[SQUEAKING]

[RUSTLING]

[CLICKING]

PROFESSOR: So OK. So in this lecture here, we are going to continue our discussion about, essentially, glass viscosity. I'm starting out with showing you this slide here that shows the different viscosity reference points that are of importance when it comes to glass processing. So horizontal axis is basically the viscosity in log scale. And there are a few important viscosity points that I want to highlight here. First one is being this working point. It corresponds to a viscosity of 10 to the 3 Pascal-second.

So below the working point, the glass basically flows just like a regular fluid, so like water-like. So it becomes very difficult to actually hold any shape for a given period of time. And that's why below that it's pretty much just considered like a fluid. It's a super cool liquid. So you need to have a sufficiently high viscosity to enable any kind of glass processing. So that's what the working point means. The viscosity has to be higher than the working point for actual glass shaping.

Then the next part is called softening point. So if you go above this softening point, which corresponds to 10 to the 6.6 Pascal-second viscosity value, then the glass melts, becomes so stiff that it becomes difficult to actually start to deform it.

So between this working point and softening point, this is what's defined as the working range for glass melt. So just to give you an intuitive example about what the viscosity is like, I have actually marked here this little arrow right in the middle of the working range. This is the typical viscosity of chewing gum. So intuitively, the glass will behave like a chewing gum within that viscosity range, and you can easily essentially shape it, change it to any kind of geometry, and you'll hold it there for some period of time that allows you to essentially sustain the shape you want. And once you cool it down, the viscosity increases, then you're sort of freezing the geometry you need.

So I have listed here-- in the next lecture, we are going to talk about different glass-shaping techniques, specifically. But you can see there are a lot of these glass-shaping techniques, they all have a viscosity value that falls within this window here.

The next reference point is annealing point. So annealing point corresponds to 10 to the 12 Pascal-second viscosity, which basically coincides with the definition of Tg. So annealing point is basically glass transition temperature. Annealing point is where, once the glass product is made, this is the temperature where you do a post-shaping annealing to release any internal stress. OK.

So at the annealing point, microscopic changes can still take place. You can relax any internal stress and strain, but macroscopic shape change no longer takes place. Because it requires low viscosity value to induce macroscopic movement. So that's basically the temperature where you actually anneal the glass products without distorting the shape while ensuring that they don't have any kind of internal stress there.

Now, if you look at this viscosity value, by the way, for pitch, which is a very viscous fluid, you see this viscosity, you can measure it from the pitch drop experiment, it's of the order of 10 to the 8. So 10 to the 12 is very high viscosity. That's why you don't see any kind of macroscopic deformation there.

Now, finally, when the glass exits the annealing furnace, its viscosity will be higher than the straining point. So straining point is the viscosity value where, above which you don't even have microstructural relaxation. So annealing essentially takes place between the annealing point and straining point. This is where you can have a strain-stress relaxation.

So we'll see this reference chart again when we actually talk about glass processing, in fact, in this lecture, the later part of this lecture. But these are the important reference points that's important to know in glass processing.

So to control the viscosity, we have a very simple knob here for glass materials. You can simply just change temperature. From the previous slide, when we talked about the Angell's plot, we know that the viscosity changes by many orders of magnitude because its thermally activated phenomena. So yeah.

So then it gives us a very easy way to essentially tune viscosity and push to the desired value for specific processes there. So then, depending on the specific kind of amorphous material you're looking at here, they can exhibit different kinds of behavior in terms of viscosity there. Specifically polymers.

So for amorphous polymers or-- lots of polymers, they are actually not purely amorphous. They are a mixture of amorphous phase and crystalline phase. But either way, as long as it contains amorphous phase, then from a rheological perspective, they all behave pretty similar. They exhibit this kind of a temperature-dependent viscosity curve, like what I'm showing on the left-hand side here.

At low temperature, they basically behave like hard plastic. They don't easily deform. It's rigid and stiff. As you start to heat it up, you go into, essentially, this sort of rubbery state. This is beyond, basically, the glass transition temperature. The molecular chains, they start to have enough energy to move around. They can change their conformation, they can move past each other. So then they go into a state that behaves more like rubber. So that's a rubbery state in the polymer language, typically what people call it. And then if you continue to heat it up, eventually it becomes a liquid, glass-forming liquid.

So you can engineer this kind of viscosity behavior like changing microstructure of the polymers. So for example, if you want to change the Tg in polymers, so that you change the softening temperature, you can add some stiff chemical groups like benzene. Benzene is a ring. It's a planar ring. It doesn't easily deform. So if you add benzenes into the polymer chain there, it increases the stiffness of the polymer chain. It becomes much more difficult to deform it. And as a result, the viscosity is going to rise.

And because Tg is defined with respect to viscosity, essentially, that means you also raise the Tg. So that's one way to essentially change the Tg. If you want to decrease Tg, on the other hand, what you can do-- typically, people put in what's called a plasticizer. Plasticizer, these are essentially small molecule solvents. They go into the polymer network and they serve as molecular lubricants. They decrease this internal friction between the polymer chains, so that it becomes a lot easier to move around. And the result is that you can actually decrease Tg in this case, which could be useful if you're trying to do some processing at greatly reduced temperatures.

One example of this kind of a [INAUDIBLE] low-Tg polymer is this kind of polymer there. You can actually buy it from Amazon. It has a glass transition temperature that's engineered to be around 70 degrees Celsius. So if you put it into hot water, it softens. It becomes something you can mold by your hand to any kind of geometry. But when it cools down back to room temperature, it becomes stiff again. This you can search for on Amazon. This is called foam cards. So this would be quite handy if you're trying to just make something quickly. And again, this all goes into how you actually engineer the polymer Tg, so that you can change its softening behavior in this case. So that's for organic polymers.

Now, for inorganic glasses, in this slide here, I'm summarizing the temperature dependence of viscosity for many different compositions of inorganic glasses. The general rule of thumb is that viscosity is a parameter that links closely with the network connectivity. And intuitively, it makes a lot of sense if you have a network that's connected together by many rigid chemical bonds that is very difficult to deform it. And therefore, you should have a high viscosity. So typically, high network connectivity would correspond to high viscosity and hence high Tg.

So if you look at this plot here, on the upper right corner, this orange curve, this corresponds to a silica glass, just SiO2. Now, you see, for SiO2, its working range, in fact, is extremely high. It's beyond this chart here, its working range. So that's part of the reason why silica glass products is much more rare. It's actually a lot more expensive. Typical glass workshops, they cannot work with silica glass, because their furnaces are not at a high enough temperature to just soften silica glass so they can process it in different shapes.

Now, the next group of glasses we're going to look at here, look at these two curves here, this blue one and this green one. These are essentially borosilicate glasses. So you notice that they still lie above the conventional soda-lime. This black line is a typical soda-lime-- windowpane glasses. So we have already talked about it. When you add boron into the glass network, you can trigger this P3 to P4 conversion, and therefore, you essentially increase the network connectivity.

And that's why borosilicate glasses, they tend to have a higher viscosity compared to soda-lime glasses. In other words, if you look at all the temperatures, all the viscosity reference points-- working range, softening point-- borosilicate glasses tend to have much higher temperatures compared to soda-lime glasses. And that's why, in fact, it's more challenging for glass workshops to actually process borosilicate glasses.

