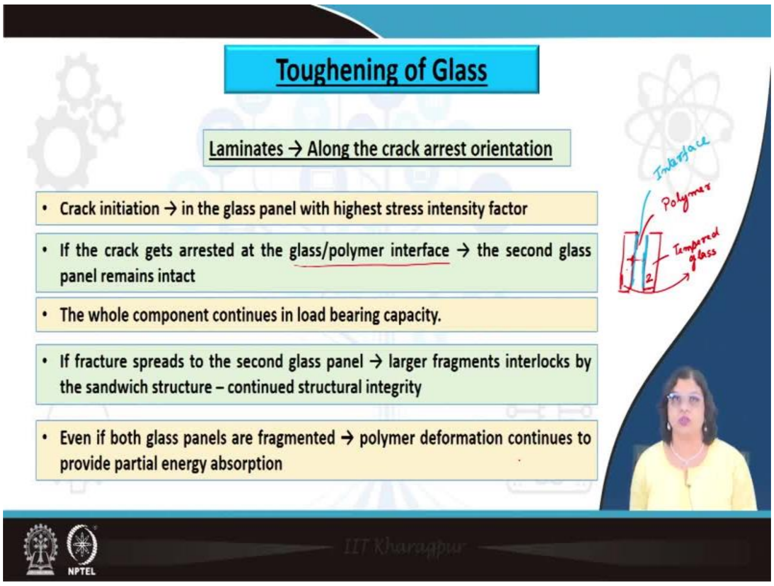

The reason for this is the fact that this laminate actually should act along the crack or arrest orientation. So, it should be positioned in such a way that the crack growth direction should be hindered and it will act as a crack arrestor. We have also discussed about the crack arrest morphology in the previous lectures and you can very well imagine that all this the sandwich structure the interfaces are nothing but a hindrance to the growth of the crack whenever there is a crack even if it grows through the sheets of the glass this will be hindered or the energy will be released as soon as it comes in contact with this interfaces which is nothing but a free surface.

So, if there is a crack initiation, which can happen in the glass panel with highest stress intensity factor. Now, this crack gets arrested at this glass polymer interface. So, as I mentioned, there is a glass plate, this glass plate anyway is toughened by tempering. So, both of these are tempered glass this one and this one and then we have the polymer here and this interface is of what is of interest. So, this is the interface that makes it really interesting and let me level this. So, whenever a crack first of all since this is a tempered glass. So, it is difficult for the crack to initiate and it requires higher value of K or effective stress intensity factor for the crack to initiate on any of these panels.

But, even if it does, if the when the crack come in contact with these interfaces, the energy will be released here the crack will get blunted and that kind of delays the fracture process in general. The whole component however, although one of the glass plate has fractured, that does not mean that the entire component will shatter that will not happen, the second glass panel will remain intact because the stress for the crack is getting released at this interfaces. So, it is not even reaching the second glass panel which means that there is no crack in the second glass panel here. If fracture spreads to the second glass panel.

So, once the crack or if we if the applied stress is higher and higher and the crack regains its sharpness and proceeds to the polymer one and reaches the second glass. So, if the fracture spreads in the second glass panel, larger fragments interlocks by the sandwich structure. So, it gets fragmented because it is already a tempered glass and this is being interlocked by the entire structure itself. So, it is not able to fall apart. And even if both the glass panels are fragmented polymer deformation continues because it may have a plastic deformation ability. So, polymer deformation continues to provide partial energy absorption. So, overall it will require much larger amount of energy till it fractures.

So, that means and fracture toughness is all about the total energy consumption it is not only the fracture strength, but the overall energy that is required. So, even if the crack has initiated in this case just an example has been explained the crack will not be able to propagate further and lead to a total failure. So, that is the advantage of using laminated glass.

