[SQUEAKING] [RUSTLING] [CLICKING]

Well, Why the theoretical strength of glass materials is so much higher compared to what you would measure in a realistic glass sample? We attribute it to the presence of some kind of defects that actually are present in bulk glass materials that can actually compromise the fracture strength.

So this is what is called the Griffith's theory. Essentially, what is proposed here is there are actually tiny little cracks inside the brittle materials, like glass. So what I'm showing you here, this is basically a slab of the material coming from the bulk. This is one little crack that goes through the thickness of the material. The length of the crack is customarily labeled as 2a.

Now, this is what happens if the crack is embedded entirely inside the material. As you'll see later, in practice, for most glasses, the defects actually come from the surface. Some kind of surface cracks is usually the weak link. So if it's on the surface, you can think of it as you can cut this whole material into two pieces, two symmetric pieces.

And effectively, the correct length would be a. So if it's on the surface, the correct length that needed to lead to the same level of strength decrease is essentially half the length compared to when the crack is in the bulk. So 2a for crack length in the bulk, a for crack length in the surface.

The stress we applied, the macroscopic stress we applied, that's what we label as sigma infinity. Infinity essentially means that we are looking at essentially the average stress far away, very far away from the crack. If you look at the stress field distribution when plotting here-- these are actually the field lines that indicate the direction of the stress.

And the density of these lines gives you, essentially, the level of stress. So you can clearly see that, near the tip of the crack, you have a concentration of the stress here so that effective stress you see at the crack tip is much higher than the applied stress sigma infinity.

So quantitatively, people have gone in and solved this so-called stress concentration factor. Essentially, the level of stress increases at the crack tip. And that's actually given by this factor here, a divided by a0. Now, a0 is what we labeled as the atomic spacing. And a, in this case, this is the half length of a bulk crack or length of the surface crack.

Now, because the length of the crack, it will be in the order of microns compared to interatomic spacing, which is like angstroms, this is many orders of magnitude higher. And that's why you can have significant stress concentration at a crack tip. So then it becomes the weakest link where material preferentially fails at the crack tip, leading to an essentially propagation of crack, which eventually leads to a catastrophic failure.

So now, we can now use that to actually calculate what is the fracture strength of a material now containing a crack. So in the last lecture, we have already mentioned that the theoretical strength of a material, sigma m, this will be given by square root gamma E a0.

So now, because of the presence of the defects here, the stress that's applied at the crack tip is effectively amplified by this factor. So the fracture strength will also be decreased by a factor corresponding to the stress concentration factor. So this will then give you the fracture strength of a flawed material.

So let me put all the equations on the board here. Sigma f is 1/2 square root gamma E a, which now depends, of course inversely, on the length of the crack. So now, you can put in some actual numbers there. We know that, for a typical silica glass, its strength is about 110 megapascals.

You plug in all the numbers, what you come up with is that they correspond to a correct length of about 5 microns. So what it tells you is that, even in the presence of tiny little defects, a crack of the length of only a few microns, that can already account for the vast gap between the theoretical strength and the actual measured strength in engineering materials.

Now, the theory has been proposed for more than a couple of centuries. But seeing is believing. Of course, people will now have ways to actually visualize the presence of these cracks and confirm the Griffith's theory. So what I'm showing you here, this is actually experimental validation actually visualizing the presence of these cracks.

So these are essentially a few different plots. On the top, these two, these are two plots of images collected using atomic force microscope. That shows the surface morphology near a crack. This is actually a little crack here. So this is actually before the crack propagation. This is after crack propagation. You see the crack actually gets longer.

Now, from the difference of these two plots, you can actually get the displacement of the materials around the crack center after the crack propagation. So there's something you can actually theoretically calculate based on Griffith's theory. So the displacement field, the theoretical predicted displacement field, is actually plotted right here.

So now, the last figure here, this is actually a difference between the theoretical prediction and what's actually measured experimentally. Now, if you look at the scale of this plot here, the maximum variation is probably of the order of about 0.2 nanometers-- basically, about 2 angstroms. That's comparable to one single atomic spacing.

So bottom line is, within the accuracy of the measurement, which is atomic spacing, the Griffith's theory did predict very well the stress/strain distribution, the displacement field of the crack. So this really validates that this theory actually works.

So besides the fact that you can actually amplify the stress at the crack tip, the other very important factor that also becomes relevant when it comes to glass materials is that these cracks can also lead to water condensation. So if you think about a little crack here, this will be like a surface crack.

Now, most glass materials, they're actually hydrophilic. So if it's hydrophilic, it essentially means that water will tend to spread on the glass surface, which is basically your experience. You have seen windows. Raindrops falling on windows, they tend to spread. They essentially become in big bubbles.

So to minimize the surface energy, essentially what happens here is that, if you have a little crack, then any water vapor will tend to condensate inside this crack here. And by doing so, you can essentially increase the maximum interface area between the water and the glass, while minimizing any free interface between the droplet and the air. So effectively, this is like this little droplet here is spreading effectively spreading on the glass surface around the crack.

Now, water can be problematic, in this case here, because, of course, we mentioned that if it's SiO bond, SiOSi bond, if you put water in there, then this can lead to essentially a breaking of the SIO bond to become SiOH.

So this will essentially accelerate this integration of the glass network. And if you have a soda lime glass or any alkaline silicate glass, the alkaline ion also tends to preferentially leach out into the aqueous solution. And when that happens, because you have OH here, if you have alkaline ion-- let's say sodium-- then what you end up having is you have a sodium hydroxide, which makes the whole solution becomes basic.

And basic solution would significantly accelerate the chemical corrosion of the glass materials. So this is called a stress corrosion. And later on, we'll have a few slides to discuss about the importance of stress corrosion in subcritical crack growth.

It essentially means that, even if the crack length is below the critical length that's predicted by Griffith's theory, leading to catastrophic failure, the crack will still slowly grow in length because of essentially this stress corrosion behavior, because of the presence of water vapor.

So now, in order to characterize the material strength, what we are seeing here is that the fracture strength, this is no longer a material constant. It depends not only on material constants like gamma and E, surface energy and Young's modulus. It also depends on crack length, which is essentially a function of your sample quality.

So to characterize the material quality using the material's ability to resist fracture, we then propose essentially this new term here called stress intensity factor. So stress intensity factor Ki is basically given as sigma infinity. This is basically the stress you applied to your macroscopic sample. You also have a factor of square root a here, which means, then it normalizes out, the dependence of the fracture strength, only crack length.