And then finally, you see that if you add a lot of alkaline, then this is the way you actually use to actually decrease network connectivity and hence the glass processing temperatures. Now, by adding alkaline, as I said, you can decrease the network connectivity and hence the viscosity. One very important fact I also want to mention here is that if you-- instead of adding just one kind of alkaline atom-- if you add two types or more than two types of alkali atoms simultaneously, the depression of the viscosity becomes even more significant. So this is known as the Mixed Alkali Effect.

So to illustrate this effect, what I'm showing on this plot here on the left-hand side, vertical axis is basically a logarithm viscosity of some silicate glasses mixed with either sodium oxide and potassium oxide. Horizontal axis, this is the molar fraction of sodium oxide. So you keep the total amount of alkaline ion constant, you are essentially changing the relative fraction, the relative concentration of sodium and potassium ions.

Now, notice that this curve, they always have this kind of a concave shape. So the viscosity decreases by a couple of orders of magnitude if you go into intermediate composition. So basically says the glass becomes a lot more deformable if you mix two kinds of alkali ions, even if you keep the total concentration the same.

I want to mention that this effect exists not only for just viscosity, it actually exists for many physical properties of glass materials, especially in terms of their transport properties. So only this middle plot here, I'm now plotting diffusion coefficient-- again, similarly as the composition of these two alkali ion atoms. And you see similar kind of a dip behavior there. You have the minimum diffusion at some intermediate composition here.

So the origin of the mixed alkaline effect-- this is still an issue still of intensive investigation. People have come up with different kinds of explanations with respect to different specific physical effects. The most commonly assumed reason is that this comes from mutual blocking of transport pathways between ions.

If you imagine, for example, you have a glass network that contains, say, only one kind of ion, let's say sodium, all the sodium ions, they have essentially their respective size that they can comfortably be sitting in. And when any kind of transport phenomena like diffusion happens, what is required is that the sodium ion, they have to hop from one sodium side to another sodium side. That's how you perform ion conduction or perform diffusion. Now, if you only have sodium, then you can imagine that all the sides, more or less, they have similar energy, so it's quite easy for them to move around without experiencing a large energy barrier.

If you go to now mix alkalines, you get two kind of sides for this kind of ions. And this creates large energy differences when they are hopping between the different sides there. For example, if you're trying to squeeze especially potassium, a larger ion, into smaller ions like sodium sides, then there's a lot of steric hindrance. And therefore, it increases the energy you need to actually move these ions. And in the end, that's why it actually inhibits this transport behavior. And that's the explanation that people are giving for this kind of mixed alkaline effect.

So I just want to mention that this mixed alkali effect, this is something that people have actually discovered long ago. So this is accounts of some historic records that mention that, in the early days, when people were actually making thermometers out of glass-- so some early thermometers, they put something like mercury into a glass tube, and looking at the thermal expansion, and use that to determine temperature.

Now, what they have noticed here is that you have freshly made glass. You directly put mercury in there. You then put it into, for example, ice water, it would show 0 degrees C. But then if you put it into boiling water and then put it back into ice water, instead of showing 0 degrees C, it would show actually negative 5 degrees C, because when you actually put the glass in boiling water, because of high temperature and then it decreases the viscosity, you start to get shape deformation and relaxation of internal stress. As a result, this leads to macroscopic deformation that then compromises the accuracy of this thermometer.

So they have noticed there that if you actually store these glasses at just an ambient condition for several months before you make it into a thermometer, then this phenomena goes away. Now, that's actually easy to explain, because now we understand this is coming from relaxation. So if you allow all the internal stress, shape deformation take place in over the several months of period, then you no longer have this effect.

However, what they have also noticed here is that if you heat it up again and cool it down, then that phenomenon comes in again. You are essentially going through the same cycle. You heat it up, back to like a super cool liquid, quenches back down, it erases any memory of the relaxation. So you have the same problem again. Relaxation comes in again.

And finally, what they have noticed there is that this relaxation effect could be diminished by a factor of 10 if only one type of alkaline ion is used rather than using mixed ions. So that's basically the first account for this kind of mixed alkaline effect. You're mixing two kind of ions, you decrease the viscosity and therefore the working temperatures.

So far, we have been discussing about the temperature dependence of viscosity in amorphous materials. The next topic I want to mention here is that viscosity, it not only depends on temperature, it also depends on shear rate. OK. And this is quite common in a lot of fluids, including glass-forming liquids.

Now, if you look at the equation we have been starting to talking about here in the very first slide, we said that if you assume a liquid has a Newtonian behavior, then its viscosity is constant. It does not depend on the strain rate, and therefore the shear stress should be proportional to the shear strain rate. In reality, you can have different kind of a dependence of the viscosity on the shear rate. So what I'm plotting on this plot here is some of this kind of typical fluids, when they exhibit different behaviors.

So the Newtonian fluid, this would be a straight line here for the stress and strain rate curve. And basically, it says that the slope of this line will give you the viscosity, and it's constant regardless of strain rate. You can have shear thinning. As you increase the shear rate, the liquid becomes thinner. It becomes easier to deform, it becomes lower viscosity. It's more flowable. Or it can be shear thickening. As you increase strain rate, it actually becomes thicker. It becomes more viscous.

Now, you can also have a so-called Bingham plastic. Bingham plastic has this interesting behavior that if your stress is below a certain threshold, it behaves more like a solid. It does not exhibit any kind of flow behavior. Now, once you exceed the threshold, now it starts to flow, now it behaves like a liquid.

In fact, the common example of Bingham plastic is toothpaste. A lot of toothpaste is actually Bingham fluid plastic. If you think about toothpaste, right, if you just leave it there, it will hold its shape. But once you start to brush, of course, it starts to deform. That's when you actually apply enough stress, exceed the threshold to induce the viscous flow. OK.

For amorphous materials, depending on what kind of material you're looking at there, they can either exhibit stress or shear thickening. And I'll give you some specific examples about this different kind of fluids there.

And then on this next slide, on the left-hand side, I'm basically now, in this case, just plotting the viscosity as a function of shear rate. Same idea as the last plot. We are just now looking at the slope from the last plot there. OK.

Microscopically, what's the mechanism for this different kind of fluids? Viscosity, as we have mentioned before, is internal friction in liquids. Viscous flow is when one part of liquid, some of the molecules, has to move past the others. And viscosity is the resistance of the material to this kind of relative motion between different parts of molecules.

So for shear thickening, what happens there is that, as you increase the strain rate, the molecules start to self-assemble together to form larger clusters. And with larger clusters, it becomes more difficult to actually deform it. And as a result, you see apparent increase of the viscosity. So this is a phenomenon called hydroclustering. It's basically illustrated here. When there is no shear stress or the molecular fragments stay separated. But once you start to apply large shear rate, then they start to organize, self-assemble together to form larger structures, which impedes viscous flow.

So lots of liquids actually exhibit a shear thickening behavior. I'm showing you this little video here. It basically shows someone that's running on liquid. This liquid, this is called oobleck. You can actually make it at home. It's quite straightforward. It's basically starch and water. You mix it with about one-to-two ratio, and then you get liquid like this. It is quite remarkable because if you do it, what happens is that if you just try to use a spoon or something to screw it up, it behaves just like liquid. But if you try to change its shape, you put it in your hand, try to mold it into some shape, as long as you do it quick enough, it behaves more like a solid. OK.