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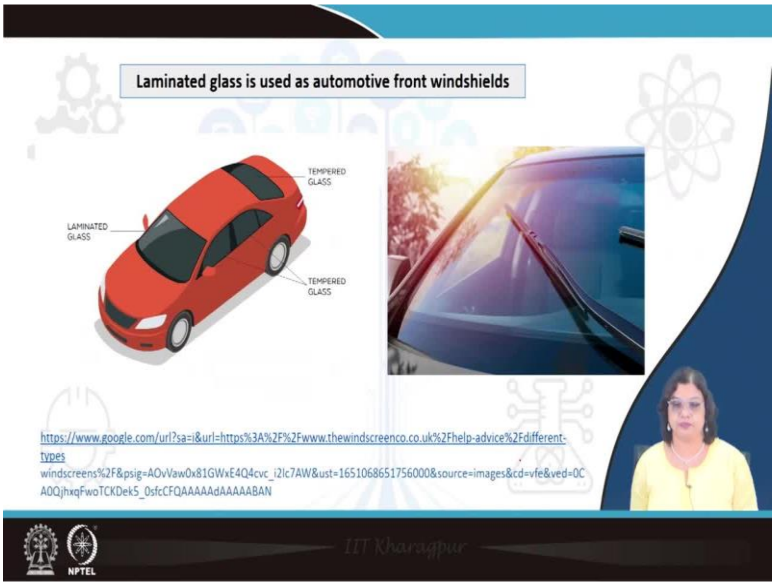

So, this is an example laminated glass is particularly used for the car windshield. So, that any kind of even if there is a storm or there is some kind of something is hitting the windshield, it should not break and if it does, even if it does, it should not fall apart all at once. It should rather if you have seen the windshield got broken, it actually still stays intact. It is not coming out of the entire structure. So, on the other hand tempered glass are typically used for the windows of a car. So, this is just an example been shown here.

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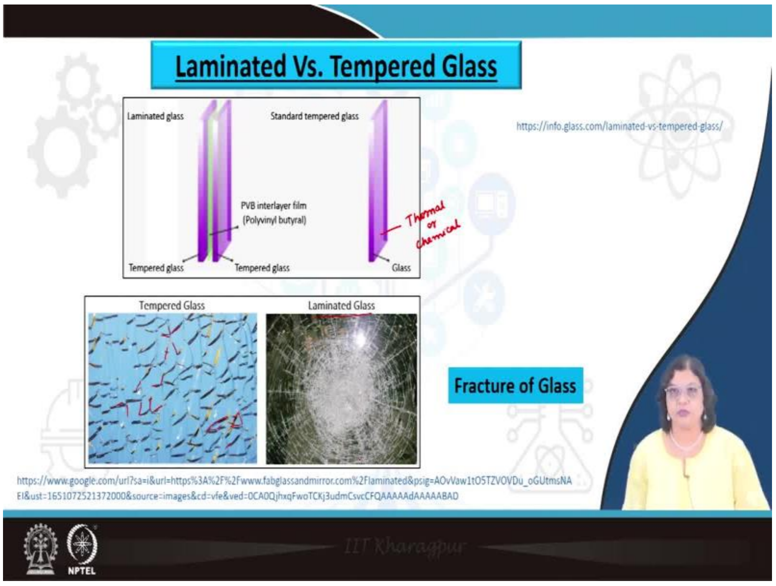

Now, let us look into the differences between the laminated versus tempered glass. So, this one is the standard tempered glass here as we have seen that this tempering can be achieved by either thermal or chemical way. On the other hand, laminated glass may use this tempered glass itself and then there is a polymer in between. So, obviously, the toughness of the laminated one will be quite higher and we can use that only when if it is totally needed for such application. The main important part for laminated versus tempered glass is the fracture behavior.

So, this is what is seen for the tempered glass you can see that glass being a brittle one typically it fails if we are talking about a soda lime silica glass which is regularly used as a glass plate for any kind of regular household application you can see that that breaks in one piece if there is any kind of stress concentration happening or there is a scratch it breaks at that point itself. Tempered glass or toughened glass as it is often the word is used as toughened glass.