So when the Ki, the stress intensity factor, exceeds this critical stress intensity factor, which is labeled as K1c here, so once it exceeds K1c, then it effectively means that sigma-- the failure criteria will be when the sigma infinity, your applied stress, becomes greater than the fracture strength. That's when the material fails.

Equivalently, that translates to your K1 becomes greater than your K1c. Now, for K1c, we can by definition plug in the terms here. K1c is basically the fracture strength times the square root of pi a. So you have your fracture strength here. So if you put in a square root pi a, this will be the expression for K1c.

Now, by looking at this equation here, you understand why people like K1c rather than sigma f as the criteria to gauge material failure. Because, if you look at K1c, it depends on surface energy and Young's modulus. And both are material constants. So therefore, K1c itself is also a material constant. It does not depend on crack length. So then K1c can be used essentially as a way to gauge the material's ability to resist fracture and resist crack propagation.

So K1c is formulated in terms of a stress and essentially the stress at the crack tip exceeding the theoretical stress. You can also define an equivalent quantity. Let's look at energy instead of stress. This is basically defined in this vector here G1 and G1c.

So it's basically K1 squared divided by the Young's modulus. This gives you essentially a strain energy release rate. And the failure criteria is the same. When G1 becomes greater than G1c, then the material will fail. The crack will now propagate, and then eventually lead to failure.

So key takeaway message here is that K1c as a material constant is independent of crack length. So the criteria to tell whether or not a material will actually fail becomes K1 will have to be greater than K1c instead of directly comparing the strength.

All right. So the Griffith's crack theory essentially applies to brittle materials. One of the underlying assumptions is that there is no plastic deformation when the crack opens. That's what Griffith assumes in his theory. So the assumption is a better assumption in the case of glass materials. I did not say it's a perfect assumption because, turns out, even for oxide glasses, which is a very brittle material, when they actually deform, when they actually break, there's also some plastic deformation that actually takes place.

Plastic deformation in oxide glass materials usually assumes the form of essentially condensation. The material essentially becomes-- I should say densification. The material, essentially, the density increases because of the compression. As a result of this kind of plastic deformation, it means that the Griffith's theory does not totally apply even in the case for oxide materials.

Now, when it comes to other kinds of amorphous materials, like amorphous metal, amorphous metal, you have an even larger component in terms of plastic deformation. And this has to do with the nature of metallic bonds.

In covalent bonds, if you have any kind of deformation, you essentially have one part of the material shifting with respect to the other part. This will involve breaking of the covalent bonds. And because a covalent bond is directional, once you break the covalent bond, it's very difficult to reestablish the chemical connection versus in the case of a metal.

Metallic bond is non-directional. So even if you have some part of atom that's flipped with respect to the other part, you can still easily reestablish this kind of atomic level connection there. So what this suggests is that amorphous metal can accommodate significantly larger plastic deformation compared to oxide glasses.

So this is manifested in the fracture behavior of amorphous metal here. That's why I have a few slides specifically highlighting the unique behavior of amorphous metal when it comes to a failure. So depending on how you do the post-fabrication thermal treatment, you can change essentially this kind of plasticity of amorphous metal here.

This is usually called intrinsic plasticity or local plasticity. So one example here, what I'm showing here, this is essentially a fracture surface, SEM an image of a fracture surface for an as-cast amorphous metal, bulk amorphous metal. If you look at the fracture surface here, unlike glass, when they fracture, you have essentially-- unless it has a smooth surface.

If you look at the cross-section here, what you end up getting is something like this. You get a bunch of surface corrugation. So these little ridges is what you observe on the SEM image here. So the presence of these ridges is actually a signature of local plastic deformation.

And the reason you have this kind of a angle in the fracture surface here is because shear stress actually gets maximum at 45 degrees. That's why locally you see a lot of ridges with an angle that's close to 45 degrees. So if you see this kind of fracture surface, this is actually indicative of a local plastic deformation. Now, you can tune this level of plasticity by essentially-- yes?

STUDENT: So the SEM on the left is the fracture surface?

JUEJUN HU: The fracture surface.

STUDENT: OK.

JUEJUN HU: If you induce essentially breakage of an amorphous metal, you then examine the surface, what it looks like.

STUDENT: Gotcha. And then compared to the one on the right--

JUEJUN HU: That's also a fracture surface. It's a different process. So what's on the left here is as-cast. So essentially, you have the metal, liquid metal. You then just put it into the mold, put it into cast, let it cool down. That's what you get on the left-hand side. That's the material.

Now, on the right-hand side, if you anneal this metal for some time-- anneal above the glass transition temperature for some time. So what we have mentioned before is that this annealing can lead to thermal embrittlement. If you anneal it, essentially you lead to a structural relaxation. It relaxes towards the supercooled liquid state, which means that free volume actually decreases.

For metal, once you decrease the free volume, it essentially means that you have less wiggle room for the atoms to move around. This decreases its capacity for plastic deformation. And therefore, it becomes more brittle. So that's why, after annealing, you see the fracture surface appear more like essentially the fracture surface for brittle material. It becomes essentially smooth and flat.

So the key takeaway point here is that, in amorphous metal, we can essentially tune this level of plasticity. And that's why they can exhibit different kinds of fracture behavior compared to oxide glasses, which is a lot more brittle.

STUDENT: Can you explain the picture on the left, how that's also displaying this pyramidal--

JUEJUN HU: This is like a cross-section.

STUDENT: OK.

JUEJUN HU: These are not pyramidal. These are like ridges. Think of it like ridges.

STUDENT: Running--

JUEJUN HU: Yeah, running around. And these are essentially ridges we're seeing here. This is like the tip of the ridges.

STUDENT: Oh, I see. OK.

JUEJUN HU: Yeah, so these are lines. If you look at the cross-section here, each of these lines would essentially have something like this.

STUDENT: So those are like lots of little pits?

JUEJUN HU: Yes, almost. Yes, yeah. And that's what happens. If it's a glass, brittle glass, when the crack opens, it just simply opens there. And we're going to talk a little bit more later about stability of crack. But basically, the crack elongates.

So when it elongates, it essentially creates this fresh, smooth surface. But for metallic glass, as it opens, there's a lot of pressure deformation happens. So it means that the two surfaces don't want to separate from each other simply. So as it deforms, essentially some part of the surface gets stretched.

And then eventually, they break because of the shear stress at the 45-degree angle. So that's what happens, if you think of it like two parts trying to stick together. And as you separate, essentially you pull this material from its original surface, leading to plastic deformation.