So that's one good example of this shear thickening behavior. And that's why you see that people can actually run on this kind of liquid. As long as you do it fast enough, you are not risking sinking into the liquid. Actually, you can find some YouTube videos where people actually play soccer on this oobleck, like a big swimming pool filled with oobleck. But you have to keep it running all the time. As soon as you stop, pssh, you sink into liquid.

Some other examples. Any of you know Silly Putty? Oh, yeah. Silly Putty. This is similar. Silly Putty, you can shape, mold into a ball. And if you throw it on the floor, it actually bounce back. It's basically like a rock, a solid. But if you try to let it flow a little bit, you put it into a container, it actually can flow and conform to the shape. So as long as you have a low stress, then its viscosity decreases and then you allow it to flow. So these are the examples of this kind of fluids there. Shear thickening.

Shear thinning. The common example of shear thinning is paint-- house paint. So shear thinning is quite desirable for paint because when you're trying to brush it, you want to make sure it's a fluid, you can actually apply it uniformly on the wall. So you need low viscosity. But once you put it on the wall, you want it to stick there. You don't want it to continue to flow. So that's why people actually engineer it so it has shear thinning characteristics such that when you stop applying any stress, its viscosity actually increases. And that's why you can actually have a uniform coating on the wall without continuing to flow before it dries.

Another more state-of-the-art example where people are using this kind of shear thinning characteristic to some benefits here is when people are doing 3D printing. So 3D printing involves-- you have some polymer. You start to squeeze it out of a nozzle. And as you translate this nozzle in 3D space, you then leave behind a trace of this polymer in 3D space.

Now, shear thinning is, again, advantageous here, because when you're trying to squeeze polymer out of a nozzle, this is basically a viscous flow process. If you have a very high viscosity, it becomes very difficult just to force the polymer out of the nozzle. And again, once you are printed or you have finished your printing, you want your shape to actually stay static.

You don't want it to continue to flow to deform things. So that's why, if you have shear thinning fluids, then at the nozzle, this is where you have very large shear rate, you have a decrease of viscosity. But once it comes out, you relax all the stress, you release all the stress, then you can have high viscosity to hold the shape.

So now coming back to glass. So what I'm plotting here, this is actually for soda-lime glass. It plots how the viscosity actually changes as a function of the strain rate. And according to this plot, you can see that soda-lime glass actually exhibits a fairly clear shear thinning behavior. So viscosity of soda-lime glasses decreases as you increase the strain rate.

Now, why is this important? When it comes to glass processing, especially in glass processes, where, in the same process, you have large differences of shear rate, then this is something that has to be taken into account. One example there would be an optical fiber join.

So we will be talking about optical fiber joining processes later on in the class. But essentially, what you do is you have a macroscopic preform, which is about a couple of centimeters in diameter, a cylinder. You then put it into a furnace, so that you start to induce viscous flow, and you apply tensile stress on one end, which then deforms this cylinder into a very thin strand of the fiber.

Now, if you look at the process here, the deformation rate, or shear rate, is very non-uniform. At this part, at this macroscopic preform here, the shear rate is actually very, very small. It barely deforms. But the shear rate scales, actually, inversely with the diameter of the glass. So when you come to the fiber part here, you actually have a very large shear rate during the formation process. So when you're actually developing any kind of a modeling process for this fiber drawing technique, you need to account for the viscosity change. The actual viscosity-- apparent viscosity of the glass is much lower here compared to up here, even if you are at the same temperature.

Otherwise, you may risk breaking the fiber or having non-uniformity there, if you don't properly account for this kind of shear rate dependence of the viscosity.

So before I talk about how to measure viscosity, I just want to show you this slide. When I was looking for literature on non-Newtonian fluids, people, obviously, have identified cats as non-Newtonian fluids. They actually published a paper. They tried to fit all kinds of fluid dynamic equations and used that to describe cat behavior. And in the illustration here-- I don't know if you can see it clearly, but it shows a few examples why they consider cat as being a fluid instead of a solid. Obviously, they can conform into different shapes. They can handle uneven substrates.

You can see there they can actually have non-wetting behavior on water surface. And this one, they can glide on a smooth surface. They can also hang onto vertical walls. So all those behaviors are unique to liquids, not to solids. So that's why they conclude that cat is actually a liquid. And they have some equations that consider the relations to actually describe cats. So quite an entertaining paper if you ever want to read it. And this is also won the Ig Nobel Prize, this research.

AUDIENCE: So they're like the author affiliations?

PROFESSOR: Oh, yeah.

AUDIENCE: [INAUDIBLE] superior radiologist?

PROFESSOR: I was hoping they should include some of the cats as coauthors. But they are important experimental subjects that contributed to the study. But whatever.

Anyway. All right. So the last point I want to mention here about viscosity is how do people characterize viscosity in glass melts. Now, viscosity is one of the phenomena that can span many, many orders of magnitude. So it's not surprising at all that you have to use different techniques to actually measure viscosity in different ranges.

So if you're trying to measure viscosity in the low-viscosity regime, it behaves more like liquid, flowable liquid. So what you're typically supposed to do is use this kind of rotating cylinder approach. You essentially put the liquid in between the rotating cylinder and the container. And you can then measure what torque you need to apply depending on the spin rate. So from that, you can actually infer what is the viscosity, the friction the liquid exerts on the spinning cylinder.

Now, if you go to a higher viscosity, this is somewhere around the working range. So chewing gum, like glasses. Instead of using this kind of rotating cylinder, you actually use a parallel plate approach. So you put some glass materials between two parallel plates. And then you start to rotate one of the plates with respect to another. And similarly, you measure what is the torque you need to apply as a function of the rotational speed.

Now, this only applies to this relatively high viscosity range, because if the glass melt flows like a liquid, it's going to leak out from the edges, so you cannot hold the shape. So that's why this applies only to intermediate viscosity range.

Now, if you go to even higher viscosity, like a round glass transition temperature, the glass will behave more like a solid in this case. The deformation actually gets pretty small. So to measure the viscosity at this high viscosity range, you use techniques that you borrow from solid mechanics, like beam bending. This is like three-point beam bending. But the difference there, that in a conventional three-point beam bending, where we're trying to measure elastic material, you are trying to measure the force as a function of deformation, of displacement. That's what you do. That's how you infer the elastic constants.

But in this case, if you're trying to measure viscosity, what we're trying to measure is the force as a function of deformation rate. It's not the absolute deformation that matters, it's how fast the beam sets. It's the movement speed is what really matters there.

So this kind of a beam bending approach allows you to measure viscosity up to about 10 to the 13. So somewhere around, like, straining point. What if you want to study something with even higher viscosity? You may feel like that's not important, but turns out it can be quite relevant if you are trying to develop precision glass instruments, like big telescope mirrors. So a lot of big telescope mirrors, they obviously are quite heavy and they need to achieve extremely high precision.