So, you can see that if the toughened glass breaks, it actually shatters into many, many pieces. If you have ever seen a broken car window, you can see that there are thousands of pieces very small pieces depending on how much it has been tampered or how much the extent it has been toughened and the total size and the impact, it depends on all those factors and which decides that on how many pieces it will break but eventually it breaks into many such pieces and as you can see here.

So, it actually looks like pieces of diamonds that if you have seen any such things and so, that means that if there is one single crack and that is propagating versus when the crack is propagating in all direction and there are multiple cracks all throughout. So, propagation of each one of them will require some amount of energy. So, obviously, there will be higher energy requirement for the fracture for the catastrophic fracture to materialize. So, that leads to an enhancement in the fracture toughness of our toughened glass or a tempered glass in this case. So, it breaks into many pieces.

On the other hand, laminated glass again, if you have seen a broken windshield or you can search for the videos and see the broken windshield of a car, you can see that even if it has broken like there are plenty of numerous scratch marks, it does not fall apart. So, this is what is shown here in the laminated one because the entire structure is hold by this sandwich components. And that makes it even tougher and we often prefer first of all our target is that we do not want an unexpected failure and that makes studying the fracture mechanics so important. We always try to figure out what is the worst possible scenario so that we know that in practice in service the condition will be much better than the expected or the lab estimated one.

Secondly, even if fracture occurs, we do not want it to be a catastrophic one. We do not want it to be an explosive one, so that there could be fatalities and all. So, for that matter, laminated glass is often use for certain applications where it is important to restrict the catastrophic failure. For example, tempered glass as I said, the tempered glass breaks into many pieces, but because of the presence of this residual stresses, there could be like an explosive burst of the residual tensile stresses which are interior. So, if someone is hitting a windshield or something is hitting the windshield and if it breaks like that into thousands of pieces and hits the driver or the passenger that will be quite difficult situation that will be quite fatal.

So, laminated glass in such kind of applications, which are very very critical is of course beneficial because even if it breaks, it does not fall apart or injure the driver or the passenger inside. So, this is just one example. Of course, laminated glass has many niche applications and bullet proof applications in armors and military in defense which justifies the usage of such material.

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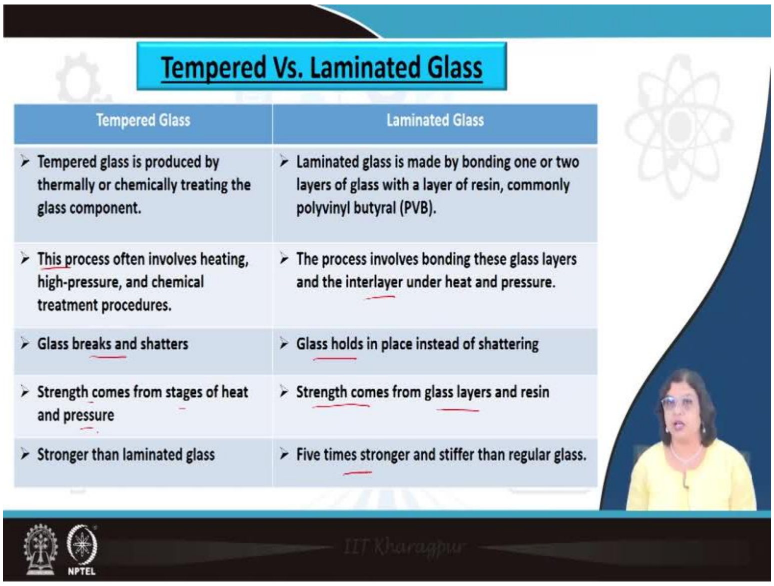

So, overall, if we now try to find out the differences between tempered versus laminated glass in sequence these are jotted down here. So, tempered glass is produced by thermal or chemical treating as we have seen and laminated glass on the other hand there is no such treatment in general, we can use a tempered glass as one of the plates but laminate motion means as the name suggests itself that there it is a kind of sandwich structure where it is a bonding of one or two layers of glass with a layer of resin or any kind of polymer is typically used.