STUDENT: So the points were the last contact points before fracture?

JUEJUN HU: Yeah. I mean, these are the surfaces where essentially eventually you have developed large slip. And then eventually, it fractures, yeah. So this is just a different fracture behavior between bulk metallic glass and oxide glass. So it's a bit special. That's why I want to highlight that.

Now, empirically, people have also developed this criteria here. Essentially, you can take the ratio of the shear modulus and bulk modulus. What empirically people found is that, if this ratio is less than this threshold number, this bulk metallic glass tends to be essentially a plastic. Above the number, it becomes brittle. And here are some experimental data that actually plots the fracture energy as a function of this ratio here.

What you clearly see is that, when the material is brittle, the energy required to actually create a fracture is much less, which makes sense because this plastic deformation absorbs lots of energy, which makes the material more resistant to fracturing.

So that's why this kind of a microscopic plastic behavior is what leads to a very high fracture toughness of bulk metallic glasses. This is different for oxide glass. Oxide glass can have very high strength, as we have shown in the previous data. But the problem is that oxide glasses, because they are so brittle, it doesn't absorb a lot of energy. It has high strength, but low toughness.

Bulk metallic glasses, on the other hand, they can have high strength and also a large toughness because you can actually create-- essentially accommodate a lot of local plastic deformation that absorbs a lot of energy and resists crack propagation.

So that's a key difference in terms of behavior here for these two classes of materials, which is what I'm plotting here. Horizontal axis is yield strength. Vertical axis is fracture toughness. That's why you see bulk metallic glasses reside in this top right corner here, which is what we desire for engineering material.

And specifically, for the material, this particular material I'm showing you here, this little star, this is one of the materials-- one of the bulk metallic glasses with very high fracture toughness. This is actually an SEM image showing what happens at the crack tip. So this is actually a little surface crack in this material.

And you can see that, as the crack opens, you see a lot of these shear lines. Essentially, these lines shows essentially they are essentially a shear deformation taking place near those locations. And you can clearly see this very large amount of deformation occurring at the crack tip. That's why this material can be very, very tough because all this shear deformation can actually absorb lots of energy, all the plastic deformation.

All right. So that's a short detour talking about bulk metallic glasses. Now, let's come back to oxide glasses. One of the questions that I think was actually asked during the demo session in the glass lab is how fast does a crack propagate in the glass material. So I actually have a little quick video here. I'm going to click Play here. Let's see, hopefully, no ads. It's a very short video. All right. It's very, very fast. So now, let me try to do it again.

Now, a couple of things to look at here-- one is where does the crack initiate. This is a bit more clear. You can see where the crack initiates, from right there. This is a clear example of essentially a surface defect, as where the crack essentially nucleates, and then propagates through the glass material.

By the way, this is taken at more than 200,000 frames per second. And we have to slow it down by another factor of 4 just to see where it originates. So from that video, you can actually infer the speed of crack propagation in glass. Any of you want to guess what the speed is?

STUDENT: The speed of sound inside glass.

JUEJUN HU: Very good guess-- close, not exactly. Let me see. Why is it not moving forward? This is the correct velocity. You can actually calculate from this plot there. This is about 1/3 to 1/2 of the velocity of sound in glass. You may wonder why is that.

It turns out, if glass is a perfectly brittle material, then your assumption would be correct. As soon as an elastic wave propagates at the crack tip, then the material will immediately exceed its fracture strength at the crack tip, then it will open up. If it's perfectly brittle, that's exactly what's going to happen. However, you may recall that I mentioned glass is not perfectly brittle, even for oxide glass, which is very brittle. It can still create plastic deformation in the form of a compression or densification.

So this plastic deformation is then going to slow down the crack propagation. And that's why the crack propagation velocity is typically about 1/3 or maybe up to 1/2 of the sound velocity in glass materials because essentially it has to essentially overcome the plastic deformation, energy absorbed by the plastic deformation. So it takes more energy to actually open up the crack.

So two things to take away here-- one is that surface is usually the Achilles heel. That's where glass tends to break because some surface defects. And that's why, later on in the next section, when we talk about how to strengthen glass materials, pretty much all the strengthening techniques are centered around how to minimize the surface defect density or find ways to prevent the surface defects from propagating.

Second takeaway message is that glass is not totally brittle. It can still accommodate plastic deformation in the form of densification. All right. So I mean, here is a little YouTube video. I'm not going to play it because of time. But basically, now, people get better videos, better cameras. So they were able to actually redo the process over large panes of glasses. It's fun. You can take a look at this video. There's also a link on here that links to an article on ceramic tech today. It's essentially talking about this particular experiment that people have done using high speed cameras.

All right. So what we are going to do instead, we're going to talk about something that I think is more fun. It's called fractography. What is fractography? Essentially, it's a branch of forensic science. It's about getting-- in our context here, it's about getting a piece of broken glass. And you have to infer why it breaks, how it breaks, essentially answering the question about what actually happened before it breaks.

So this is used a lot in things like crime scene investigation. You'll see some of the references I actually quoted from books. I actually specifically talk about crime scene investigation. That's what people use this for. If a glass pane is broken by a projectile, then what's that projectile? Where does it hit? What does it look like? Where does it nucleate? All those kind of things.

Now, I also want to mention that this fractography is important not just to a crime scene investigation, this is also critical to people who live in the Stone Age, when they are actually trying to process all kinds of stone tools. They essentially leverage this very unique breaking behavior of glass materials to actually create the tool of the specific geometry they need.

You probably have the experience that when-- any of you have broken glasses, glassware at home? All of you have, right? Yeah, exactly. So have you actually looked at the cross-section of broken piece of glass? You notice that seashell pattern, that kind of texture?

That's quite unique to brittle materials like glass. That's called a conchoidal fracture. It's actually a useful behavior if you look at, for example-- in this case, this is actually arrowheads made of obsidian, which is basically a natural glass. You clearly see these kind of patterns there. This is actually the way the ancient people have actually mastered the technique to leverage this conchoidal fracture to create the desired breakage and to shape things into the target geometry.

Now, what we're going to do next, we're going to explain what actually happens, how do you actually look at the fractured glass surface. Instead of the black and white image, I like to show you this one here. This is probably a bit more clear.

So what I'm showing you here, this is a microscopic image of a piece of a broken glass. This is actually a glass rod that was shattered. Now, when you're looking at the fracture surface here, what you want to do, you want to look for a region-- it's a flat region here. That's called a mirror.