The surface has to have a shape deviation that's less than a fraction of the wavelength of the light. Otherwise, you risk distortion of optical images there. So over time, a time period of several years, these big mirrors, they can slowly deform, mostly due to gravitational force. So how do you measure this kind of a viscous flow in an instrument like this, where the viscosity is obviously very high?

So the technique they use is basically optical interference. So what they will do, they can, for example, put the piece of glass you want to measure, you hold it on the side, and then you put it against the reference plate. So the bottom one, this will be your reference plate. And this is your sample.

What you do, you then shine a light from on top. So then when light passes through this gap in between these two samples here, it can bounce back and forth many times between the sample and the reference plate. And then depending on whether you get integral, multiple wavelengths or maybe half-integral or multiple wavelengths, you can get constructive versus destructive interference. So if you use a white light to shine through this plate here, some wavelengths constructively interfere, some wavelengths destructively interfere. So you actually see color in the reflected image. So this is very similar to when you have oil films spreading on water. And then you see this kind of color oil film there. Same idea. This is basically called interference.

So from the color fringe, you can now infer what is the gap width between these two pieces here with very high precision, down to, like, single-digit-- a few nanometers of precision. So now with this technique, you can then carry out this measurement over an extended period of time to determine what is the viscosity at this high viscosity range.

So I'm quoting here. This is basically from one paper. The authors perform the measurement over a period of six years. And they were able to measure deformation of the order of a few nanometers to calculate viscosity of the order of 10 to 15, 16, 17 Pascal-second. Yes. Again, not a very good topic for PhD thesis, but you know, six years, maybe tolerable. Better than the pitch drop experiment.

You get one paper after six years? That's actually a true story. I was actually at a glass conference. Someone was-- the thesis topic was actually studying glass aging or relaxation. So they actually inherited a bunch of samples from previous PhD students. And then they actually measured all the properties. And then studying why you have this kind of relaxation. So yeah, some of these long-term experiments can be legit PhD topics. But it requires transition of samples between different generations of PhD students.

So now if we are now able to measure or characterize the viscosity of glasses, even to this very high range there, we can now come back to the question we have asked in the beginning of the class. So is glass a solid or a viscous fluid? Is the flow of glass completely negligible under ambient conditions? So this question has actually been investigated by a few authors. This is one of the most recent attempts that people from a group of scientists from Corning, they actually performed some calculations. Essentially, they experimentally measured the viscosity of glass using whatever technique we mentioned there. Then they can extrapolate this viscosity to room temperature using the [INAUDIBLE] equation. Remember the equation we talked about for how to describe viscosity dependent on temperature?

So then they could use that to then infer what's the viscosity of glass, normal glass at room temperature. And then from that, they can then estimate what is the time that's needed to deform the glass, for example, for a few nanometers. And the conclusion there is that at room temperature, the viscosity is of the order of 10 to 24 to 10 to the 25 Pascal-second. That's 12 orders of magnitude higher than glass transition temperature.

And if you think about pitch, this is like 16 orders of magnitude higher viscosity compared to pitch. So it's not surprising that it would take some-- the conclusion here is that it takes a billion years to just have a maximum flow of order of about 1 nanometer. So conclusion-- glasses at room temperature-- I mean soda-lime glass. You're not talking about these low-Tg glasses. For things like soda-lime glasses, you can pretty much treat them just like [? electric ?] solids. The viscous behavior is pretty much completely negligible because it's extremely high viscosity.

Now, you may have the question. For those medieval cathedral color windows, why the bottom tend to be wider than the top? The answer is actually quite simple. Because when the construction workers, when they assemble it, they know at the time the window is not uniform, thickness is not uniform. So in order to ensure mechanical stability, they tend to put the thicker side at the bottom, then the thinner side on top.

Now, one of the examples to support this is that people do find mistakes. They do sometimes see these window pane glasses where the thicker side is actually on top. That's just because it's assembly error of the construction workers.

So just to conclude what we have talked about here, I decided to put this quote-- "chocolate smells, flowers wilt, diamonds are forever." You can obviously see where this is from. This is from a shop that sells diamonds. But from what we have learned here, you see that glasses can do equally well. In fact, diamonds are not thermodynamically stable. Graphite is a thermodynamically stable state. So glasses are forever. So forget about diamond rings. I think glass rings can work equally well. OK. Think twice about it. That's the next chapter.

We're going to talk about mechanical property next. So hold on to that. You are going to see some surprising numbers there as well. Glasses are also pretty good in terms of mechanical properties. You should be more precise. It's a hardness that really makes a difference. Mechanical properties-- glasses are quite good as long as they are defect-free. OK.

So just to quickly summarize what we have talked about here, we have discussed about two kinds of contrasting phenomena-- elasticity and viscosity. We talked about elasticity being instantaneous. Viscosity, the key point here is that it's rate-dependent. It's permanent but then the shear stress depends on the shear strain rate. So these come from different microscopic mechanisms of viscosity versus elasticity. Elasticity comes from the repulsive and attractive forces between molecules. And that's why they become very temperature-insensitive. Versus viscosity always involves relative motion of molecules or atoms with respect to each other.

So once you involve motion of atoms or molecules, this tends to be a thermally activated process. And that's why you tend to see a large change of viscosity as a function of temperature. You describe the phenomena depending on whether you have a strong fluid or you have a fragile fluid. You can either use the Arrhenius equation or maybe the [INAUDIBLE] equation, or VFT equation for those kinds of behaviors there.

And finally, we talked about this simple Newtonian model does not always hold for glasses. You can have a non-Newtonian viscous flow. So the viscosity actually depends on strain rate as well.

So that's pretty much about the basic knowledge about viscosity there. Any questions before we move on to talk about how to apply the [? phantom ?] side we have learned into shaping glass products? Questions? All good? All right.

So now glass shaping. Before I go in to talk about any technical details, I just want to show you this little paragraph, which I exerted from an online forum, where people are essentially asking questions about why people like to use glasses to make all different kinds of everyday products. What's the benefits there in terms of processing? So I quite like this quote here. It says that viscosity makes things happen essentially in slow motion. And this is a unique behavior that only exists in glass, where you have this continuous viscosity temperature behavior. So you can tune viscosity precisely with respect to temperature.

So to illustrate the difference here between a crystalline material and glass, let's think about-- let's say this is, for example, volume versus temperature. This is a curve we have seen many, many times. So if it's a crystalline material, then what you will get is a curve like this. You have a liquid state, but when you get to melting point, abruptly, you suddenly change from a solid into a liquid. So there's a very large switch of the deformation behavior of the material. Liquid tend to have a low viscosity. So as a result, things start to chip away. That's what I'm showing there. Essentially, you cannot hold the shape when it goes through this abrupt transition there.

Glass, on the other hand, you have a continuous viscosity temperature curve. As you go through this glass transition here, by controlling temperature, you can quite precisely determine the viscosity of the glass melt. And by choosing a glass melt with appropriate viscosity, you can ensure that you can easily deform it, but yet it can also hold its shape, in that it's not dripping away, it's not collapsing. That's what is put here.

So if it's a crystalline solid, as soon as you reach the melting point, a drop of liquid forms and falls away from the melting surface. Glass, on the other hand, can gradually transform from a high solid to a slowly softening liquid. And the liquid now allows you to-- it gradually stiffens as it cools, because the viscosity increases. And it gives you a window to allow glass workers to then process it into different kinds of shapes by manipulating it.