Tempered Glass often involves heating and that leads to high pressure and chemical treatment procedures which often leads to dimensional changes in case of particularly for the thermal tempering. On the other hand, laminated glass involves bonding the glass layers and the interlayer under heat and pressure of course, there also has to be some heat and pressure that needs to be applied. So, that the bonding is strong enough firm enough and it should not come out. Tempered glass breaks and shatters and that is how the internal residual energy is being released. On the other hand, laminated glass holds in place instead of shattering.

So, as I mentioned that is one big advantage of laminated glass sheets. Strength comes from the stages of heat and pressure. And in for the case of tempering so, how much heat and pressure we are using for tempering for the process of tempering particularly for the thermal tempering one that dictates the overall strength and toughness of the tempered glass on the other hand for the laminated glass strength comes from the glass layers and resin. So, it is a kind of load sharing that is happening also the mechanism of deformation is changing as it passes from glass to the polymer to the glass again.

Tempered glass sometimes could be stronger and laminated glass on the other hand is much more stronger and stiffer compared to the regular glass. So, as I mentioned that depending on the application and the criticality of application, we often need to use a tempered versus laminated glass. If we think in more details, we should also try to we should also appreciate the fact that in case of laminated glass is not fully glass so, there is a polymer in between. So, obviously that kind of deteriorates the entire property of the glass, because there is a face which is softer than the two other glass structure.

But still it has some application with benefits in the sense that it does not allow the component the laminated glass component to fail in a catastrophic fashion. So, often even if the overall strength and toughness could be lower or particularly the strength could be lower than the tempered glass we often preferred to use a laminated glass for certain applications.

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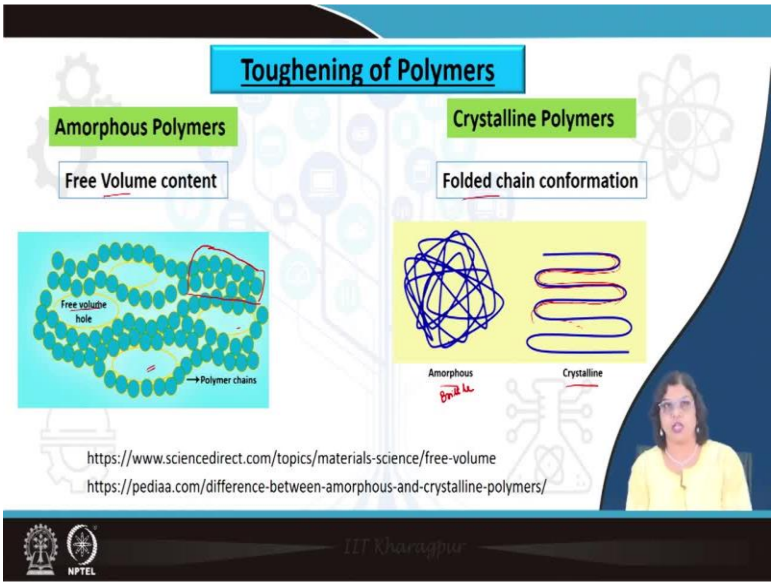

Now, that we have learned some things about glass and previously for ceramics and of course on metals, let us now focus on the another category of material which is polymer. So, how are toughening of polymer can be achieved? Now, polymer typically could be of two different types there could be amorphous polymer or the crystalline polymer and crystalline polymers are actually of higher toughness compared to the amorphous polymer. So, similar to what we have seen that the amorphous structure is more brittle and that means that the toughness is lesser. So, similarly here for the case of polymers also crystalline one are tougher than the amorphous one.

So, what do we mean by crystalline and amorphous polymer is the chains. The polymer always have these chains and these chains are arranged in a regular fashion for the case of the crystalline polymer. As, you can see that there is a regular fashion repeated fashion that can be seen for the case of crystalline polymer.