A mirror is next to the origin of the defect. So in this particular case, you can actually see right here this is where the surface crack eventually leads to catastrophic failure. So if you look at the glass surface here, you see essentially large regions with essentially a lot of surface undulation.

If you trace it back, you usually see a small region where it's actually smooth and flat. It reflects light like a mirror. That's why it's called a mirror, this particular region here. Now, in the center of the mirror region, you usually find where the crack initiates.

Now, the reason you have a mirror region-- mirror is where the crack starts to propagate. So when the crack starts to propagate, its velocity is relatively small. And as a result, the crack propagation is quite stable. Essentially, say this is the crack. It essentially opens up, like that. So this then leaves behind a well-defined flat surface after it fractures. This is what a mirror surface looks like.

Now, as the crack gets longer, we know that the stress at the crack tip actually gets amplified. The stress concentration factor scales with the correct length. So as the correct length gets longer, the stress at the crack tip actually increases.

This increasing stress means that the energy release rate increases. And as a result, the crack propagation becomes less stable. It will start to essentially create micro-branches. The crack starts to branch out as it propagates.

Now, once it starts to branch out, the surface is no longer smooth and flat. You start to get lots of surface roughness. So that's when you transition from this mirror region into this called mist region. So around it, you see this region here where it becomes start to become foggy. This is called mist region. This is essentially at the onset of unstable propagation of the crack.

So if that continues, then you enter the region, so-called the hackle. I also have this one here. This is similar. This is a black and white image. But you see these are actually hackles. Hackles are essentially these ridges that go along the radial direction that traces back. They point towards the origin of the failure.

So this hackle, the reason you have so much surface roughness, is because you now have a very high energy release rate. Then to accommodate this very high energy release rate, the glass will try to create more fracture surfaces. And this is done through essentially creating a lot of this surface corrugation. So that's why you see this large surface roughness. These are essentially the hackle regions.

Now, this hackle region continues to propagate. And then if you move even further, you start to see these lines here. These are called Wallner lines. These are ridges. The Wallner lines is what actually forms the seashell pattern you see on a fractured glass surface. Those lines essentially are actually tiny little ridges. Those are called Wallner lines.

Now, Wallner lines is formed because of the velocity difference between the correct propagation and the sound velocity in the glass. So the sound wave velocity, this is also velocity where the elastic deformation propagates. Elastic wave propagates essentially with sound velocity.

Now, that's actually faster than the crack propagation velocity because of the elastic deformation. So what that means is that this elastic wave is going to propagate through the material before the crack tip. And then this elastic wave can get reflected or get scattered because any kind of non-uniformity-- for example, you have some kind of surface non-uniformity or whatever-- they can essentially serve as a secondary source that then scatters this elastic wave.

This irregular scattering of elastic waves would then actually cause essentially reflection of secondary waves. These secondary waves, they interact with the propagating crack tip leading to instability of crack tip. So essentially, it create this kind of waviness, periodic waviness.

So this periodic waviness is what then generates these Wallner lines. In fact, what people have found is that, from the period or the spacing between the Wallner lines, you can determine the crack opening velocity. There are tons of papers looking into this. In general, if you have a faster crack opening velocity, the spacing between the Wallner lines gets smaller. That's a rule of thumb.

The shape and the orientation of the Wallner lines also has a lot to do with where the defect is initiated. So if you look at-- this is what I quoted from this reference here, *Criminal Investigation.* Now, what it says is that if you essentially have a flat pane glass that's essentially fractured due to some kind of impact, you may want to decide which side the impact is coming from.

So the way to do that is through this 4R rule. The 4R rule basically says ridge lines on radial fractures are at right angles to the rear. So the ridge lines, this is essentially the known scientific name for Wallner lines. Essentially, these are the Wallner lines.

If you look at the Wallner line orientation on these flat pane glasses, you notice that they all come in this orientation here. And on this side, the Wallner lines essentially come in a surface normal direction. So this is the direction where the fracture propagates. You will see the origin of the defects on top here.

And then this side, where the Wallner lines come in right angles with the surface, is the rear surface. So essentially, the point of impact is on this side of the surface. This is the front side, where the impact happens. This is actually the back side. So by just looking at essentially a cross-section of glass, you can tell where the impact-- which side the impact is actually coming from.

STUDENT: [INAUDIBLE]

JUEJUN HU: What is that?

STUDENT: Time to pull up a crime scene.

JUEJUN HU: Yeah, you can look at that. Actually, if you look online, there are actually people that actually make a living on this. There are people doing consulting just by looking at fractured glass surfaces.

STUDENT: So these curved lines are the same Wallner lines?

JUEJUN HU: They are the Wallner lines. They actually come from, as I said, the interaction of the elastic waves with the crack tip.

STUDENT: OK. And then if you were to take a cross-section going this way--

JUEJUN HU: This way is which way?

STUDENT: [INAUDIBLE] Yeah, parallel to the plane of the glass, perpendicular to this fracture that we're being shown. That's when you would get the circular--

JUEJUN HU: It's right here. So this is the glass pane. And then this is where the cross-section is. So you are seeing essentially these lines going like this. This is actually similar to this cross-section.

STUDENT: But the point of impact face is how you would see this region and the mirror--

JUEJUN HU: Right here? Yeah, yeah. Near the point of impact is where you actually see the mirror, and then essentially the mist and hackle. And outside that, in larger macroscopic regions, that's where you actually start to see these Wallner lines.

Yeah. I mean, if you look at the length scale here, so this is 200 microns. So the mirror region, the size of the mirror region actually depends on how much stress you apply. The higher stress you apply, the smaller mirror region is, which makes sense.

The higher stress means that you have a high energy release rate. The crack easily becomes more stable-- sorry, it becomes more unstable. So that's why mirror region becomes smaller. But typically, the mirror region is of the order of a few hundred microns. So you can see it on the naked eye, this small region there. And then outside, this is typically of essentially like millimeter region, hackle and mist. And then beyond that, several macroscopic scale, you see Wallner lines coming out. Yeah. Yes?

STUDENT: So back to the other slide, so how does the thickness of the glass affect the Wallner lines? Is it just a longer--

JUEJUN HU: It gets longer.

STUDENT: Or--

JUEJUN HU: It gets longer. The Wallner lines, the main difference that actually impacts the Wallner line morphology is actually the velocity difference between the elastic wave and the crack propagation velocity. In fact, people have this empirical formula that basically says that the spacing d between the Wallner lines is roughly given by V-- let's see, elastic wave. Let's say Ve minus Vc.