So the key takeaway message here is that this continuous viscosity temperature curve is really important. That underlies the process versatility of amorphous glass materials.

I just also want to mention that in a couple of weeks, we're going to have a demo session at the MIT Glass Lab. You can find the date on the first slide deck in the class there. It's basically the first lesson in March. So we are going to meet directly at the MIT Glass Lab. We are going to show some demos about how to use this viscous flow behavior to shape different glass products.

So as I promised you, I'm going to show you this plot again, because this is actually quite important to glass processing. Key takeaway message is that most of the glass processes takes place in this working range, where you have a chewing gum-like fluids that you can easily shape and deform. You do notice here that this float glass goes in the relatively low viscosity end. And that's because in a float glass process, we're going to talk about it in a few slides, is when you have molten glass floating on a tin bath to get large, flat sheets, because in this case, the glass needs to flow. So that's why people like to do it at slightly lower viscosity points.

Now, this one, this is precision glass molding. So precision glass molding takes place at higher viscosity ranges, sometimes right outside the working range. Because unlike other processes here, precision glass molding, you apply very large pressure. If you apply large pressure, we know that the shear rate depends on-- it linearly scales with shear stress. So high stress essentially means that you can afford to have low viscosity while still maintaining a decent stress rate. So basically, pressure expedites the process. That's why you can afford to have a higher pressure there.

Now, last one. Annealing Lehr. Lehr is basically just another name of "furnace." So when we talk about glass shaping in this chapter, you're going to see a lot of terminologies that's pretty unique only to glass processing. "Lehr" is one of them, but "Lehr" basically is just a furnace, annealing furnace. In a Lehr, you anneal the glass, so it releases any kind of internal stress. So prevent any premature cracking of the glass products during usage.

So now, in this slide, I'm summarizing the typical viscosity reference points for different conditional glasses-- soda-lime, borosilicate, fused silica. Takeaway message-- fused silica, you see this temperature, it's softening point is very high, working point is basically absent. Its temperature is too high. So that's why, as I said, nobody really processes fused silica. You can get them, they get quite expensive.

Borosilicate, due to a higher network connectivity, all of this temperature reference point is actually higher than the corresponding soda-lime glass. They also have a much lower coefficient of thermal expansion. So that's why, when you're trying to make borosilicate products, you can make it in the glass workshop, but it becomes very difficult if you're trying to mix soda-lime glass with borosilicate glass. Because when you're processing these glasses, when you're shaping them, you do it at a high temperature.

If you're trying to fuse something together, then, as you cool down, due to the large CTE mismatch, you accumulate a huge thermal stress in between the soda-lime glass and borosilicate glass. And that tends to actually fracture. In fact, when you go to a glass workshop, you're going to do one of the demos there, we're going to draw canes out of both borosilicate and soda-lime, essentially long glass, thin glass wires.

We are then trying to fuse two canes together, borosilicate with the soda-lime. And once it cools down, you'll notice that it immediately bends, much like a bimetallic strip, and it eventually cracks into small pieces. So you're going to see that when we go to the glass shop demo. All right. Questions? OK.

So in the next few slides in this part here, I'm going to show you a few processes-- how people use to actually shape glasses into different kinds of products. The earliest process that people do for the common glass form factor, which is flat glass, like window pane glass. The earliest process people developed is so-called crown glass. So crown glass, you have a big bubble of molten glass. You open the hole there at the end, so it becomes a big, flat piece. And then you start to spin. You put it onto a little steel rod. At the end, this is your glass piece. You start to spin it, so then this glass piece starts to rotate. And due to the centrifuge force, it forms this thin, flat sheet. So like a cylindrical, big, thin, flat sheet.

So you can then use that to actually create this-- cut it and create this kind of flat glass panels there. But then you notice, obviously, this process is not very well controlled. You see that there's actually a big defect right in the center. This is where your glass rose, or pontil, as the glass workers call it, comes into contact with the glass piece. OK.

AUDIENCE: Is it like pizza spinning?

PROFESSOR: Similar. Very similar to that. Yeah. You are doing it this way, OK? And you're just rotating it. Yeah.

So in fact, I was looking at some Instagrams. They have pictures of this [INAUDIBLE] glassware of preparing for a glass lecture. And people were commenting here, like, whoa, this glass window looks so cute. Why you only see in Europe and not in the US? Because we don't have those old buildings. That's it. We all use a newer process to actually make the windows.

So one of the standard process that people use today to make large flat glass sheet, this is called float glass process. So what I'm illustrating here is a continuous process flow-- how people actually manufacture this kind of flat glasses here. It's all a continuous process. You started out from feeding the raw material all the way to coming out, having glass sheets coming out continuously. And non-stop. 24/7. It's a continuous manufacturing process. So basically, the process involves starting with mixing different kinds of ingredients.

So for soda-lime glasses, the ingredient would be sand, SiO_2. You have soda, which is sodium carbonate, for example. You also have some minerals that actually contain calcium oxide, like dolomite. OK. That gives you the rare earth element. And then finally, you also add some broken glasses, used glasses. Those used glasses are called cullets. OK. This is a name to use-- you put some weighted glasses into your feeding material, into the furnace. Now, this is actually quite important. Why do they need to put cullets there? Because if you think about it, if you don't need to have the cullets, you just have all the raw minerals coming in there, they're all solid, crystalline solid-- in order to melt it, you need to go all the way to the melting point, and then you start forming the liquid phase.

On the other hand, if you have cullets, they are glasses. It means that they start to soften, and you form an early liquid phase well before you actually reach the melting point. Now, that's important because for any kind of solid-state reaction, diffusion or any kind of transport phenomena always happens a lot faster in the liquid phase compared to the solid phase, which makes a lot of sense. Liquid phase molecules move around. So of course, you can get much higher molecular transport or reaction compared to any solid.

So having these cullets allows you to form this early liquid phase, and that helps you to reduce the energy consumption in the process. You don't have to melt the material all the way by going all the way up to the melting point. So then you can significantly cut down the power consumption by something like 20% by just adding cullets into the process there. So that's why waste glasses is actually quite important ingredient.

In fact, I have seen people doing-- they do internship at glass products. They make glass bottles and stuff. If they see any glass bottles that's defective, they don't try to fix it or anything. Just take it out, throw it into a cullet piece, because they need it anyway. Yeah. OK.

So then once you mix the material, you then melt it. And then the melting furnace has the liquid that then feed into a floating bath. So for the floating bath, you basically have molten tin. So molten tin has a density that's higher than glass melts. So then this molten glass is then going to float on top of tin. And now, due to the action of surface tension and gravity, then the liquid then spreads on top of this molten tin to form a flat glass surface. OK.

At the end, when it comes out from this floating furnace there, then it enters into the annealing Lehr. So annealing Lehr then helps you to relax any internal stress inside this flat glass sheet before it really comes out from here to get your-- then it can be cut and packaged into all kinds of flat glass products.

So what I will do next is I'm actually going to play a little YouTube video, which probably talks all about this process and gives you a visual feeling of how things are done much better than I do.