On the other hand, in amorphous polymer, there are still chains, but those are haphazard and there is no regularity maintained. So, that is the typical signature of an amorphous polymer and that makes any kind of deformation very very difficult to proceed or continue and that leads to breakage of the bond and overall catastrophic failure like a brittle one.

So, that is why amorphous one is showing us more brittle behavior compared to the crystalline one. Now, deformation for the case of amorphous polymer there are definitely some amounts of deformation unlike glass and that is related to the free volume content, on the other hand for the case of crystalline polymer, there are this folded chain conformation and any kind of deformation proceed in a continuous manner through this folded chain.

So, when I said free volume or the chain so, this is one example how it is being arranged. So, typically, the polymer chains are arranged in some fashion in most of the places where there is some regularity is maintained like this small location here, we can see that, that is the crystalline part.

On the other hand, if there is some haphazard way by which the chains are arranged that could be an amorphous part and in between there are some free spaces. So, unlike the metallic system or the crystal structure found in the metallic system, these are not very regularly arranged or there are some amount of free spaces available there, not so closely packed and this is the one which is known as the free volume and through which the deformation proceeds particularly for the case of amorphous one.

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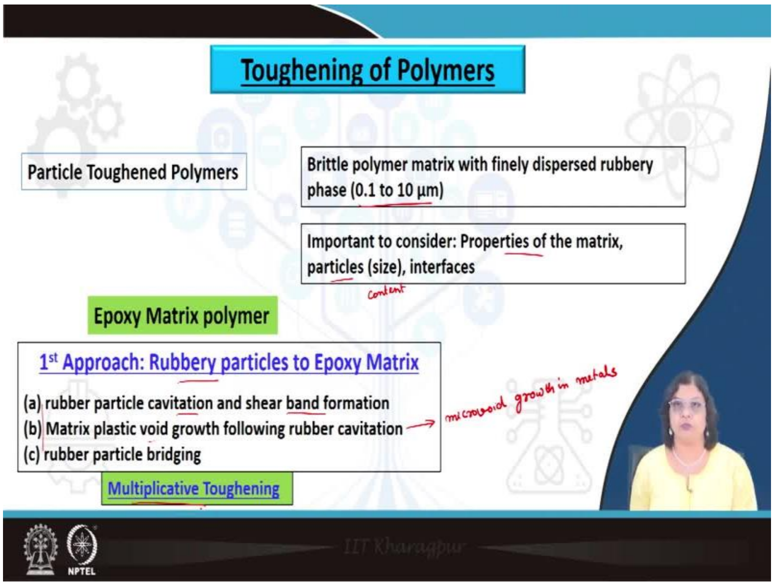

Now, if we want to toughen a polymer, one of the very used practice is to toughening fit particles. So, that is known as particle toughened polymers. So, what we do here is if there is a brittle polymer matrix, there are some particles typically rubbery phase that are used as particles of size 0.1 to 10 micrometers. We can vary the size and we can vary the content of those rubbery phases and we can make a particle toughened polymer while we do that, it is very important to consider the properties of the matrix as well as the particles, the size of the particles the overall volume fraction of the particles, And of course the interface. As we have seen for the case of the laminated glass or for that matter any such kind of structures, where there are two different phases, the interfaces are very very important and they are the properties and the deformation characteristics changes completely. So, we have to be careful of choosing the different particles into different sizes and shapes and different volume fraction on the brittle polymer matrix. Matrix also can be altered depending on the application that we are looking for.

Now, one such kind of particle toughened polymer is epoxy matrix polymer where we use the epoxy as the basic matrix and there we add different kind of particles. The first approach is when we use a rubbery particles. Now, these rubbery phases actually under the application of stresses there could be cavitation and shear band formation of these rubbery phases and that leads to the matrix undergoes a plastic void formation and the growth of that. So, that is similar to the micro void growth formation that we have seen for the metallic system.