So Vc will be the crack velocity. And Ve is elastic wave propagation velocity, which is basically sound wave velocity. And f will be the frequency of elastic waves. So that's what I'm saying. Because Vc is always smaller than Ve, so you have a higher correct propagation velocity. The spacing between Wallner lines actually essentially gets bigger. Yeah.

And then Vc also has to do with essentially, for example, intrinsic plasticity in the glass materials. It has to do with how much stress you apply. So there are lots of things you can infer just by essentially looking at the morphology of the fracture surfaces there.

Now, one more thing I also want to mention here is that, for this particular kind of morphology, this only applies to essentially non-tempered glasses, so not strengthened. Temper is basically a process that you essentially do a fast annealing, fast quenching on the glass material to introduce surface compressive stress. We're going to talk about it later.

But it just suffices to highlight that, if it's tempered glass, the cross-section looks quite different. This is actually what it looks like. So actually, this is a top surface. This is a bottom surface. This is essentially a tempered glass pane.

When it fractures, you usually have center-- essentially, you have the mist hackle band. So in the center, this is where you actually have a lot of tensile stress. This is where usually the defect initiates in the tempered glass. This is unlike regular glass, where you usually have surface defects.

In tempered glass, the defects usually initiate in the inside, in the interior, where you have large tensile stress that facilitates crack opening. So that's why you see the mist and the hackle actually in the center, rather than near the surface.

And then you see the Wallner lines. You have two symmetric Wallner line propagation patterns on the outside. And then near the surface, you see this horizontal pattern. This is actually indicative of the high compressive stress on the surface. That's what leads to these horizontal lines.

You can also look at the pattern of the breakage here. You essentially have these primary cracks that propagate in the radial pattern. And then you also have these secondary cracks that essentially branch out. You can always trace back to the center of defect, right here. You see this butterfly-like pattern? This is actually called a butterfly, if you look at the fractography. And the defect usually is right here, where I'm pointing there. That's where the initial defect actually happens.

OK. So this really just scratches the surface of fractography that people actually spend decades essentially looking into this. But at least next time, if you do break any kind of glass materials or glass pieces, don't panic. Do your fractography. You can then go back to tell your parents or whoever that it's not your fault. Most likely, a surface defect is the culprit, 99% of the cases. OK. Any more questions about fractography?

STUDENT: Yeah. Is this-- do these patterns only occur when there's total fracture? Or is it happening--

JUEJUN HU: It depends.

STUDENT: Hackles and the Wallner lines when it's still just crack propagation but not yet fractured?

JUEJUN HU: Well, it depends on which face. I mean, the problem with glass is that, once you get a crack starting to propagate, unless you very promptly terminate the stress, it's going to propagate very quickly. So it's hard to see a half open crack thing. You have to terminate it in a fraction of a second.

STUDENT: You wouldn't really get to, oh, the hackle region--

JUEJUN HU: [INAUDIBLE]

STUDENT: We saved it--

JUEJUN HU: You could. Think of it-- the propagation velocity is like 1,000 meters per second. And the width of the region is like a few hundred microns. So you'd have to stop it really at the microsecond level. If you can precisely control that, then you will actually see it.

STUDENT: But they are sequential?

JUEJUN HU: They are sequential. You start with mirror, mist, hackle, and then eventually Wallner lines.

STUDENT: OK.

JUEJUN HU: Yeah. So by looking at fracture surface, you're already tracing back in time. That's how it actually initiates.

STUDENT: Even if it's a very short amount of time.

JUEJUN HU: It's a very short amount of time. Exactly, yeah. Now, let's talk about crack propagation over a much longer period of time. So the Griffith's theory has one important limitation. It's that time is actually not a function in Griffith's theory.

Griffith's theory is very simple. If the stress at the crack tip exceeds the material strength, crack is going to open. Once it starts to open, the crack gets longer. The stress actually gets more amplified. Then it means that essentially the crack opens at an even higher velocity. So it's a one-way street. It just quickly, immediately leads to catastrophic failure.

However, what people observe in glass materials is, even if the stress, applied, stress, is below the fracture stress of glass, if you keep the load, over time, the glass will still fail, even if sigma infinity applied stress is less than sigma f. So the reason that happens is actually-- this is called essentially a fatigue in glass materials. And it actually has to do with the stress corrosion. It's because of water vapor getting condensed into the crack tip.

So what I'm showing you here, essentially this is called static fatigue. Essentially, it means that you apply a static load, sigma infinity that's less than sigma f. And then you can measure the time to failure for glass pieces. And you can generate a plot like what I'm showing here.

So the vertical axis is essentially the sigma infinity, which is the applied stress normalized to the fracture stress. You see that this is below 1. So it means that you are looking at another catastrophic failure of glass material. This is essentially a fatigue failure that takes a long, long period of time. So this is below the fracture stress.

Horizontal axis, this is the time to failure. Now, this is a pretty messy plot with lots of different symbols, whatever. Let's don't worry about that. Let's just focus on one line here. Each of these lines essentially represents one type of glass sample with a specific surface preparation.

These different symbols here, each of them represents a different level of abrasion. Now, abrasion, you can think of it as essentially trying to create surface defects. Different levels of abrasion give you different surface crack size. So these are essentially different glass materials with a different surface crack sizes.

So if you focus on only one of the lines here, what you see is that, as you increase the applied load, the time to failure decreases, which makes sense. And it decreases in this logarithmic manner because this is actually an exponential, essentially a logarithmic axis in the horizontal axis. Essentially, the time to failure increases logarithmically with respect to the applied stress.

STUDENT: But it still fails quite quickly.

JUEJUN HU: Yeah, it's under a second. Under a second, essentially. Or it can be like hundredths or thousandths of seconds, either way. Yeah?

STUDENT: [INAUDIBLE]

JUEJUN HU: Yes.

STUDENT: Even at, like, very less than, like, half [INAUDIBLE].

JUEJUN HU: So for these curves here, these are measured for different samples. What we can also do is we can try to normalize all the curves with respect to the intersection point with the horizontal line here. So this horizontal line corresponds to when the applied stress is half of the fracture stress.

So if you normalize all the curves with respect to their cross-section points with the horizontal line here, then turns out all of them collapse into one single line. This is called a universal static fatigue curve. It gives you a way to predict how long the glass sample will last under different levels of applied stress.

STUDENT: I don't think I understand.

JUEJUN HU: OK. The way it works, the horizontal axis, this is t divided by t 0.5. Now, t 0.5 is basically the intersection point of one of the curves with this line here. So this line corresponds to essentially the time to failure if you apply a stress that's half of the fracture stress.