[VIDEO PLAYBACK]

- Today a modern float glass line produces an average of several hundred tons of glass each day. It runs 24 hours a day, 365 days a year for over 15 years. There are about 450 float glass lines around the world. Together, they produce more than a million tons of float glass worldwide every year.

Until the 1960s, flat glass was produced using the sheet and plate glass manufacturing process. This method was highly labor-intensive. Invented by Sir Alastair Pilkington, the float glass manufacturing process quickly became the universal method for producing high-quality flat glass. Today, float glass manufacturing supplies glass to a variety of different markets, including automotive, architectural, solar panel, and many other technical applications. Glassmaking uses some of the Earth's most abundant raw materials. The primary ingredient is sand, accounting for 60% of what is called the batch. Lime and dolomite are added to assist the weathering properties of the finished glass, while soda and sulfate lower the temperature at which sand will melt. But glass itself is also an important ingredient.

Broken glass, called cullet, is recovered from the manufacturing process and then crushed before being added to the batch. This further accelerates the melting process and reduces the amount of energy required for melting by up to a fifth. All raw materials are rigorously checked to ensure the purity of the batch.

It is then fed automatically into the filling end of a furnace. Natural gas burned in preheated combustion air then heats the batch up to 2,800 degrees Fahrenheit. Once heated, the batch materials melt and change from a semi-molten state to molten glass. Melting, refining, and homogenizing take place within separate zones of the furnace. Processes within the furnaces are managed from the control room to ensure that the glass is homogeneous and free of bubbles.

Inside the furnace, heat is applied from alternate sides in 15-minute cycles. This assists fuel efficiency by ensuring that combustion takes place in the presence of preheated air. This continuous melting process can last as long as 50 hours. The glass leaves the conditioning end of the melting zone at a temperature of 2,000 degrees Fahrenheit through a narrow canal, where it passes to the heart of the process, the tin bath.

Molten glass enters the tin bath and floats on top of the more dense, molten tin like oil floating on water. Here, the glass spreads out, following the perfect flatness of the tin, so that the upper and lower surfaces of the glass remain absolutely flat and parallel with perfect spectral properties. The glass is made thicker by confining its initial outward spread over the tin. To make thinner glass, the top rollers controlling the width of the glass are sped up to produce a gentle stretching action. A controlled atmosphere of hydrogen and nitrogen within the bath prevents the tin from oxidizing.

When it emerges from the tin bath, the glass is sufficiently hard so as not to be marked by the conveyor rollers. The float glass manufacturing process can produce clear, tinted, and coated glass products. Online pyrolytic hard coatings are produced by depositing microscopically thin layers of metallic oxides using the chemical vapor deposition process. This process produces extremely durable products that can be easily handled, cut, tempered, bent, and fabricated. Pyrolytic-coated glass include low-E coatings for solar and thermal control, self-cleaning, anti-reflective, and many other special applications.

The glass now enters the annealing Lehr, where any stresses are removed by a controlled cooling process. In a length of over 800 feet, equivalent to three football fields, the glass is taken from 1,100 degrees Fahrenheit down to room temperature. At this stage, the glass is perfect.

Now the glass is scored, so it can be snapped to predetermined sizes. Indentations left by the top rollers are removed on conveyors and sent to be reintroduced as cullet at the beginning of the melting process.

After passing through the automatic handling stages, customers' orders, which might involve a range of thicknesses and sizes, as well as special coatings, are packaged for delivery.

As a leading global glass manufacturer, the NSG Group provides one of the broadest ranges of--

[END PLAYBACK]

PROFESSOR: OK, so basically you see the visuals of the process, yeah-- it's that the temperature monotonically decreases from one end to the other end. And then it's a continuous process that manufactures glass products.

So one thing I also mentioned here is about the ingredient they have mentioned here. They talk about dolomite increasing weathering properties. That's one way to mention is to say that they are improving the chemical resistance or chemical stability of the material. So when we talk about glass structures, we say that these rare earth elements, they have a twofold coordination. So they help to maintain some network connectivity and therefore improving the-- reducing the chemical sensitivity there. So that's why they added dolomites there. The sodium sulfates, those are to add the alkaline to decrease the glass processing temperature. All right.

So the video shows here-- this is basically talking about a standard process for making things like windowpane glasses or architectural glasses. I want to mention that this float glass process has also been further advanced. You can now even actually get high-end glass products, like consumer electronic products for [? hover glasses ?] and things like that, also using the float glass process.

So this is actually one example. This paper basically reports the manufacturing of ultra-thin glass with a thickness that's down to about 0.1 millimeters. That's about a human hair thickness, OK? And it's a four-meter-wide flat sheet. So I actually had the opportunity to visit one of these plants. And when this glass kind of moves around on the rollers, you can basically see ripples. They are essentially flexing. They are flexible. So it's quite a remarkable process.

Now, if you look at how they actually did it, they spent lots of time trying to optimize the temperature distribution across zones here. They even spent lots of time optimizing the location of these rollers on the side to ensure it generates uniform stretching force rather than having stress or strain localization.

So in the end, they were able to get glass surface roughness-- for example, on the top surface-- down to about 1.5 nanometers [? RMS ?] value, which is quite remarkable. This basically just relies on surface tension. So that's quite good.

Now, the downside, though, is that if you use this kind of tin bath, on the bottom surface, you still have the contact of the glass with the tin surface. This increases the surface roughness up to about 3 or 4 nanometers. Also, at the same time, this may cause a little bit of contamination. There can be a little bit of diffusion, interdiffusion between tin and the glass. Also, any kind of a mechanical vibration or any kind of surface unevenness of the tin bath is going to translate into unevenness of the surface of the glass as well at the bottom surface.

So that's why, if you're looking for very high-end, extremely high-quality surface glasses, for example, for semiconductor manufacturing processes, people tend to use a different manufacturing process. Where the glass surface is formed without contact into any substance.

So there's a bunch of these kinds of variants of this process there. They are typically called down-draw process. I'm showing you two variants of this process. On the left-hand side, this is a process that's developed by Schott, which is a German glass manufacturer. So the way it works is that you have your molten glass, it comes out from an orifice at the bottom of the furnace, and then this glass melt essentially just drops. It comes down by gravitational force.

And in the process here, this glass surface is not coming into contact with anything. So you maintain the pristine glass quality. And in the end, you then go through annealing furnace and then go to a roller. You can get continuous glass ribbon coming out from the furnace that way.

Now, Corning has its own patented process. They call it the fusion process. I'm going to show you a little video that shows how this is done. So same idea. You start by mixing them, put them into a furnace. It's also a continuous process. It can be a continuous process. So then, you keep on adding these materials until it overflows. So you see that the glass melts comes down from the bottom, goes into a big crucible.

Then because you continuously add the glass melt, it starts to overflow from the top. Then the glass doesn't come out from two sides of the crucible. You engineer the crucible so that the bottom has this kind of wedge shape. So when the liquid comes down, it comes at the bottom, merges, and forms a thin sheet of glass. And it cools down as it drops. So that's why they call it fusion process-- because it involves a fusion of two liquid streams at the bottom of the crucible there. OK. So same idea there.