So, similar kind of mechanisms are also seen for the case of epoxy matrix polymer when we are using the rubbery particles as a second phases there and when these micro voids are forming, then the rubber particle kind of bridges with each other. So, that overall leads to maintain the integrity such that it does not fracture and that leads to an enhancement in the toughness of the material. So, this is since all these are acting simultaneously.

This is an example of multiplicative toughening by which we achieve higher toughness compare to the actual toughness of the matrix or for that matter the toughness of the polymer. So, we are getting a beneficial effect of both of them. So, that we achieve higher toughness.

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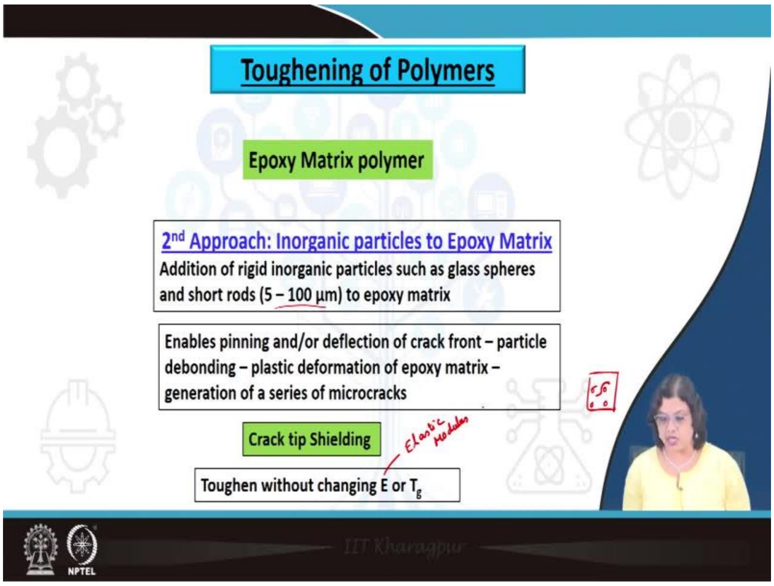

The second approach is well, instead of the rubbery phase we use a inorganic particles. So, glass spheres or beads or the rigid particles as a second phase. So, this could be of any size from 5 to 100 micrometer to the epoxy matrix that is added. And this second phases glass particles or the inorganic particles hard particles basically that enable spinning or deflection of the crack front. So, even if there are defects that are the crack that is there in the matrix that is getting pin either pin, so that the crack is not able to grow any further it is getting hindered or the crack has to deflect around the particle.

So, if you have a matrix and then there are these particles and there is a crack. So, this crack has to deflect its direction of growth and obviously, that means, that more energy will be consumed in deflecting the crack and changing the direction of the crack and that means, that the toughness will be increased. Of course, along with that, there could be some amount of plastic deformation of the epoxy matrix also and because of the strain mismatch between this glassy phase as well as the matrix phase, there could be a generation of a series of micro cracks.

We have already seen this for the case of metallic system also the generation of this micro cracks lead to stress release whenever there is a progressing crack and it comes in contact with the micro crack interacts with the series of micro cracks the energy is being released at each point because the micro cracks are nothing but free surfaces and every time a crack comes in contact with such free surfaces as the energy is getting released and it is getting blunt. And if the crack tip is getting blunt, it means, that we need to apply more and more stresses for the crack to regain its deep sharpness and to grow further.

So, this leads to kind of crack tip shielding. This approach if you are adding these glassy phases actually toughened the material overall composite without changing much of the elastic modulus or the glass transition temperature of the component. So, this is just for clarity that this E here stands for elastic modulus and the T_g as I have mentioned earlier, this T_g is nothing but that glass transition temperature.