You then normalize the time to failure to that t 0.5. And then you take the logarithm. What you end up getting is this mostly linear relation. So it says that essentially the stress scales the logarithm of t basically. So with this plot, essentially if you know your-- if you know your t 0.5 and you know your load, you can then use it to actually predict the time to failure for your sample. Yeah.

Now, what we want to do is let's take a look at, in more details, what exactly is the microscopic mechanism that lead to this kind of static fatigue. So as I've already mentioned, this has to do with stress corrosion. So what happens is that, inside a crack, surface crack, you always get condensation of water vapor.

And this water vapor then leads to essentially a disintegration of the glass network through this chemical reaction there, which can also get further accelerated if you have alkaline present in glass network. They can preferentially reach out, go to the solution, form the hydroxide, lead to a basic solution that essentially attacks the glass network even faster.

So what I'm showing on the right-hand side plot here, this is the crack velocity as a function of the applied stress. Basically, stress intensity factor basically is essentially a parameter that synthesizes both applied stress and the crack length. So what we are seeing here is that, for different kinds of glass materials, you have different crack velocity.

You have essentially soda-lime. This line lies on top means it has the highest correct velocity under static load, which makes sense because soda-lime has lots of soda, lots of sodium. So the sodium essentially is what's causing this accelerated chemical attack due to this stress corrosion versus silica glass.

This line at close to the bottom, it's a little more chemically stable because it doesn't contain these sodium ions. So this is one evidence showing that the presence of this sodium ions is the culprit that leading to stress corrosion.

Now, more carefully, people also did more careful study looking into the kinetics of this process here. So again, this is a very messy plot. Let me try to explain what happens. So in this plot, what people are looking at is the crack velocity. This is the crack growth velocity under constant load as a function of the stress intensity factor.

Now, the stress intensity factor, if you keep the load constant, then the stress intensity factor basically correlates with the length of the crack. The larger the length of the crack, the larger the stress intensity factor. So horizontal axis, you can treat it as the length of the crack or square root of the length of crack, to be exact.

So then what we are seeing here is that there are different groups of curves. Each of these curves corresponds to a relative humidity level in the ambient air. So this is 100% relative humidity. This is 0.017% relative humidity. So in each curve, it goes like this. It starts to rise, plateaus, and then suddenly goes to this conversion single line there.

So we can divide this behavior into three different regions here. Region 1 is this linear increased region. Region 2 is the plateau. And region 3, all the curves essentially collapsed into one single line. So now, let's see what happens.

Region 1, this is where, if you have a larger stress or longer crack, you have a higher stress intensity factor. The crack opening actually becomes faster. That's what it says. Also, you clearly see that, if you have a higher relative humidity, you get more water condensation. Then the process actually gets expedited exponentially. This is clear evidence that water vapor actually plays a significant role in the subcritical crack growth.

Now, if you come to region 2, what happens in region 2 is that the crack growth rate becomes independent of the stress intensity factor-- or in other words, independent of the correct length. Now, normally, if you have a longer crack length, you should have a higher stress. You have more stress concentration at the crack tip. So you should have higher stress at the crack tip.

So the reason that you have a-- now the crack propagation velocity becomes independent of crack length is because now the kinetics actually controlled not by the stress, but by the mass transport. If a longer crack, it takes longer time for the water vapor to diffuse into the crack and reach the crack tip. And water vapor needs to get to the crack tip in order to cause all the chemical reactions. So region 2 is basically a transport limited region. Yes?

STUDENT: So technically, when people are making glass lenses and we use water around the drill, if it's not moving as fast as it is to not let the water enter the region--

JUEJUN HU: It will enter. It will enter. I mean, if you at it, this kind of a subcritical crack growth occurs even for relative humidity of like 0.017%. That's like extremely dry. So the problem is that glass surface is extremely hydrophilic. So even if there's only a tiny amount of water vapor, they will tend to condense at the crack tip. So it will get in there, regardless of what you do. [INAUDIBLE] Yeah, and so water is so--

STUDENT: Just basically, it's like, oh, people usually use water as some of cleaning [INAUDIBLE] for drilling. It's just like, oh, water is actually making it prone to cracking.

JUEJUN HU: It is. Yeah, it is. It is, yeah. Yeah, that's why later on we're going to talk about some surface treatments. People do local firing and stuff, essentially trying to heal the cracks. So if you really want your piece to be strong, that's the surface treatment you have to do. Yeah, and glass lenses, it's usually OK. People don't care so much about the mechanical toughness. So it's OK. But in other cases, where you have that requirement, you have to do surface treatment. Yeah, you cannot just leave it like that.

OK. And then the third region, this is when you have a sufficiently long crack, where you start to get essentially expedited crack opening. Once you get to the third region, the crack velocity essentially quickly grows. And this eventually leads to a catastrophic failure. Eventually, the fracture strength, the applied stress reaches the fracture stress.

Then the crack immediately opens. It leads to a very high speed crack propagation. And then the material just fails. OK. So this is essentially what the three regions describes. So bottom line, glass material can fail even if the applied load is actually below the fracture stress because of stress corrosion.

All right. So the last couple parts of the talk, I will describe a little bit about the characterization of fracture behavior in glass materials. So to measure the fracture toughness, people have established standards. Essentially, these are ASTM standards you have to follow to actually measure fracture toughness.

To measure fracture toughness, because the definition of the fracture stress, it has to do with the length of the crack, so to precisely measure fracture toughness you need to find ways to actually generate cracks with a predefined length.

And that's why people designed these specific sample geometries just to generate cracks with a specific length. So for example, if you look at this one here, it's a sample with a notch. You prepare this sample with a notch. And then at the tip of the notch, you then use static fatigue to generate a crack.

You have to look at it under an optical microscope to essentially look at the correct length to ensure that when, you actually do the testing, the correct length is exactly at what we specified. So you can see that this is a pretty laborious process, just to do a fracture toughness testing, if you want to comply with ASTM standards.

You have to essentially prepare a sample, wait 'til the crack goes to the desired length. And you also have to do active monitoring to ensure that's actually the case. Then once you have this sample, you can put it into a loading machine. You can measure the load displacement curve. From that, you can actually infer the stress toughness of the material here.

Now, as I have already mentioned, this can be a pretty complicated process. It's quite difficult to comply with the standards. So that's why people have also come up with simpler methods to infer what is the fracture toughness of materials using techniques-- for example, as an indentation.