You want to make sure that when you're actually trying to form the glass surface, you don't have any contamination or it doesn't come into contact with any other substances. So that's why this is mostly used for high-end applications like flat-panel displays, where you need to process all kinds of electronic transistors on top. So it requires extremely high surface quality free of contamination.

Question.

AUDIENCE: Is-- for the Corning method, is the crucible hot on the exterior? Are there binding issues as the two glass faces--

PROFESSOR: Oh, you mean like-- ah. OK. Normally no, because it's actually at a high enough temperature. So the glass is basically just a fluid. So when they come together, it's just basically two fluids mixing together. It's not two solid sheets trying to bind together. Basically, it's a fluid stream. And it slowly cools down and the viscosity increases. That's when it becomes solid glass. OK. Yes?

AUDIENCE: What is the benefit of that versus just having a thicker [INAUDIBLE]?

PROFESSOR: Like this one?

AUDIENCE: Yeah. What is the benefit of the Corning technique there?

PROFESSOR: OK. Patent. Yeah. Each of the glass company have their own patents on the process. Schott holds patent on this process, Corning holds patent on that process. They cannot use the other people's process. So that's why they develop their own variants of the down-draw process. I mean, that's the main reason, honestly. I don't see a big difference, to be honest, between the fusion process and the down-drawn process. They are more or less the same. If you look at other glass manufacturers, AGC in Japan, Pilkington in the UK, they also have their own variants of this kind of down-draw process.

AUDIENCE: I'm going to create the up-draw process.

[LAUGHTER]

PROFESSOR: You are going against gravity. You can patent it, but you are going against gravity. That's the downside there. This is a little easier. You just let things flow.

AUDIENCE: I can corner the market. So.

PROFESSOR: You could do a horizontal draw maybe. [LAUGHS] Oh, by the way, do you know when this process was first developed?

AUDIENCE: Like any sort of down-draw method?

PROFESSOR: Yeah. When, I mean. When was it-- yeah.

AUDIENCE: Recently?

PROFESSOR: I mean, the demand really only comes in recently. It's basically when all the consumer electronics companies started to want to make this kind of high-quality glasses, that's actually when the market matures. It was developed back in the 1960s. Yeah. So people at the time, they were thinking that they need a high-end glass process to make the windshields for cars. The market doesn't exist. Nobody needs these high-end glasses with a very high precision surface quality.

So Corning actually goes back to their dossier, right, looking into old literature. When? Like 20 years ago when Apple was approaching them trying to make iPhone cover glasses. They actually had to go back into their dossier, dig out this old process and kind of scale it up to actually manufacturing. So yeah, I mean, it's an old process, but it has a renewed interest now because of the electronics industry. OK. How do I go to the next slide? Oh, all right.

So far we've been talking about how to make flat-panel glasses. Big, flat glasses, right? So next, I'm going to talk about something that's a little bit different. It's glassblowing-- using air to help to conform glasses into different shapes. There are a few different variants of glassblowing here. In this slide, I'm showing you the manual version, where this is what people do in a glass workshop. This is what you're going to see in the MIT Glass Lab. We're going to try to make pumpkins, for example, that involves the glassblowing process.

So in the glassblowing process, you basically have this big blow pipe, which is hollow in the middle, so you can blow air through it. You then collect a big gob of glass. Big chunk of glass. They call it big "gob" of glass. You start to see these specific terms that people use when it comes to glassmaking. This big gob of glass, then you collect it at the end of the blowpipe. You can blow air bubble into it, and you essentially push it against the mold as you blow air into it.

So then the outer surface of the gob then conforms to the shape of the mold. And this kind of structure is essentially a specific shape, and the air bubble in it is called a parison. Sort of like pre-formed glass. But that's the name people use to call this kind of thing.

And then you can then open it up, or you can take it to different kinds of geometries. There are a ton of different ways people can modify this process to create all kinds of delicate glass products. You're going to see that at the MIT Glass Lab. It's a lot easier for you to see it than for me trying to explain it, what happens.

The person that actually does the blowing job is called a gaffer. Depending on context, if you go to different industries, "gaffer" means different things. If you go to a movie industry, "gaffer" is the person in charge of lighting. If you go to a sports team, "gaffer" means the manager of the club. If you go to glass, "gaffer" is the person actually in charge of glassblowing. So it's basically like the boss. OK?

So now, this job for gaffer, or glass worker, it's very much a technical know-how that's usually passed down from one generation to another of glass makers. You don't learn it from a textbook. You learn it by actually doing it.

And even up till today, there's still demand, a lot of demand into making specialized glass products. These are some scientific instruments that people make using this kind of glassblowing process. And you just cannot simply buy it. This is not off-the-shelf products. You need to have a good glass blower that can actually create these kinds of things for you. So it's a very skill. It requires lots of skill. It's a job that requires a lot of skill and experience to design the process. OK. OK.

So this is the more manual process here. Now, at the industrial scale, people also use a similar blowing process to create, in this case, glass containers. So what I'm showing you here, top and bottom, these are two kinds of glass containers that are created using this similar process here. On top, this is for narrow-neck containers-- like beverage bottles. So for beverage bottle, you do a so-called blow-and-blow process.

So what you do, you start from a gob of glass. You put it into a mold. You have an opening at one end where you use compressed air to blow this mold. And then it's going to conform to this closed mold here. Then you get this parison. You then put this parison into a second mold, you blow compressed air again to go to final geometry.

Now, you may wonder, why bother doing this two-step blowing process? Why not just simply using one-step blowing? The reason for that is a couple of things. One is that people want to minimize any kind of very large local shear strain, because those can cause strain accumulation and maybe leading to cracking of the products.

So by designing this two-step process, they can separate the engineer, the deformation in the two blowing steps there. And this minimizes local strain accumulation. Makes it more uniform. Makes the deformation more uniform, basically.

Now, the other thing also to consider here is that this blowing process takes place at fairly high temperature, where glass is actually liquid, right? It also involves quite a bit of friction between this glass gob and the mold you're using there. So this friction is harmful because it leads to wear and tear of the mold.

So in order to ensure longevity, you want to make sure that this glass deformation takes place ideally along the surface normal direction of the mold. You try to avoid any kind of shear motion on the surface of the mold. So having a two-step process also helps with that. It gives you more degree of freedom to engineer the process to minimize any kind of wear and tear due to the shearing motion between the glass gob and the glass parison and the mold.

Now, at the bottom here, this is for wide-open jars, like [? Mark's. ?] And this is done using a so-called press-and-blow process. It's quite similar. You replace the first compressed air blowing process with just a mechanical mold. You use a mechanical press to essentially form the parison shape rather than using a blowing process. OK. OK.

So what I will do next is I will again show you another video that actually illustrates this glassblowing process. Hopefully no ad this time.

[VIDEO PLAYBACK]

- Why choose glass? The benefits of glass [INAUDIBLE]. It is sustainable. It is virtually inert. It is 100% recyclable, reusable, and refillable. It is safe to store food and drinks in it, and it is a premium way to market your products. Glass containers do not contain phthalates, or biphenyl-A, or any other potential hormone disruptors or carcinogens. It offers long shelf life as high levels of vacuum and carbonization can be maintained, and it can protect the product from the harmful effects of light.

Manufacturing process. Where do we start? Stage one, raw materials. The major raw materials used in glass container production--

PROFESSOR: The same as the flat glass. Mixing different elements.