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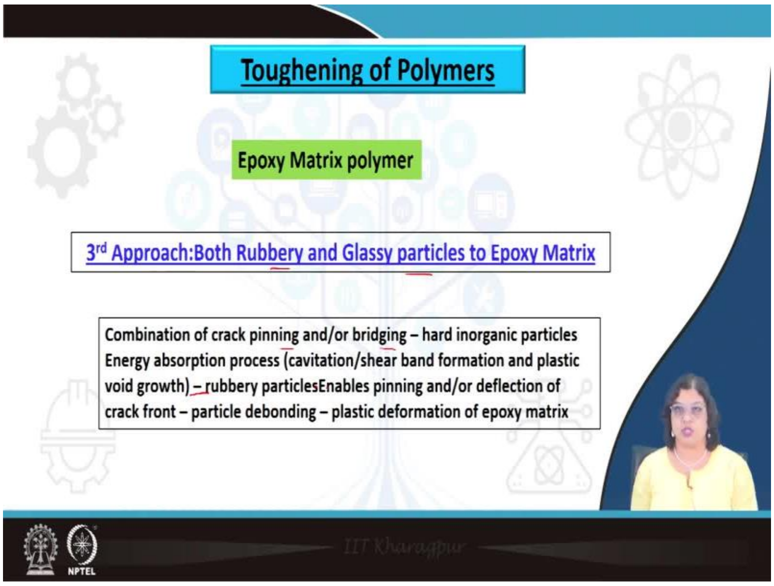

Now, there is a third approach also, which is combining both the first and the second one in which we have both the rubbery and the glassy particles in the epoxy matrix. And what happens here is that there are both the mechanisms which gets active now, we have the crack pinning or bridging by this hard inorganic particles and that leads to an energy absorption process, cavitation, shear band formation and plastic void growth this could be because of the rubbery particles and all of this enables pinning and deflection of the crack front and that leads to particle D bonding and overall plastic deformation of the epoxy matrix on top of that will lead to an overall enhancement in the toughness of the material. So, that is how a much more enhanced or improved toughness can be obtained for even a brittle epoxy matrix or epoxy polymer in general.

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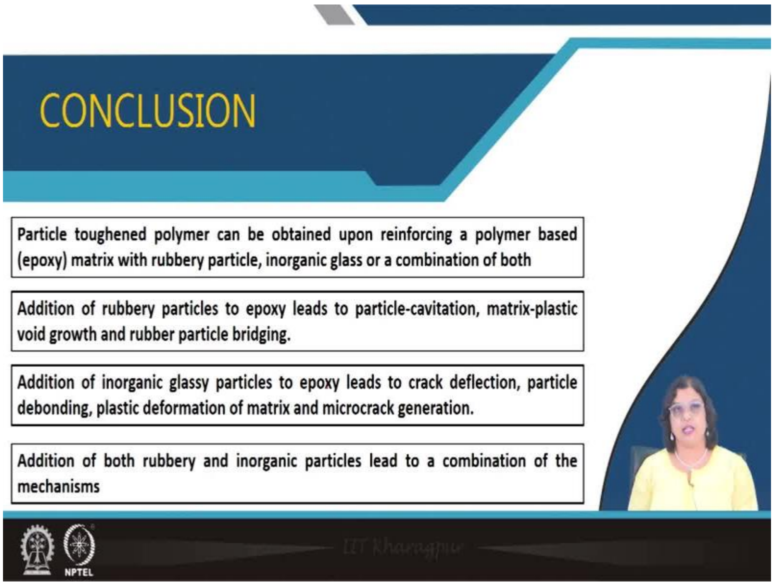

So, what we can conclude from these lectures are the following. We have seen that the surface compressive strength of chemical toughening glass is higher than the thermal toughening one. Laminated glass on the other hand is a type of safety glass that is made with a sandwich of two layer of soda lime glass with a plastic layer of PVB, polyvinyl butyral or polycarbonate in the middle. So, that is how we achieve the higher toughness and most importantly the laminated glass does not undergo catastrophic failure. It still holds even after breakage. Whereas, the tempered glass always shatters into many numbers of pieces, thereby releasing the residual stress.