So indentation essentially means that you have a stylus. The stylus has some kind of tip. You then press it against your material. And then you apply a load. Then this is going to press the stylus, which is made of some kind of hard material, into your material. And then once you remove the load, it's then going to cause some crack. From the crack propagation behavior, you can then use that to actually infer what is the fracture toughness of the material.

The downside with this kind of indentation method, while being very simple, is that sometimes it's a bit more on the empirical side. The correlation of the data you collected using indentation does not correlate always very well with the data you get from the standard ASTM measurements. So take with a grain of sand. If you see people reporting fracture toughness values using these indentation samples, there can be considerable dispersion based on the specific details of the measurement.

But just to show you one example here-- I mean, there can be different tip designs. This is a Hertziqan tip, which is basically a sphere. This is the more commonly used Vickers indenter tip. It has pyramidal geometry. So if you press one of these Vickers tips against a glass sample, let's see what happens.

So what I'm showing you here, this is actually a few optical microscopic images showing you essentially this is the pit or the dent that's caused by this stylus on the glass surface. This is during loading. And this after unloading. So the first one, this is during loading cycle. This is 50% of the maximum force applied. This is at full load. This is when you start to essentially release the stylus. And this is after complete unloading.

Now, what you notice here is that, during the loading cycle, the dent increases in size because the stylus essentially gets pressed against the sample wall. But there's no crack formation. The crack only starts to nucleate when you start to unload the stylus. This is quite typical for glass samples. Glass samples, typically, they don't fracture under compressive stress. They fracture when you have essentially a tensile stress.

Now, you may wonder where the tensile stress is coming here in this kind of compressive test. So what actually happens is that a glass material, when you actually compress against it, it will deform both elastically and plastically.

So when you start to unload, the part that deforms elastically is going to try to restore its original geometry. But the part that has deformed plastically, it will try to keep the original shape, the deformed shape. So then the mismatch between the plastic deformed regions and elastically deformed regions then will lead to essentially this fracture and the crack propagation.

So that's why you see the crack formation during unloading cycle because of this mismatch here. And you can clearly see the crack propagate in this kind of a crisscross pattern corresponding to the four corners of the Vickers tip. This is where you have high stress there. And then from the size and shape of these cracks, you can use that to infer the fracture toughness of the material. So that's basically the idea there.

One thing I also want to mention about this kind of measurement here is that, because the glass's fracture toughness depends on the length of the crack. So it means that any kind of fracture toughness measurement is inherently statistical.

For different glass samples, even if they are prepared normally using the same technique, the distribution of the defect size is statistical. It's random. And the ultimate strength of a glass sample actually is determined by the longest crack, the longest crack corresponding to the weakest link.

Now, the maximum crack length is a statistical parameter in different glass samples, even if they are prepared nominally using identical conditions. So that's why, when you actually try to measure fracture toughness, you should not only just measure one single glass sample. You should always measure a large group of glass samples and look at the statistical distribution of the fracture toughness. So that's the way to go.

And that's why people have also developed all kinds of fracture statistics methods looking into the distribution of fracture toughness in glass samples. So the most commonly used distribution, this is called the Weibull distribution. What this function describes is the so-called cumulative failure probability.

Essentially, what it says is that F gives you the fraction of samples that fractures at stresses below sigma. So now, if you think about the ideal case, if there's no distribution, there's no statistical distribution, all the samples are exactly identical, they should all fail under the same stress.

So in that case, in the ideal scenario, then the curve will basically be a step function. Below the fracture strength, nothing is going to break. Above it, all, your pieces are going to break. That would be the ideal scenario.

Now, obviously, because of the statistical nature of a glass failure, what you end up getting is this kind of sloped function there. And this function here, this so-called Weibull modulus, the exponent here, and then characterizes how steep this diffusion is.

A larger Weibull modulus corresponds to a more tighter distribution. So a large Weibull modulus essentially means that you have a better control over the quality of your sample. You have a more tighter distribution of its fracture strength.

So that's one way to characterize this kind of statistical behavior of glass fracturing. Alternatively, you can also use a probability density. You take the derivative of F with respect to sigma. What it gives you is then the probability of sample to fracture at a particular stress level.

So if you go to your ideal sample, then what you have here for this probability is going to be a delta function. All the samples should break right at the fracture stress. So if you have a statistical distribution, then the delta function broadens into a peak. Same thing, higher Weibull modulus gives you a tighter distribution. It means that you have a better control over the quality of the sample.

So now, if you actually go and do a project and try to measure the statistics of glass fracturing, how would you actually process the data? So what you do is you essentially prepare a large number of samples nominally under the same condition. You subject all of them under this tensile stress test and recall what the stress they feel.

Then from that, you can then try to fit this function here by essentially using essentially a slightly different form of this function. You try to fit this function. You essentially apply a double logarithm. You can transform it into this form here.

Now, the beauty of using this form of the function is that now, if you plot this double logarithm of 1 minus F as a function of logarithm sigma, the slope of the curve will then give you m. And then the intersection of the curve with horizontal axis, this corresponds to essentially sigma equal to sigma 0, where sigma 0 gives you the average failure stress. So by plotting your theta on this curve here, you can then infer what is the Weibull modulus, as well as your average failure stress of the material.

So in the bottom right corner here, I'm showing one example I quoted from literature. This is actually measurements for four different sets of samples here. You can see that, for three groups of samples, the first three groups, you get a reasonably good linear fit, which allows you to infer the Weibull modulus and the average fracture strength.

Now, this last group, D here, is a bit peculiar because you see there's a very clear inflection point where the line essentially changes slope. So what this indicates is that you have essentially a bimodal diffusion of defects. In some samples, you see that, if you extend this line, you intersect with the horizontal axis with a different sigma 0.

So different sigma 0 essentially means that these samples tend to have this bimodal behavior. You have two groups, two subgroups, where each of the groups has a distinctive average fracture strength. So that just means that you need to essentially look a little bit more in the processing of that sample.

There's some kind of inconsistency there that generates-- possibly generates essentially larger defects in some subgroup of samples over the others. So this is also a good way for you to gauge about the consistency of your process and how reproducible your process is, in terms of generating a defect of certain size. Does that make sense?

All right. So this is so much about the basic theory about fracturing. I'm not going to go through a bullet point list here. But the key point is that we essentially discussed about why the material strength is much lower than theoretical strength. We talked about the role of the crack in lowering the theoretical strength, as well as the role of stress corrosion that can play in the subcritical crack growth.