- --limestone.

PROFESSOR: Batching process. This is called batching process. You mix different elements together.

- --cullet. Cullet is recycled glass that helps to reduce the amount of raw materials needed to make new glass. Cullet provides an important energy savings by lowering the temperature required for the melting process, helping to reduce greenhouse gas emissions.

Stage two, batching. One, raw materials are delivered into the batch house, where they are visually inspected prior to being stored in silos. Two, it is then weighed and mixed to produce batch. Three, the batch is then delivered and stored at the furnace, where it is melted to form glass. Stage three, melting. The batch is continuously fed into one end of the furnace via a batch charger. A combustible mixture of natural gas and air is forced into the furnace to generate a temperature of approximately 1,565 degrees Celsius. It is here that the batch is melted to produce glass.

Stage four, feeders. At the end of the forearm, the glass is then forced through an opening in the bottom of the spout called an orifice ring. The glass is then cut by blades called shears.

PROFESSOR: Those are [INAUDIBLE] the technologies that--

- --elongated cylinders of glass called gobs. Each gob has the correct amount of glass to produce one container. At this stage, they are ready to be formed into glass containers and are delivered to the forming machine.

Stage five, forming. The forming machine uses compressed air to transform the gobs into containers in a two-step process. The gob is delivered to the blank side of the machine, where it is formed into a parison, which is a blank form of a container. It is then transferred onto the mold side of the machine, where it is blown into the final shape of the container.

Stage six, hot end coating. Tin coating. Once formed, the containers are sent through a hot end coating hood and are covered with a thin layer of tin. This is part one of a permanent coating process.

Stage seven, annealing. When a new glass container is formed, the outside surface cools more rapidly than the inside surface, causing stresses in the glass. The process to relieve these stresses is called anneal and is done in a lehr. The lehr reheats the containers and gradually and evenly cools them to room temperature. The time taken to travel through the lehr depends on the container, which, on average, is between 60 and 80 minutes.

Stage eight, hold and spray. Duracote. At this stage, a thin layer of polymer is applied to the container to provide them with a scratch-resistant coating. This coating will also allow the containers to travel along the customer's filling line without jamming up.

PROFESSOR:

It's like a lubricant, reduce the friction.

- --Inspection. Before packaging, each glass container undergoes a rigorous inspection process to ensure the highest quality. It is inspected at multiple stages of the production process. Bottles that do not meet OIPJC's stringent design specifications are rejected and recycled as cullet.

Finished containers are prepared for shipment by our packaging department. From our warehouses, our products are shipped all over Southeast Asia.

[END PLAYBACK]

PROFESSOR:

All right. So there are a few things that's actually mentioned there in this process that I just want to highlight. One is that they talk about this tin coating. So the reason they do a tin coating-- there are two purposes there. One is that the tin oxide, when the glass contains tin oxide, it has a higher hardness compared to normal glass. And higher hardness is really important in preventing any kind of scratch damage.

So later on when we talk about mechanical properties, you're going to find that the Achilles heel of glass in terms of mechanical properties is usually surface defects. If there are any surface defects, they become the weak link. You can have cracks initiate and propagate quickly from those defects. So that's why having a surface treatment to empower glass with a higher scratch resistance is quite important. That's why they do a tin coating. One purpose.

Now, second purpose is that if you think about glass, its surface is-- if it's not treated, it's hydrophilic. That's why you see, during rain, raindrops can hang on glass windows. But after you have done the hot end coding, we're trying to do the cold end coating. That's a polymer coating, duracote, to reduce friction and also further improve scratch resistance.

So the polymer coating is hydrophobic, so it doesn't stick very well to the glass surface. So by adding tin there, tin actually renders a more hydrophobic surface, which helps improve adhesion between the subsequent polymer coating with the glass surface. So that's why, actually, people do this tin coating there, just to serve their purpose. OK? Yes?

AUDIENCE: Do they have to remove the coating when they recycle the glass? Or do you just get-- or maybe that concentration of tin becomes negligible?

PROFESSOR: Great question. There are actually two coatings, right? There's also-- well, it depends. When you recycle glass products, there is a thin layer of polymer coatings. Those things just burn away in the glass furnace. Becomes carbon dioxide. The tin, because it's only on the surface, it's a very, very small amount, so it barely impacts the process. So that's why they can go back immediately. It's only a very thin layer of coating there, like a few hundred nanometers. So if you look at the actual fraction, it's negligible. Yes?

AUDIENCE: Is it possible-- so I mean, I guess the primary way that they kind of recycle glass is by using it as cullet, which is basically, like, 30% of the [INAUDIBLE]. So is it not possible to do the full recycling of all produced glassware?

PROFESSOR: You could. Yeah. If you have enough stream, a stable supply stream of weight glasses, then in principle, yeah, you can do that. Yeah. Yeah, it's a supply chain problem. It's not about the technology problem. Yeah. And that's one advantage about glasses. Glasses, in principle, they are fully recyclable, unlike other kind of products. The glass industry is very power-hungry because it takes lots of energy to actually melt the glass. So being able to recycle is quite important in reducing carbon footprint of the industry. Yeah.

Now, the second thing I also want to mention here is that for this kind of container glass, they also have to go through a process called dealkalization. So these are soda-lime glasses. They have sodium. We have mentioned that sodium-- the problem is that when it comes into contact with aqueous solutions, sodium tends to slowly leach out. And when they leach out, they become sodium hydroxide. So it turns the solution more basic.

It also changes the taste of the beverage over time. So that's why, for these container glasses, they tend to add basically SO_2 or SO_3 at the end of the process. And then they let them react with the sodium on the glass surface, which then turns them basically into sodium sulfate. Sodium sulfate is water-soluble, so you can just simply remove it using the rinsing process.

Now, practically, the way they implement it, instead of using glass-- sorry, using gas here, this gas is a pollutant, so they don't want to really use the gas phase. They just put something like ammonia sulfate, for example. So it's a solid material. You put a little bit into the glass container, you heat it up, it decomposes, forms these gases. In the process, you seal the glass containers, so you don't have any kind of leakage of the pollutants into the atmosphere. After you finish the reaction, you rinse it and then you actually get the surface that's depleted of sodium. So that's also how you can help improve the chemical resistance for container glasses, OK?

OK. We are right on time here. Any last-minute questions before we conclude?

AUDIENCE: OK. I wanted to ask. So since the cullets, they could come from different types of glasses, did they separate the different--

PROFESSOR: They have to. They have to. I mean, if it's soda-lime-- most of soda-lime are more or less the same, so it doesn't really matter. But you really cannot mix-- for example, if you have borosilicate glasses, no, it really cannot go into the same batch. It has to be separated. Yeah. Or if you have silica glass, that's creating more problems than it solves. [LAUGHS] Yeah.

So you do have to sort glasses, essentially. Yeah. And if they also have any kind of specialized coatings or any kind of contaminants or whatever, they all have to be sorted out before you go into that process there. Yeah.

So that's why the best cullet is the factory's own product. It's exactly the same. Any kind of a product that doesn't qualify, it doesn't meet the quality standard just goes back as cullets. Yeah. OK. All right. Thank you very much.