Laminated glass typically is used for crack arrest application, since polymer deformation provide partial energy absorption during the fracture this polymer in between helps in enhancing the toughness of the entire structure and toughening of amorphous polymer is dependent on the free volume content. Crystalline polymer anyway is tougher compare to the amorphous one and there the toughness is related to the chain formation and the deformation through that.

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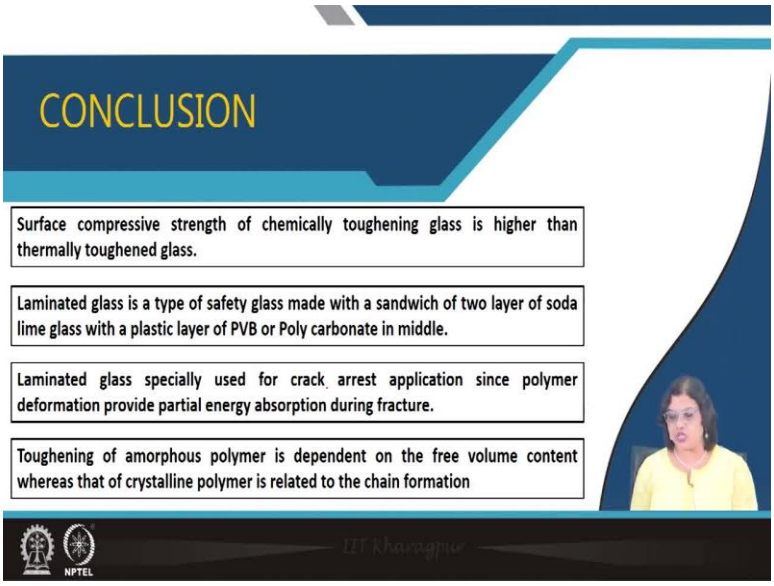

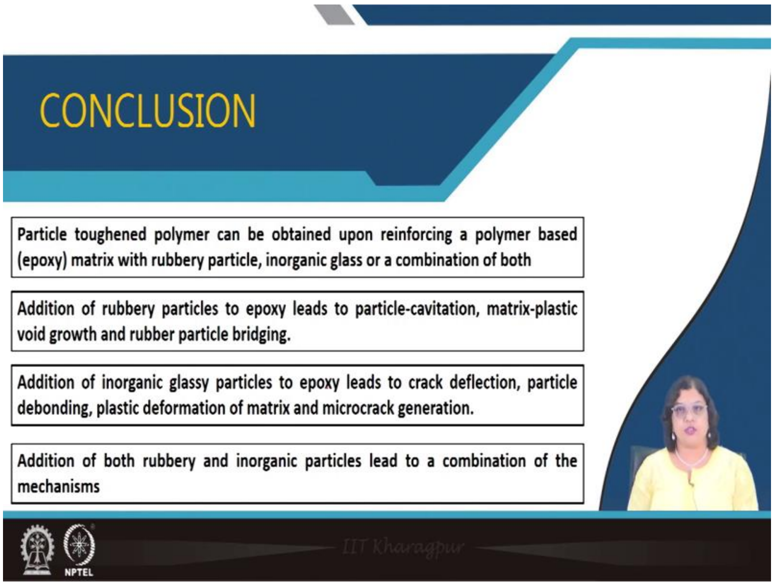

Particle toughened polymer can be obtained upon reinforcing a polymer such as an epoxy-based polymer matrix with a rubbery particle or inorganic glassy phase or a combination of both of them. So, addition of rubbery particles to epoxy matrix leads to particle cavitation and matrix plastic void growth of the matrix and the rubber particle bridging. On the other hand, if we are using an inorganic glassy particle to this epoxy matrix that lead to crack deflection particle rebounding plastic deformation of the matrix and in general micro crack generation and that leads to crack tip shielding and overall enhancement in the toughness. Now, addition of both rubbery and inorganic particles lead to a combination of both the mechanisms and that lead to an enhancement in the toughness of the overall component.

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So, following are the references that has been used for this lecture. Thank you very much.