The key takeaway point here is that the weakest link in glass material usually tends to be a surface. The surface is where you come into contact with all kinds of [? enemy ?] environments. You can have mechanical abrasion. You can have essentially water condensation. So you tend to have the highest density of defects on the glass surface.

And when the glass fails, those surface defects are usually where the crack nucleates. So if you want to strengthen the glass material, what you have to do is try to find ways to essentially either eliminate those defects or to find ways to prevent the crack propagation from the surface.

So that's what we are going to cover in this application section here where we talk about practical ways how people actually strengthen glass. So strengthened glasses, they have many practical applications. They can be applied in, for example, solar panels, which is the one good example where you need to have glass materials that's not only transparent, but also have good mechanical strength. They can withstand all kinds of natural weathering and even extreme weather conditions like hail. They cannot break under extreme conditions.

Display is the same story. People are always looking for stronger display glass. And there's also a trade-off there. For display, people also like to use glasses with smaller thickness, which reduces weight. And smaller thickness obviously creates a compromise in the mechanical overall strength. So how to enhance the glass strength while reducing the weight is a big topic in that kind of applications.

The glass material can be so strong that people even apply them for defense applications. The windows on tanks, for example, they are actually made of strengthened glasses so that they can actually be bulletproof. So we're going to discuss about strategies how to increase the mechanical strength of glass materials, so they can resist projectiles like bullets.

OK. So this slide essentially summarizes, at a high level, what are the different strategies how you enhance the strength of glass materials. Three different ways-- you can look at essentially-- goes back and look at what we have here.

So you want to maximize sigma F. What you can do, you can either increase your K1c-- if you increase your K1c, you improve your glass material so it inherently becomes more resistant to crack propagation. So you can change your glass chemical formulae to essentially enhance this ability to resist crack propagation. That's one way.

What you can also do is that you can reduce the defect density or reduce defect severity. It essentially means that you try to minimize the generation of any long cracks on the surface. Because K1 scales with square root of the correct length, so effectively you are reducing K1 and, therefore, enhancing the longevity of the glass material. So you can eliminate surface defects. That's another way.

The third way here is to prevent the crack propagation. Even if you try all the methods you talk about in the second example here, it's very difficult to still completely eliminate any kind of surface defects. So a very common way to enhance the strength is to introduce essentially a surface compressive stress.

So even if there are some defects or cracks that's already happening on the surface, this compressive stress will try to keep the crack closed so that it doesn't propagate and, therefore, it doesn't lead to failure. So these are the three general strategies how to actually enhance the strength of glass materials.

Now, for the first one, for example, you can do crystallization. Surface crystallization helps in several different ways. First of all is that the crystalline material, which is basically ceramics, they can mechanically be more stronger than glass. So that actually helps.

And also, the material you crystallize in this manner here, starting from glass, this is actually called glass ceramics. Glass ceramics can also have superior mechanical properties sometimes, even compared to ceramics, you prefer using traditional methods, which is basically sintering.

The advantage of this kind of glass ceramics is that you're starting from a completely dense matrix. Glass is essentially a pore-free matrix. It's not porous. Unlike the case of sintering, you start from a powder. Inevitably, there's always a little bit of air gap in your preform.

So glass ceramics can give you a higher density compared to conventional sintering methods, which can sometimes translate to better mechanical properties. Also, crystallization can also change the surface stress. And this can be seen by essentially looking at the volume versus temperature curve.

So if you think about this, the curve we have seen for many, many times-- this is temperature. This is volume. This is glass. This will be the corresponding ceramics. So if you heat up the material to some point here to crystallize it, the crystallization temperature will be above the TG.

So then the volume change for glass will be given by essentially this vertical offset here. The volume change for ceramics, on the other hand, will be this. Sorry, the volume change for ceramics will be this one because, once you introduce crystallization, at high temperature, the stress will be relieved.

So what's causing the ultimate change of volume, when you actually cool it down, will be the volume contraction due to the thermal expansion. Now, this volume change is actually smaller for ceramics as compared to glass. So that means, because if you introduce, for example, crystallization on the surface of the glass materials, then the interior will contract more. The surface will contract less.

So as a result, the surface will then be under compressive stress. And compressive stress will help to prevent opening of the cracks. So that's also one way, by introducing a surface crystallization, you can actually also introducing surface compressive stress and therefore improve the stability of the material. So that's why crystallization can sometimes help.

The downside of crystallization, obviously, is that you lose some of the desirable properties of glass, like transparency. You can also change essentially-- you can also go to composites. Instead of using one layer of glass, you can combine it with other materials-- for example, with polymers.

So you can take the best of both worlds, both the high strength of glass, as well as the ductility of the polymer materials to give you a better durability. You can also engineer glass structures, which I'm going to talk about in the next slide.

Now, second general strategy here, you want to reduce the defect density. A common way of doing it is so-called fire polishing. Now, what I'm showing you on this photo here, this is a photo of a test tube, glass test tube. You probably notice that, for the glass test tube, which is basically made from cut glass tubes, the edge is usually smooth. It's rounded.

The reason it's rounded is because, once it's freshly cut, they usually essentially basically fire it, subject it to high temperature. When you subject the surface to high temperature, essentially it goes beyond the glass transition point. It becomes a viscous fluid. It starts to flow a little bit.

And because in this flow process you're going to fill in any surface cracks and create a smooth surface. And under the action of surface tension, you can create this smooth surface finish free of cracks. So that's one way to reduce surface defect density, just simply by using a viscous flow property of glass materials.

You can also do surface etching. That's straightforward. You just etch away the surface layer, which brings away any kind of surface defects. You can also do a surface coating. We already talked about one example when we talk about essentially making glass containers.

When you make glass containers, there are two surface coating steps-- [? hardened ?] coating and [? coolant ?] coating. [? Hardened ?] coating is essentially putting a tin coating there. And tin oxide has a higher mechanical strength compared to glass materials, which is beneficial to increase this abrasion resistance.

You then put in the [? coolant ?] coating, which is a polymer layer, which serves as a lubricant that minimizes any risk of generating the surface defects due to essentially wear and tear. So that's another strategy there. And finally, we'll spend also a lot of time talking about compressive stress, two ways of generating compressive stress, either through thermal tempering or through ion exchange, or so-called chemical tempering process.

Now, let me come back a little bit, start by talking a little bit about how to actually tailor the-- in fact, we are running out of time. So we'll probably stop here. In the next lecture, we are going to discuss about the specific strategies, how to follow through with three different ways to enhance the strength of glass materials. Any more questions for the lecture here? OK. Then let's stop here.